Flexible Manufacturing System

- Introduction to FMS
- Features of FMS
- Operational problems in FMS
- Layout considerations
- Sequencing of Robot Moves
- FMS Scheduling and control
- Examples
- Deadlocking
- Flow system
- Complex control FMS
- General Shop-Floor Control Problem
Why do we need flexibility in manufacturing systems?

• Variety in products *thus* options for the consumers
• Optimizing the manufacturing cycle time
• Reduced production costs
• Overcoming internal changes like failure, breakdowns, limited sources, etc.
• External changes such as change in product design and production system.
Flexibility in Manufacturing System:

- Flexibility can be defined as collection of properties of a manufacturing system that support changes in production activities or capabilities (Carter, 1986).

- Ability of the manufacturing system to respond effectively to both internal and external changes by having built-in redundancy of versatile equipments.
Various types of flexibility?

- **Machine flexibility**
  - Capability of a machine to perform a variety of operations on a variety of part types and sizes

- **Routing flexibility**
  - Alternative machines, sequences or resources can be used for manufacturing a part for changes resulting from equipment breakdowns, tool breakages, controller failures, etc.

- **Process flexibility**
  - Ability to absorb changes in the product mix by performing similar operations, producing similar products or parts.

- **Product flexibility**
  - Ability to change over to a new set of products economically and quickly in response to markets

- **Production flexibility**
  - Ability to produce a range of products without adding capital equipment

- **Expansion flexibility**
  - Ability to change a manufacturing system with a view to accommodating a changed product envelope
Volume-variety relationship

**FIGURE 13.1** Volume-variety relationships categorizing production systems.
Classification of the manufacturing system based on Volume-variety considerations:

*Transfer Line (High-Volume, Low-Variety Production system, H-L)*

- Machines dedicated to manufacture of one or 2 product types.
- Nearly no flexibility
- Maximum utilization and high production volume
- Direct labor cost is minimal
- Low per unit cost

*Stand Alone NC machines / Flexible Manufacturing module (Low-Volume High-Variety Production system, L-H)*

- Highest level of flexibility
- Low utilization and low production volume
- Very high per unit cost

*Mid-Volume Mid-Variety Production systems, M-M*

- *Manufacturing Cell*
- *Flexible manufacturing system*
- *Special Manufacturing System*
**Manufacturing Cell**

- Low to mid-volume, most of the parts are manufactured in batch mode
- Similar to an FMS, but no central control
- Most flexible in CIM category
- Lowest production rate in CIM systems

**Flexible manufacturing system**

- Actual M-M manufacturing system.
- Automated material-handling system, NC machines (flexible machines), automated tools and pallet changer, auto-gauge systems, etc.
- Allows both sequential and random routing of a wide variety of parts.
- Higher production rate than manufacturing cell
- High degree of overlap between this and cell manufacturing system
- Higher flexibility than special manufacturing systems

**Special Manufacturing System**

- Least flexible category of CIM system
- Multispindle heads and low-level controller
- High production rate and low per unit cost
- **Main difference:** - Fixed-path material-handling system links the machines together.
  - Sequence based dedicated machines.
What is FMS?

• “an automated, mid-volume, mid-variety, central computer-controlled manufacturing system”

• Activities covered: machining, sheet metal working, welding, fabricating, assembly

• Physical components:
  – Potentially independent NC machine tools capable of performing multiple functions and having automated tool interchange capabilities
  – Automated material handling system to move parts between machine tools and fixturing stations
  – All the components are hierarchically computer controlled
  – Equipment such as coordinate measuring machines and part-washing devices
1. Four Milacron CNC Machining Centers (Floor space reserved for adding three more)

2. Four Tool Interchange Systems (One per machine), computer-controlled tool delivery via cart

3. Three remotely controlled carts with wire-guided path

4. Two load/unload, clean/orient stations with coolant/chip handling

5. One Inspection Module (Coordinate Measuring Machine)

6. Two automatic workchangers (10 pallets each) for part overflow and queue

7. Raised office (Cart path under)

8. Cart maintenance station
A FMS consists of:

• Physical subsystem
  
  - Workstations: NC machine tools, inspection equipment, part-washing devices, load & unload area.
  - Storage-retrieval systems
  - Material handling systems

