Factory Automation and Control Methods
Lecture 3: Manufacturing Metrics and Economics

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Outline

- Production Performance Matrices
- Manufacturing Cost

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Cycle Time Analysis

Typical cycle time for a production operation

$$T_c = T_0 + T_h + T_{th}$$

Where

T_c = cycle time (min/pc).
T_0= processing time for the operation (min/pc),
T_h = handling time (min/pc),
T_{th} = tool handling time (min/pc).

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Production Rate (pc/hr): determined based on the operation cycle time for the three types of production: job shop production, batch production, and mass production

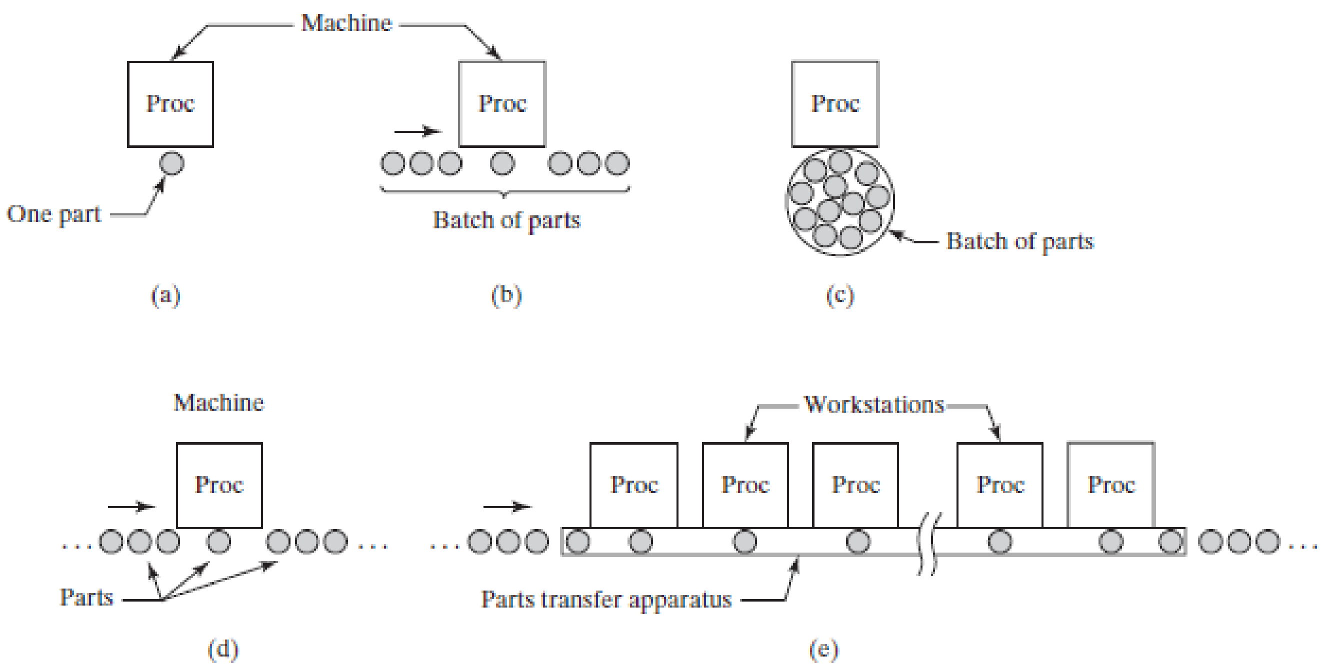


Figure 3.1 Types of production operations: (a) job shop with production quantity $Q = 1$, (b) sequential batch production, (c) simultaneous batch production, (d) quantity mass production, and (e) flow-line mass production. Key: Proc = process.

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Job shop production ($1 \leq Q \leq 100$):

For $Q = 1$, $$T_p = T_{su} + T_c$$

Where, T_p = average production time (min/pc), T_{su} = setup time to prepare the machine to produce part, T_c = cycle time.

The production rate for the unit operation time, usually expressed as hourly rate

$$R_p = 60/T_p$$

Where R_p = hourly production rate (pc/hr)

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

In sequential batch processing,

$$T_b = T_{su} + QT_c$$

Where T_b = batch processing time (min/batch), T_{su} = setup time to prepare the machine for the batch (min, batch), Q = batch quantity (pc/batch), T_c = cycle time per work unit.

