# Chapter 4

# Workflow and Yield

# 4 Introduction

Production of a product or delivery of a service may require several operations. They may be performed sequentially or simultaneously with multiple workers at multiple workstations. The workstations are often located separately, which requires the movement of work units from one operation to the next in sequence. In many cases, the most practical way to accomplish the processing is to produce work units in batches.

## 4.1 Sequential Operations and Workflow

Sequential operations are processes where tasks are performed one after another in a specific order. Each task must be completed before the next one begins. The work units may be materials, parts, products, or people.

In sequential operations, there are usually machine or processing limitations on the order in which the operations can be performed. These limitations are called ***precedence constraints***, which are rules that dictate the order in which tasks must be performed. They ensure that certain tasks are completed before other tasks can begin. An example is a hole that must be drilled before it can be tapped to cut the threads. A second example is that passengers must be checked in and processed through security at an airport before being allowed to board an airplane. A third example is a dental patient must be anesthetized before the dentist performs a root canal.

The term ***workflow*** refers to the physical movement of processing materials and work units in sequential processing. Closely related to the physical workflow is an information flow to monitor and control the movement of work units, which is governed by the production schedule and individual job tickets.

## 4.2 Workflow Patterns

Two basic types of workflow patterns can be distinguished:

1. In a ***pure sequential pattern***, all work units follow the same sequence of workstations and operations. There is no variation in the processing sequence.
2. In a ***mixed sequential pattern***, there are variations in the workflow for different work units. Different work units may be processed through different workstations.

A pure sequential pattern (a) and a mixed sequential pattern (b) are illustrated in Figure 4.1 below.

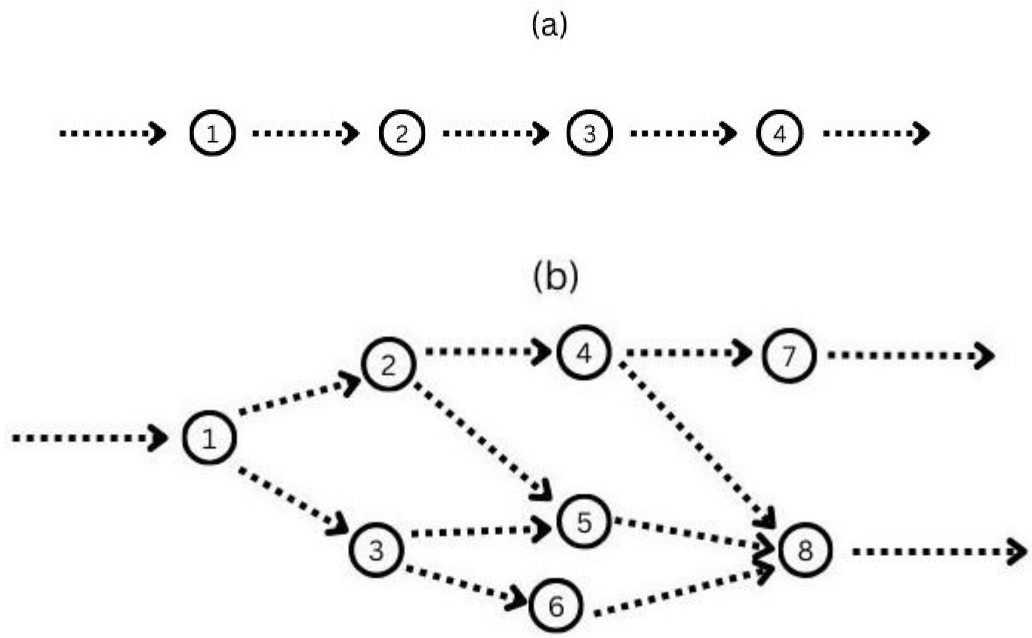


**Figure 4.1.** Diagrams illustrating (a) pure sequential workflow and (b) mixed sequential workflow.

Different work units may experience any of four types of movements in a sequential workflow.

- Linear flow. This occurs with the transfer of one work unit from a current operation to an immediate downstream operation in a forward direction but cannot reverse back upstream.
- Bypassing. This occurs when a work unit moves in the forward direction leapfrogging the neighboring workstation to another workstation downstream.
- Backflow. This occurs when a work unit moves in the backward direction by at least one workstation.
- Repeat operation. This occurs when an operation is repeated at the same workstation. It may be that several attempts are required to complete the operation, or two or more operations must be performed at the same workstation and the operations must be separated for some reason (i.e., a different setup is required for each operation).

The four types of movements are illustrated in Figure 4.2.