• Control subsystem
  
  - Control hardware
  - Control software
NC machine tools: The major building blocks of an FMS, determine the degree of flexibility, determine the capabilities. Machining centers with numerical control of movements in up to five axes. Spindle movement in x, y and z directions, rotation of table, and tilting of table.
Workholding and Tooling considerations

- Fixtures and pallets must be designed to minimize part-handling time
- Strategies required for storage/retrieval of different fixtures
- Integration with AS/RS and material handling system
- Machining centers are equipped with tool storage known as tool magazine.

*FIGURE 13.4 Various types of tool magazines: (a) disk type, (b) drum type, (c) turret type, (d) chain type, and (e) chain type. (Kusiak, Andrew: Intelligent Manufacturing Systems, © 1990, Figure 2.23, p. 40. reprinted by permission of Prentice Hall Inc., Englewood Cliffs, NJ.)*
Control systems in FMS

• Work-order processing and part control system
  – Part process planning module, part routing module, part setup module, etc.

• Machine tool control system
  – DNC transmitter control module, NC editor, machine monitor and control module

• Tool management and control system
  – To control the processing of parts and enhance the flexibility to manufacturing variety of parts. Tool identification, tool setup, tool routing, tool replacement strategies are accomplished by the system

• Traffic management control system
  – Material handling and storage control system coordinates part routing, fixtures, pallets and tool modules
• Quality control management system
  • Capabilities include collection, storage, retrieval, and achieving of work-piece inspection data.

• Maintenance control system (service control system)
  • On-line help, alarms due to problems, etc.

• Management control system
  • Provides the management status of output performance.

• Interfacing of these subsystems with the central computer
FMS Architecture

- An FMS is a complex network of equipment and processes that must be controlled via a computer or network of computers.
- System is usually divided into a task-based hierarchy.
- One of the standard hierarchies that have evolved is the National Institute of Standards and Technology (NIST) factory-control hierarchy.
- This hierarchy consists of five levels and is illustrated in Figures.

![Diagram](image-url)
• The system consists of physical machining equipment at the lowest level of the system.

• Workstation equipment resides just above the process level and provides integration and interface functions for the equipment.
  • Pallet fixtures and programming elements are part of the workstation.
  • Provides both man-machine interface as well as machine-part interface.
  • Off-line programming such as APT for NC or AML for a robot resides at the this level.

• The cell is the unit in the hierarchy where interaction between machines becomes part of the system.
  • Provides the interface between the machines and material-handling system.
  • Responsible for sequencing and scheduling parts through the system.

• At the shop level, integration of multiple cells occurs as well as the planning and management of inventory.

• The facility level is the place in the hierarchy where the master production schedule is constructed and manufacturing resource planning is conducted.
  • Ordering materials, planning inventories, and analyzing business plans are part of the activities that affect the production system.
Operational Problems in FMS

- Part selection and tool management
- Fixture and pallet selection
- Machine grouping and loading, considering part and tool assignments

Part Selection

- **Batching approach**
  - Part types are partitioned into separate sets called batches. The selected part types in a particular batch are manufactured continuously until all the production requirements are completed. Then processing the next batch, removing all the tools, loading new tools for the new batch.

- **Flexible approach**
  - When the production requirements of some part types are finished, space becomes available in the tool magazine. New part types may be introduced into the system for immediate and simultaneous processing if this input can help increase utilization of the system. This requires more frequent tool changes.
Part Selection (continue….)
Hwang’s Integer Programming model (Optimization approach)

Part types \( i = 1,2, \ldots, N \)
Cutting tool types \( c = 1,2, \ldots, C \)
Tool magazine capacity \( t \)

\( b_{ic} = 1 \) if part type \( i \) requires tool \( c \)
\( = 0 \) otherwise

\( d_c = \) number of tool slots required to hold cutting tool \( c \) in a magazine of each machine