In simultaneous batch processing,

$$T_b = T_{su} + T_c$$

To obtain the average production time per work unit T_p for the unit operation, the batch time is divided by the batch quantity:

$$T_p = \frac{T_b}{Q}$$

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

For mass production

$$R_p \rightarrow R_c = 60/T_c$$

since $\frac{T_{su}}{Q} \rightarrow 0$ (Q is very large)

Where

R_c = operation cycle rate of the machine (pc/hr)

T_c = operation cycle time (min/pc)

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Production Rate

Flow-line production:

Bottleneck station is the station with the largest operation time (with highest utilization)

$$T_c = T_r + Max\ T_0$$

T_c = cycle time of the production line (min/cycle)

T_r= time to transfer work units between workstations each cycle (min/cycle)

$MaxT_0$ = operation time at the bottleneck station (min/cycle). The max of the operation times for all stations on the line.

$$R_c = \frac{60}{T_c}$$

R_c= theoretical (ideal) production rate (cycles/hr)

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Equipment Reliability

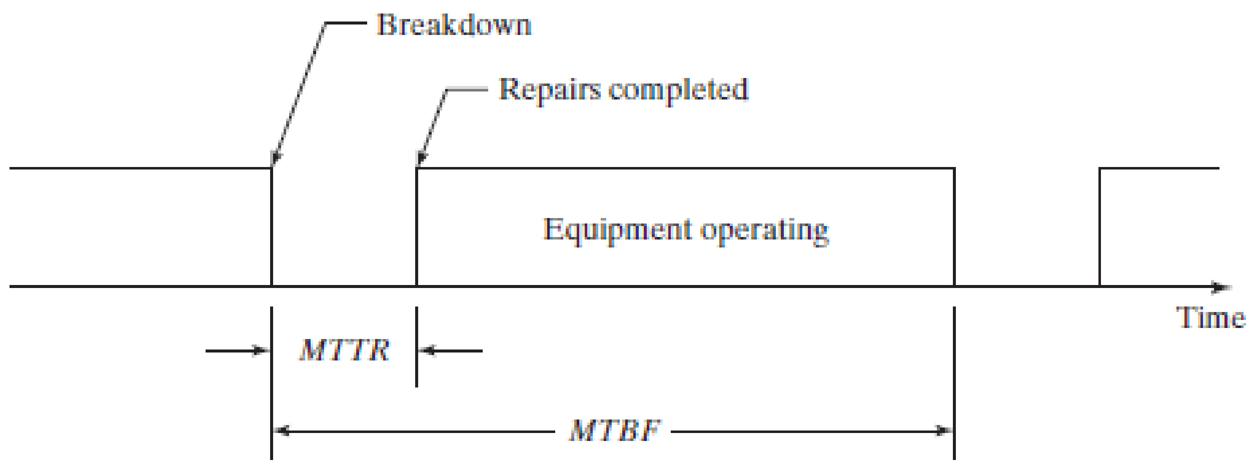


Figure 3.2 Time scale showing *MTBF* and *MTTR* used to define availability *A*.

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Equipment Reliability

Availability can also be defined using two other reliability terms,

$$A = (MTBF - MTTR)/MTBF$$

Where MTBF = mean time between failures and MTTR = mean time to repair. MTBF is the average length of time the piece of equipment runs between breakdowns, and MTTR is the average time required to service the equipment and put it back into operation when a breakdown occurs. Availability is typically expressed as a percentage.

1. Production Performance Matrices
1.1 Cycle Time and Production Rate

Production Capability

Ex. Plant or factory …

"Max rate of output that a **production facility** is able to produce under a given set of **assumed operating conditions**"

- Number of shifts per day
- Number of days per week
- Employment levels
- …..