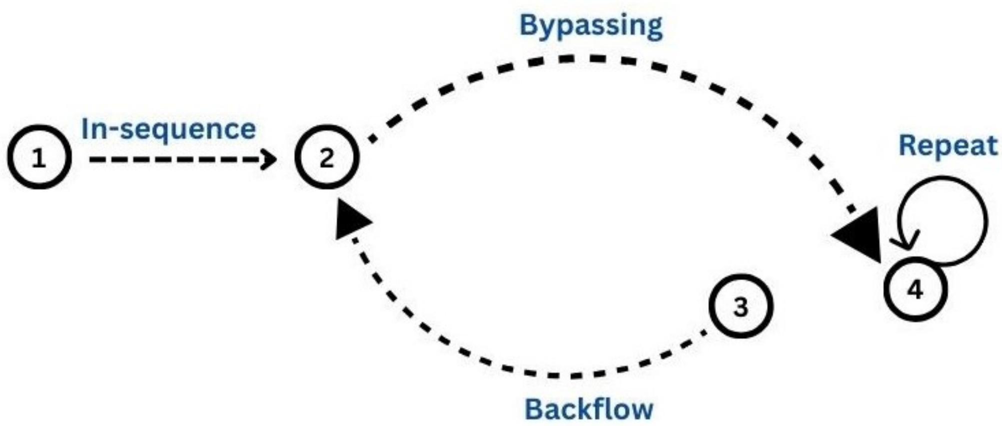


**Figure 4.2.** Diagram of four types of movements in a sequential workflow.

### 4.3 Bottlenecks in Sequential Operations

A ***bottleneck*** is a stage in the process where the flow is restricted, such as a slow machine in the production line, slowing down the entire system. In the long run, upstream operations must produce at a rate that is no greater than the bottleneck operation, otherwise a bottleneck occurs. ***Blocking*** occurs when upstream operations are blocked from further production, meaning that the production rate of one or more upstream operations are limited by the rate of a downstream operation. Additionally, downstream operations can work no faster than the rate at which a bottleneck operation feeds work units to them. For example, a storage area that is full so the production line must stop. ***Starving*** occurs when downstream operations are starved for work, meaning that the production rate of one or more downstream operations is limited by the rate of an upstream operation (i.e., a bottleneck). For example, a machine is waiting for raw material stock from the forklift operator.

#### 4.3.1 Reasons for Bottlenecks and Ways to Relieve Them

The primary reasons why bottlenecks occur are: (1) equipment breakdowns, (2) variability in processing times, and (3) limited capacity. Some ways to relieve bottlenecks include adding extra capacity or resources (i.e., people, machinery, overtime, cross-training, farm-outs, etc.), improving maintenance and reliability of machinery and equipment, and balancing workloads and production lines.

#### 4.3.2 Batch Processing

***Batch processing*** is a method where items are processed in batches, or lot sizes, rather than individually. The work units can be materials, products, information, or people. Batch processing is common in production, logistics, and service operations. Examples of batch processing include producing a lot size of 1000 identical parts before switching to produce a different part, passengers traveling by airplane, or washing a load of laundry.

There are two types of batch processing:

(1) ***Sequential batch processing***, in which batches are processed one after the other (i.e., baking multiple batches of bread one after another in the same oven).
(2) ***Simultaneous batch processing***, in which multiple batches are processed at the at the same time on different resources (i.e., baking batches of bread simultaneously in multiple ovens).

## 4.4 The Pros and Cons of Batch Processing

Some pros and cons of batch processing are discussed in sections 4.4.1 and 4.4.2, respectively.

### 4.4.1 Pros of Batch Processing

The following are some of the pros of batch processing:

- Economies of scale. This means the ***cost per unit*** decreases when units are produced in batches rather than individual units.
- Work unit differences. Because of the differences in work units, it is often necessary to make changes to the production methods, tooling, or equipment to accommodate these differences, commonly referred to as ***setups***. In a mass production environment, once a setup is complete, it becomes cost effective to produce a batch of product rather than one.
- Machine or equipment limitations. Machine or equipment capabilities may impose restrictions on the size or weight of materials or quantity of work units that can be processed.
- Material limitations. Sometimes material must be produced as one unit, but later divided into sub-units due to the small size or weight of each sub-unit. This is referred to as running **“*multiple-out*”**.