\( z_i = 1 \) if part type \( i \) is selected in the batch
\( = 0 \) otherwise

\( y_c = 1 \) if cutting tool \( c \) is loaded on a machine
\( = 0 \) otherwise

\( z_i \) and \( y_c \) are the decision variables. Consider the system of identical machines,

Maximize \( \Sigma z_i \)
subject to \( \Sigma d_c y_c \leq t \)

\( b_i z_i \leq y_c \) \( \forall i, c \)
\( z_i = 0 \) or \( 1 \) \( \forall i \)
\( y_c = 0 \) or \( 1 \) \( \forall c \)

• Objective function max. the number of parts in a batch.
• Tool magazine capacity is the constraint for that machine type.
• By repeatedly solving the problem subsequent batches are formed, after deleting already selected part types from the model.
Consider the following example of 8 parts and corresponding tools required given in the tables. The tool magazine capacity is limited to 5 tool slots. Determine the batches of the part types selected:

**Part types and required tools:**

<table>
<thead>
<tr>
<th>Part Types</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of</td>
<td>t1</td>
<td>t2</td>
<td>t3</td>
<td>t4</td>
<td>t1,t2</td>
<td>t3,t5</td>
<td>t6</td>
<td>t1,t2,t7</td>
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<tr>
<td>tools required</td>
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</table>

**Tool types and required slots:**

<table>
<thead>
<tr>
<th>Tool types</th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
<th>t4</th>
<th>t5</th>
<th>t6</th>
<th>t7</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of slots req.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
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</tbody>
</table>

Solution: Max $f = z_1+z_2+\ldots+z_8$

subject to: $y_1 + y_2 + y_3 + y_4 + y_5 + 2y_6 + 2y_7 = < 5$

$z_1 - y_1 =< 0, z_2 - y_2 =< 0, \ldots$.

The integer programming model results in the following batches of the part types selected.

Batch 1: P1, P2, P3, P4, P5, P6

Batch 2: p7

Batch 3: p8
Stecke and Kim Extension of Hwang’s Model

Modified objective function of Hwang’s model by incorporating the number of tool slots required for all operations for each part type as a coefficient. Here, the objective function aims to select the part types with the largest number of required tools. This permits the consideration of more tool overlaps. The modified model is

Maximize \( \sum_i (\sum_c b_{ic} d_{ic}) z_i \)

Subject to \( \sum_c d_{ic} y_c \leq t \)

\( b_{ic} z_i \leq y_c \quad \text{all}\ i,c \)

\( z_i = 0 \text{ or } 1 \quad \text{all}\ i \)

\( y_{ck} = 0 \text{ or } 1 \quad \text{all}\ c \)

Example

Part types and required tools:

<table>
<thead>
<tr>
<th>Part Types</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
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<tr>
<td>Types of</td>
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<td>t2</td>
<td>t3</td>
<td>t4</td>
<td>t1,t2</td>
<td>t3,t5</td>
<td>t6</td>
<td>t1,t2,t7</td>
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Tool types and required slots:

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<th>t3</th>
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<tbody>
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<td>No. of slots req.</td>
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</table>

Solution: Max \( f = z_1 + z_2 + z_3 + z_4 + 2z_5 + 2z_6 + 2z_7 + 4z_8 \)

subject to: \( y_1 + y_2 + y_3 + y_4 + y_5 + 2y_6 + 2y_7 \leq 5 \)

\( z_1 - y_1 \leq 0, \ z_2 - y_2 \leq 0, \ldots \) (same as previous constraints)

The integer programming model results in the following batches of the part types selected.

Batch 1: P1, P2, P3, P5, P8

Batch 2: P4, P6, P7

(Number of batches is reduced to 2, compared to 3 in the previous solution)
Tool Allocation Policies / Tool Management

Tool Allocation Strategies:
- Bulk exchange policy
- Tool migration policy
- Resident Tooling Policy
- Tool Sharing Policy

Resident tooling policy:
- Forms cluster different combinations of tools representing similar processing requirements of parts.
- Formed clusters are made permanently available at various machines
- Benefits: Ease of tool condition monitoring
  Easy identification of tools for replacement.