The number of hour a plant operation per week is a crucial issue in defining plant capacity. Ex. Continuous chemical production (24/7), automobile final assembly (one or two shift depends on the demands)

Full capacity

1. Production Performance Matrices
1.2 Production Capability and Utilization

Determining plant capability

Plant capability for facility in which parts are made in one operation $(n_0 = 1)$

$$PC = n\, H_{pc} R_p$$

Where

PC = production capability of a given facility (pc /period)
n = number of machines
H_{pc}= the number of hours in the period being used to measure production capability
R_p = production rate (units/hr)

1. Production Performance Matrices
1.2 Production Capability and Utilization

Determining plant capability

In cases in which different machine produce different parts at different production rates, the following equation applies for quantity-type mass production:

$$PC = H_{pc} \sum_{i=1}^{n} R_{pi}$$

Where n = number of machines in the plant, R_{pi} = hourly production rate of machine i, and all machines are operating full time during the entire period defined by H_{pc}.

1. Production Performance Matrices
1.2 Production Capability and Utilization

Determining plant capability

Ex. The automatic lathe department has five machines, all devoted to the production of the same product. The machines operate two 8-hr shifts, 5 days/week, 5- weeks/year. Production rate of each machine is 15 unit/hr. Determine the weekly production capability of the automatic lathes department.

Ans: 6000 pc/wk

Further reading, pages 51 - 54

1. Production Performance Matrices
1.2 Production Capability and Utilization

This capability model assumes that all n machines are producing 100% of the time and there are no bottleneck operations due to variations in process routings to inhibit smooths flow of work through the plant.

There are some operations that are fully utilized while other operations occasionally stand idle waiting for work.

That is, utilization varies.

1. Production Performance Matrices
1.2 Production Capability and Utilization

Determining plant capability

In job shop and batch production, each machine may be used to produce more than one batch, where each batch is made up of a different part style j.

Let f_{ij} be the fraction of time during the period that machine i is processing part style j . Under normal operating conditions, it follows that for each machine i,

$$0 \le \sum_j f_{ij} \le 1 \quad \text{where } 0 \le f_{ij} \le 1 \text{ for all } i$$

Machine is utilized 100% of the time during the week

$f_{ij} \ge 1 \Rightarrow$ this can be interpreted as the machine is being used on an overtime basis beyond the number of hours H_{pc} in the definition of plant capacity.

1. Production Performance Matrices
1.2 Production Capability and Utilization

Utilization

"The proportion of time that a productive resource (e.g a production machine) is used relative to the time available under the definition of plant capability"

$$U_i = f_{ij}$$

Where U_i = utilization of machine i , and f_{ij}= fraction of time during the available hours that machine i is processing part style j. An overall utilization for the plant is determined by averaging the U_i values over the number of machines

$$U = \frac{\sum_{i=1}^{n} \sum_j f_{ij}}{n} = \frac{\sum_j U_i}{n}$$

1. Production Performance Matrices
1.3 Manuf. Lead Time and Work-In-Process

In the competitive environment of global commerce, the ability of a manufacturing firm to deliver a product to the customer in the shortest possible time often wins the order.

1. Production Performance Matrices
1.3 Manuf. Lead Time and Work-In-Process

Manuf. lead time

"The total time required to process a given part or product through the plant, including any time due to delays, parts being moved between operations, time spent in queues, and so on."

Manufacturing lead time for a given batch is defined as

$$MLT_j = \sum_{i=1}^{n_{oj}} \left(T_{suij} + Q_j T_{cij} + T_{noij}\right)$$

Where

MLT_j = manufacturing lead time for a batch of part or product j (min),
T_{suij} = setup time for operation I on part or product j (min),
Q_j = quantity of part or product j in the batch being processed, (pc),
T_{cij} = cycle time for operation I on part or product j, (min/pc),
T_{noij} = nonoperation time associated with operation i (min),,
n_{oj}= number of separated operations through which the work unit must be rooted
i indicates the operation sequence in the processing ,$i = 1,2,3, \ldots n_{oj}$

1. Production Performance Matrices
1.3 Manuf. Lead Time and Work-In-Process

Manuf. lead time

The average manufacturing lead time over the number of batches to be averaged is given by the following:

$$MLT = \frac{\sum_{j=1}^{n_b} MLT_j}{n_b}$$

Where MLT = average manufacturing lead time (min) for n_b batches (parts or products) over which the averaging procedure is carried out.