### 4.4.2 Cons of Batch Processing

- Interruptions, such as discontinuity between batches, may be attributed to setups, or changeovers (i.e., breaking down the setup of the previous order and setting up the next order). Setups are a necessary step to produce each order; however, the

downtime associated with setups adversely impacts production output because this is lost production time that cannot be recouped. Changeovers are also common in non-production processes (i.e., airplanes, buses, or railroad cars at a terminal unloading and loading passengers).
- Multiple batches may build up in front of a workstation resulting in long lead times and accumulated work-in-process (WIP) inventory buildup.

The cyclical patterns of setups and production runs in batch production are illustrated in Figure 4.3.

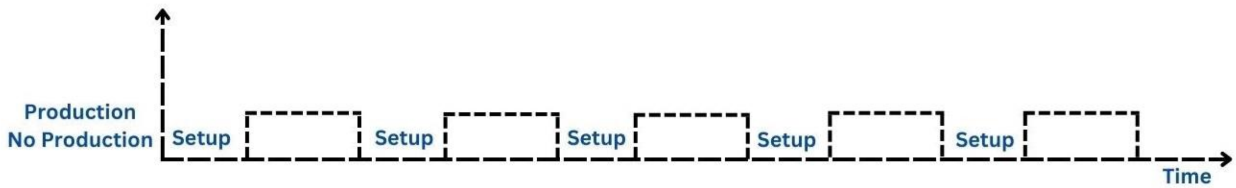


**Figure 4.3.** Alternating cycles of setups and production run time in batch processing.

## 4.5 Economic Order Quantity Model

Figure 4.4 illustrates a model of inventory level over time in a typical make-to-stock situation.

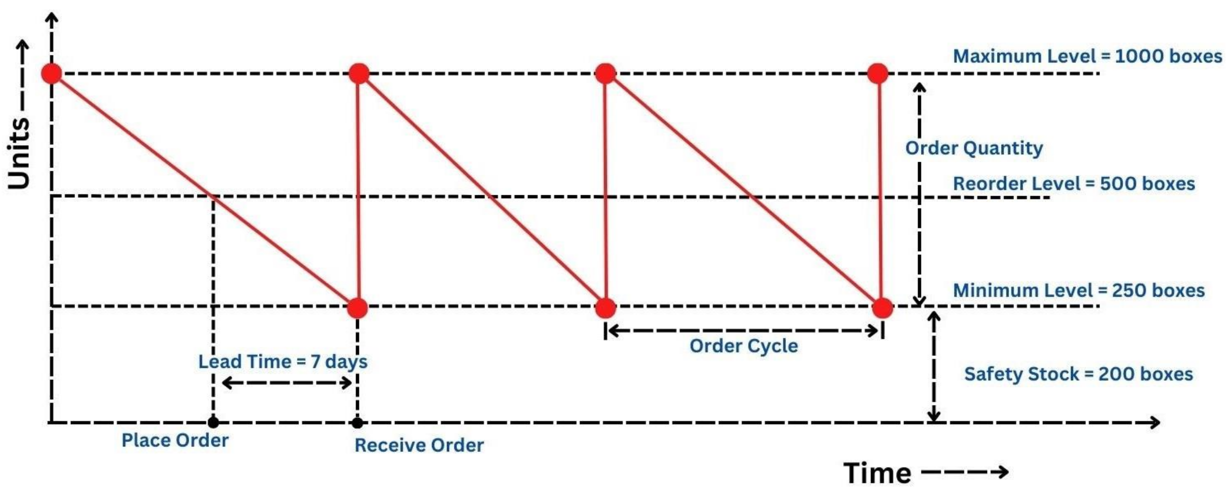


**Figure 4.4.** A model of inventory level over time in a typical make-to-stock situation.

Figure 4.4 assumes a constant demand rate is in effect and that inventory is gradually withdrawn over time and then replenished to a predefined maximum inventory level that is determined by the order quantity. Notice that the average inventory level is equivalent to one-half of the maximum inventory level, Q, which is multiplied by the inventory carrying cost per item. The annual setup cost is equal to the number of setups per year multiplied by the cost per setup. The equation for total annual inventory cost is given by the following equation:

$$TIC = \frac{C_h Q}{2} + \frac{C_{su} D_a}{Q} \tag{4.1}$$

where *TIC* = total annual inventory cost (holding cost plus ordering cost), \$/yr; *Q* = economic order quantity, pc/order; $C_h$ = inventory carrying cost, \$/pc/yr; $C_{su}$ = setup cost and/or ordering cost for an order, \$/setup or \$/order; and $D_a$ = annual demand for the item, pc/yr.

On the right side of the equation, the ratio $D_a/Q$ represents the number of orders, or batches, produced per year. Equivalently, this yields the number of setups per year.