Example of the above policy:

<table>
<thead>
<tr>
<th>Tool Type and Part Type Matrix</th>
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<th>p11</th>
<th>p12</th>
<th>p13</th>
<th>p14</th>
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<td>Tools</td>
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Solution: Using similarity coefficients between tools and the Single linkage cluster analysis approach, 2 tool groups have been obtained.
First: (t1, t2, t5, t6), (p1, p3, p5, p6, p10, p11, p13, p15)
Second: (t3, t4, t7, t8, t9), (p2, p4, p7, p8, p12, p14)
Fixture and Pallet Selection:

The approximate number of pallets required can be estimated:

\[
\text{Number of pallets} = \frac{\text{parts req. per shift} \times \text{avg. pallet cycle time}}{\text{Planned production time per shift} \times \text{no. of parts per pallet}}
\]

Example:

Parts req. per shift = 20
Avg. pallet cycle time = 120
Planned production per shift = 480
No. of parts per pallet = 1

Solution: Number of pallets req. = \((20 \times 120) / (480 \times 1)\)  
= 5
Layout Considerations

- Layout is one of the important design characteristics of FMS design.
- The layout of machines to process part families in an FMS is determined by the type of material handling equipment used.
FIGURE 13.5  FMS layouts: (a) linear single-row machine layout; (b) double-row machine layout; (c) circular machine layout; (d) cluster machine layout; (e) loop machine layout.
A model for the Single-Row Machine layout problem:


Objective:
Minimize the total cost of making the required trips between machines by determining the non-overlapping optimal sequence of machines

\[ m = \text{number of machines} \]

\[ f_{ij} = \text{frequency of trips between all pairs of machines (frequency matrix) for all (i, j), i not equal to j.} \]

\[ c_{ij} = \text{material-handling cost per unit distance between all pairs of machines for all (i, j), i not equal to j.} \]

\[ l_i = \text{length of the ith machine} \]

\[ d_{ij} = \text{clearance between machines i and j.} \]

\[ x_j = \text{distance of jth machine from the vertical reference as shown in figure.} \]

\[ \text{Minimize} \quad Z = \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} c_{ij} f_{ij} |x_i - x_j| \]

Subject to:

\[ |x_i - x_j| \geq \frac{1}{2} (l_i + l_j) + d_{ij} \quad \text{for all } i, i = 1, 2, \ldots, m-1 \]

\[ j = i+1, \ldots, m \]

\[ x_i \geq 0 \quad \text{for all } i = 1, \ldots, m \]

\[ \text{FIGURE 13.6 Machine location relative to reference line.} \]
A simple heuristic algorithm for circular and linear Single-Row machine layouts:

*Data required*

- \( m \) = number of machines
- \( f_{ij} \) = frequency of trips between all pairs of machines (frequency matrix) for all \((i, j)\), \(i \) not equal to \( j\).
- \( c_{ij} \) = material-handling cost per unit distance between all pairs of machines for all \((i, j)\), \(i \) not equal to \( j\).

Step 1: From the frequency and cost matrices, determine the adjusted flow matrix as follows:

\[
\bar{F} = [\bar{f}_{ij}] = [f_{ij}c_{ij}]
\]

Step 2: Determine \( \bar{f}_{i'j'} = \max[\bar{f}_{ij}, \text{ for all } i \text{ and } j] \).

Obtain the partial solution by connecting \( i' \) and \( j' \). Set \( \bar{f}_{i'j'} = \bar{f}_{j'i'} = -\infty \)

Step 3: Determine \( \bar{f}_{p'q'} = \max[\bar{f}_{ik}, \bar{f}_{kl} : k = 1,2,...,m; l = 1,2,...m] \).

Step 3.1: Connect \( q' \) to \( p' \) and add \( q' \) to the partial solution.
Step 3.2: Delete row \( p' \) and column \( p' \) from \([f_{ij}]\)
Step 3.3: if \( p' = i' \), set \( i' = q' \); otherwise, set \( j' = q' \).