1. Production Performance Matrices
1.3 Manuf. Lead Time and Work-In-Process

Manuf. lead time

The average manufacturing lead time over the number of batches to be averaged is given by the following:

Exercise. A certain part is produced in batch sizes (Q) of 100 units. The batches must be routed through five operations to complete the processing of the parts. Average setup time (T_{su}) is 3.0 hr / batch, and average operation time (T_c) is 6.0 min/pc. Average nonoperation time (T_{no}) is 7.5 hr for each operation. Determine the manufacturing lead time to complete one batch, assuming the plant runs 8 hr/ day, 5 days/wk.

Ans: MLT_j=102.5hr

1. Production Performance Matrices
1.3 Manuf. Lead Time and Work-In-Process

Work-in-process

A plant's work-in-process (*WIP*) is the quantity of parts or products currently located in the factory that either are being processed or are between processing operations.

$$\mathrm{WIP} = \mathrm{R_{pph}}(\mathrm{MLT})$$

Where WIP= work-in-process (pc), R_{pph} = hourly plant production rate, pc/hr

Work-in-process represents an investment by the firm, but one that cannot be turned into revenue until all processing has been completed. Many manufacturing companies sustain major costs because work remains in-process in the factory too long.

2. Manufacturing Costs
2.1 Fixed and Variable Cost

Manufacturing costs can be classified into two major categories:

- Fixed costs: one that remains constant for any level of production output. Examples include the cost of the factory building and production equipment, insurance, and property taxes. All of the fixed costs can be expressed as annual amounts. Expenses such as insurance and property taxes occur naturally as annual costs.

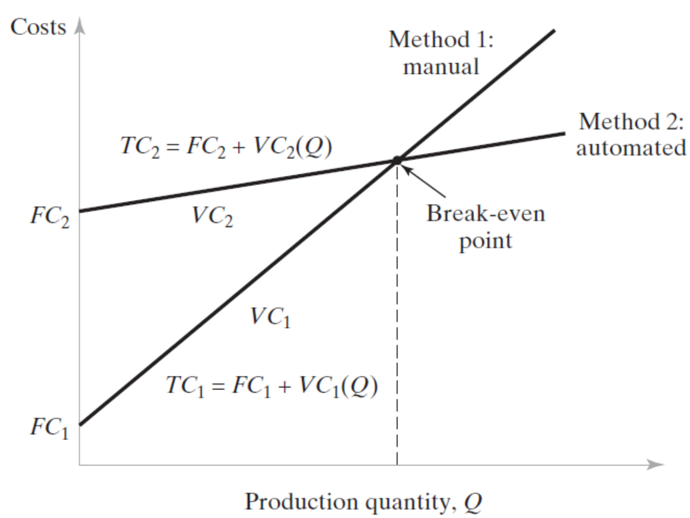
- Variable costs: one that varies in proportion to production output. As output increases, variable cost increases. Examples include direct labor, raw materials, and electric power to operate the production equipment

2. Manufacturing Costs
2.1 Fixed and Variable Cost

Adding fixed and variable costs results in the following total cost equation:

$$TC = C_f + C_v Q$$

Where TC = total annual cost (\$/yr), C_f= fixed annual cost, (\$/yr), C_v= variable cost (\$/pc), and Q = annual quantity produced (pc/yr)



2. Manufacturing Costs
2.1 Fixed and Variable Cost

Exercise. Two production methods are being compared, one manual and the other automated. The manual method produces 10 pc/hr and requires one worker at $15.00/hr. Fixed cost of the manual method is $5,000/yr. The automated method produces 25 pc/hr, has a fixed cost of $55,000/yr, and a variable cost of $4.50/hr. Determine the break-even point for the two methods; that is, determine the annual production quantity at which the two methods have the same annual cost. Ignore the costs of materials used in the two methods.

Annual cost of manual method: $TC_m = 5000 + \left(\frac{1.5}{10}\right) Q$

Annual cost of the automated method $TC_a = 55000 + \left(\frac{4.5}{25}\right) Q$

At the break-even point $Q = 37879 \text{ pc}$

Comment: It is of interest to note that the manual method operating one shift (8 hr), 250 days per year would produce 8(250)(10) = 20,000 pc/yr, which is less than the break-even quantity of 37,879 pc. On the other hand, the automated method, operating under the same conditions, would produce 8(250)(25) = 50,000 pc, well above the break-even point.