Holding cost, $C_h$, refers to the total cost of holding inventory and consists of warehousing costs, (i.e., rent, utilities, salaries), financial costs (i.e., opportunity cost), and inventory costs related to perishability, shrinkage, and insurance.

If the actual annual cost of part production is included in Equation (1), then annual cost is given by the following equation:

$$TC = D_a C_{pc} + \frac{C_h Q}{2} + \frac{C_{su} D_a}{Q} \tag{4.2}$$

where $D_a C_{pc}$ = annual demand (pc/yr) multiplied by cost per item (\$/pc).

The economic order quantity (*EOQ*) in Equation (4.3) is derived by taking the derivative of either Equations (4.1) or (4.2) with respect to *Q* and setting the derivative equal to zero and solving for *Q*.

$$Q = EOQ = \sqrt{\frac{2 D_a C_{su}}{C_h}} \tag{4.3}$$

where *EOQ* = economic order quantity (the number of parts to be produced per batch, pc/order.

**Example 1. Economic Order Quantity**

The annual demand for a certain item made-to-stock is 2,000 pc/yr. One unit of the item costs $10.00 and the holding cost rate is 15%/yr. Setup time to produce a batch is 1.5 hr. The cost of equipment downtime plus labor is $150/hr. Determine the economic order quantity (EOQ) and the total inventory cost for this case.

**Solution:**

Setup cost $C_{su}$ = 1.5 hr x $150/hr = $225. Holding cost per unit = 0.15 x $10.00/pc = $1.50. Using these values and the annual demand rate in the EOQ formula, from equation (3), we have

$$EOQ = \sqrt{\frac{2(2{,}000)(\$225)}{\$1.50}} = 774.6, or \sim 775\ units$$

Total inventory cost (*TIC*) is given by equation (1).

$$TIC = \frac{(\$1.50)(775)}{2} + \frac{(\$225)(2{,}000)}{775} = \$1161.90$$

Including the actual production costs in the annual total and using equation (2), we have:

$$TC = 2{,}000(\$10.00) + \frac{(\$1.50)(775)}{2} + \frac{(\$225)(2{,}000)}{775} = \$21{,}161.90$$

## 4.6 Workload and Available Time

Workload refers to the sum of the quantity of work units to be produced multiplied by the cycle time per unit divided by 1 – scrap rate as in Eq. (4).

$$WL = \frac{\sum_j Q_j T_{cj}}{(1-scrap\ rate)} \tag{4.4}$$

where

$WL$ = scheduled workload, $Q$ = quantity to be produced, $T_c$ = cycle time per unit, and $j$ = part number.

We can expand this concept in a simple example to determine the number of workers and workstations required, given one worker per workstation and a certain workload with Eq. (5).

$$w = \frac{WL}{AT} \quad or \quad n = \frac{WL}{AT} \tag{4.5}$$

where

$w$ = number of workers, $n$ = number of workstations, and $AT$ = available time of one worker in the period under study.

**Example 2. Determining Worker and Machine Requirements**

Future production requirements in the engine lathe department must be satisfied through the acquisition of several new machines and the hiring of new operators, the exact number to be determined. There are three new parts that will be produced. Part A has annual quantities of 25,000 units; part B, 30,000 units; and part C, 41,000 units. Corresponding standard times for these parts are 6.2 min, 3.4 min, and 7.6 min, respectively. The department will operate one 8-hour shift for 250 days/yr. The machines are expected to be 97.8% reliable, and the anticipated scrap rate is 3.2%. Worker efficiency is expected to be 100%. How many new engine lathes and operators are required to meet these production requirements?

**Solution**:

Let WL = scheduled workload

AT = available time

n = no. of workstations

w = no. of workers

$Q_j$ = quantity for part j

$T_{cj}$ = cycle time for part j

$$WL = \frac{\sum_j Q_j T_{cj}}{(1 - scrap\ rate)}$$

$$= \frac{(25{,}000\ pc \times 6.2\ min/pc) + (30{,}000\ pc \times 3.4\ min/pc) + (41{,}000\ pc \times 7.6\ min/pc)}{(1 - 0.032)}$$

$$= \frac{155{,}000\ min + 102{,}000\ min + 311{,}600\ min}{0.968}$$

$$= \frac{568{,}600\ min}{0.968} \times \left(\frac{1\ hr}{60\ min}\right)$$

$$= 9{,}789.9\ hrs$$

$$AT = (hr/day)(days/yr)(reliability) = \left(\frac{8\ hr}{day}\right)\left(\frac{250\ days}{yr}\right)(0.978) = 1{,}956\ hr/yr$$

$$n = w = \frac{WL}{AT} = \frac{9{,}789.9\ hrs}{1{,}956\ hrs/yr} = 5.005\ (rounded\ down\ to\ 5\ workers\ and\ 5\ lathes)$$

Reliability refers to the probability that a product will perform its intended function under specified environmental conditions (i.e., stated operating conditions) for a specified period.

Availability refers to the proportion of time the equipment is available to run relative to the total time it could be used. It is the proportion of time that the equipment is not malfunctioning or broken down.

### 4.7 Fraction Defect Rates

In a sequence of operations, defective units may be produced in any or all the operations. Therefore, the defect rate must be considered in determining both the final quantity of good units produced as well as the starting quantity.[2]

#### 4.7.1 Defects in Unit Operations

Figure 4.5 illustrates how defect rates, $q$, impact the final quantity produced, $Q_f$, from a starting quantity, $Q_o$.

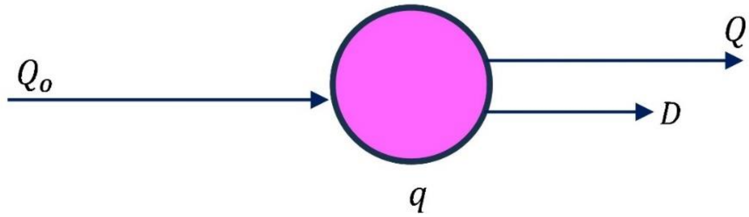


**Figure 4.5.** Processing of $Q_o$ starting units to produce $Q_f$ good units and D defects.

The input/output relationship in a sequence of n unit operations is given by Eq.4.6:

$$Q_f = Q_o(1-q_1)(1-q_2)\ldots(1-q_n) \tag{4.6}$$

where $Q_f$ = final quantity and $Q_o$ = starting quantity; $q_n$ = fraction defect rate of each different defect rate, $D_f = Q_o - Q_f$, the number of defective units; and *Yield* = $Y = Q_f/Q_o$.

**Example 3. Multiple Processes with Same Fraction Defect Rates**

A starting batch of 7000 work units is processed through 5 sequential operations, each of which has a fraction defect rate of 2%. (a) How many good parts and (b) defects are in the final batch, and (c) what is the yield of the operation sequence?

**Solution:**

(a) $Q_f = Q_o(1-q_1)(1-q_2)\ldots(1-q_n)$
$= 7{,}000(1-0.02)^5 = 7{,}000(0.98)^5 = 7{,}000(0.9039) = 6{,}327\ units$

(b) $D_f = Q_o - Q_f = 7{,}000 - 6{,}327 = 673\ defective\ units$

(c) $Y = \frac{Q_f}{Q_o} = \frac{6{,}327}{7{,}000} = 0.9039\ \times 100 \sim 90.4\%$

**Example 4. Multiple Processes with Different Fraction Defect Rates**

A starting batch of 20,000 parts is processed through 4 sequential operations. Operations 1 and 2 each have a fraction defect rate of 2%, operation 3 has a fraction defect rate of 3%, and operation 4 has a fraction defect rate of 6%. (a) How many good parts and (b) defects are in the final batch, and (c) what is the yield of the operation sequence?

**Solution**:

(a) $Q_f = Q_0(1 - q_1)^2(1 - q_2)^1(1 - q_3)^1$

$= 20{,}000(1 - 0.02)^2(1 - 0.03)^1(1 - 0.06)^1$

$= 20{,}000(0.9604)(0.97)(0.94)$

$= 17{,}514$

(b) $D_f = Q_0 - Q_f = 20{,}000\, pc - 17{,}514\, pc = 2{,}486\, defects$

(c) $Y = \frac{Q_f}{Q_0} = \frac{17{,}514}{20{,}000} = 0.8757 \times 100 = 87.57\%$

## 4.8 Summary

In a production environment, understanding and managing workflow patterns, bottlenecks, batch processing, EOQ, workload, available time, and fraction defect rates are crucial for optimizing efficiency, reducing costs, and maintaining high-quality standards. These elements collectively contribute to a streamlined and effective production process, ensuring that limited resources are used efficiently, and output meets the desired quality and quantity.

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## References

[1] Groover, M.P. *Work Systems and the Methods, Measurement, and Management of Work*, Upper Saddle River, NJ: Pearson Prentice Hall, 2007.

[2] Goetsch, D.L., and S.B. Davis. *Quality Management: Introduction to Total Quality Management for Production, Processing, and Services*. 4th ed. Upper Saddle River, NJ: Prentice Hall, 2003.