2. Manufacturing Costs
2.2 Direct Labor, Materials and Overhead

- Direct labor cost is the sum of the wages and benefits paid to the workers who operate the production equipment and perform the processing and assembly tasks.
- Material cost is the cost of all raw materials used to make the product.
- Overhead costs are all of the other expenses associated with running the manufacturing firm. Overhead divides into two categories: factory overhead and corporate overhead.

2. Manufacturing Costs
2.2 Direct Labor, Materials and Overhead

Factory overhead

Plant supervision	Applicable taxes	Factory depreciation
Line foreman	Insurance	Equipment depreciation
Maintenance crew	Heat and air conditioning	Fringe benefits
Custodial services	Light	Material handling
Security personnel	Power for machinery	Shipping and receiving
Tool crib attendant	Payroll services	Clerical support

Corporate overhead

Corporate executives	Engineering	Applicable taxes
Sales and marketing	Research and development	Office space
Accounting department	Other support personnel	Security personnel
Finance department	Insurance	Heat and air conditioning
Legal counsel	Fringe benefits	Lighting

2. Manufacturing Costs
2.2 Direct Labor, Materials and Overhead

Factory overhead rate

$$FOHR = \frac{FOHC}{DLC}$$

Where $FOHR$= factory overhead rate, $FOHC$ = annual factory overhead cost, \$/yr and DLC = annual direct labor costs, \$/yr.

Corporate overhead rate

$$COHR = \frac{COHC}{DLC}$$

Where $COHR$ = corporate overhead rate, $COHC$ = annual corporate overhead costs \$/y, and DLC = annual direct labor costs (\$/yr).

2. Manufacturing Costs
2.3 Cost Equipment Usage

The machine annual cost is the initial cost of the machine apportioned over the life of the asset at the appropriate rate of return used by the firm. This is done using the capital recovery factor, as

$$UAC=IC(A/P,i,N)$$

Where UAC = equivalent uniform annual cost, \$/yr; IC= initial cost of the machine,\$; (A/P, i,N) = capital recovery factor that converts initial cost at year 0 into a series of equivalent uniform annual year-end values, where i= annual interest rate and N= number of years in the service life of the equipment.

For given values of i and N, (A/P,i,N) can be computed as follow:

$$(A/P,i,N) = \frac{i(1+i)^N}{(1+i)^N-1}$$

2. Manufacturing Costs
2.3 Cost Equipment Usage

The total cost rate for the machine is the sum of labor and machine costs. This can be summarized for a machine consisting of one worker and one machine as follows:

$$C_0 = C_L(1 + FOHR_L) + C_m(1 + FOHR_m)$$

Where C_0= hourly rate to operate the machine, \$/hr; C_L = direct labor wage rate, \$/hr; $FOHR_L$ = factory overhead rate for labor; C_m = machine hourly rate, \$/yr; and $FOHR_m$= factory overhead rate applicable to the machine.

2. Manufacturing Costs
2.3 Cost of a Manufactured Part

The unit cost of a manufactured part or product is the sum of the production cost, material cost, and tooling cost. The unit production cost for each unit operation in the sequence of operations to produce the part or product is given by:

$$C_{oi}T_{pi} + C_{ti}$$

Where C_{oi} = cost rate to perform unit operation i,\$/min, T_{pi} = production time of operation i (min/pc) and C_{ti} = cost of any tooling used in operation i , \$/pc.

The total unit cost of the part is the sum of the costs of all unit operations plus the cost of raw materials. Summarizing,

$$C_{pc} = C_m + \sum_{i=1}^{n_0} C_{oi}T_{pi} + C_{ti}$$

Where C_{pc} = cost per piece ,\$/pc; C_m = cost of starting materials, \$/pc; and the summation includes all of the cost of the n_0 unit operations in the sequence.

Reference

Mikell P. Groover, “Automation, Production Systems and Computer-integrated Manufacturing” , 4th edition, Pearson, chapter 2