Step 4: Repeat step 3 until all the machines are included in the solution.
Ex: Five machines in a FMS to be observed by an AGV. A linear single-row is recommended because of AGV. The data on the frequency of AGV trips, material-handling cost per unit distance, and clearance between the machines are given in the following tables. Suggest a suitable layout.

Frequency of trips between pairs of machines:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>20</td>
<td>70</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0</td>
<td>10</td>
<td>40</td>
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<td>3</td>
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<td>0</td>
<td>18</td>
<td>21</td>
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<td>40</td>
<td>18</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
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<td>21</td>
<td>35</td>
<td>0</td>
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Cost Matrix:

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<th></th>
<th>1</th>
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<th>4</th>
<th>5</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
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<td>4</td>
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<td>1</td>
<td>2</td>
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<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
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</table>

The machine dimensions:

<table>
<thead>
<tr>
<th>Machines</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine sizes</td>
<td>10*10</td>
<td>15*15</td>
<td>20*30</td>
<td>20*20</td>
<td>25*15</td>
</tr>
</tbody>
</table>

Clearance Matrix:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
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<td>0</td>
<td>1</td>
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<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Solution:

Step 1: Determine the adjusted flow matrix (given below):

Step 2: Include machines 1 and 3 in the partial solution as they are connected.

Step 3: a) Add machine 4 to the partial solution, as it is connected to machine 1. Delete row 1 and column 1.

Step 3: b) Add machine 2 to the partial solution, as it is connected to machine 4. Delete row and column 4 from the matrix.

Step 3: c) Add machine 5 to the partial solution.

Step 4: Because all the machines are connected, stop. The final sequence is 5, 2, 4, 1, 3. It is obtained by arranging the adjusted flow weights in increasing order while retaining the connectivity of the machines. Accordingly, the final layout considering the clearances between the machine is as shown.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>40</td>
<td>490</td>
<td>250</td>
<td>90</td>
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<tr>
<td>2</td>
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<td>10</td>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
<td>10</td>
<td>0</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>160</td>
<td>18</td>
<td>0</td>
<td>105</td>
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<tr>
<td>5</td>
<td>90</td>
<td>30</td>
<td>42</td>
<td>105</td>
<td>0</td>
</tr>
</tbody>
</table>

FIGURE 13.7 Final layout of the linear single-row machine problem.
Sequencing of robot moves

Alternative sequences of robot moves in a two-machine robot moves.

fig (a): Robot picks up a part at I, moves to m/c M1, loads the part on m/c M1, waits at M1 until the part has been processed, unloads the part from M1, moves to m/c M2, loads the part on M2, waits at M2 until the part has been processed there, unloads the part from M2, moves to O, drops the part at O and moves back to I.

Cycle time $T_1$ for fig (a) = $\varepsilon + \delta + \varepsilon + 3\delta + \varepsilon + \delta + \varepsilon + a + \varepsilon + \delta + \varepsilon + b$

$$T_1 = 6\varepsilon + 6\delta + a + b$$

where,

- $a$ and $b$ are processing time on Machine 1 and 2 respectively.
- ‘$\varepsilon$’ is the robot pick up/release time.
- ‘$\delta$’ is the robot move time between M1 & M2
Sequencing of robot moves

Alternative sequences of robot moves in a two-machine robot moves.

fig (b): Robot picks up a part P1 at I, moves to m/c M1, loads the part on m/c M1, waits at M1 until the part has been processed, unloads the part from M1, moves to m/c M2, loads the part on M2, moves back to I. Picks up another part P2 at /I, moves to M1, loads P2 on M1, if necessary waits at M2 until the earlier part P1 has been processed, unloads P1, moves to O, drops P1 at O, moves to M1, if necessary waits at M1 until part P2 has been processed, unloads P2, moves to M2, loads P2 on M2, and moves to I.

Cycle time $T_2$ for fig (b) = $\varepsilon + \delta + \varepsilon + 2\delta + w_1 + \varepsilon + \delta + \varepsilon + 2\delta + \varepsilon + \delta + \varepsilon + \delta + w_2$

$T_2 = 6\varepsilon + 8\delta + w_1 + w_2$

taking $\alpha = 4\varepsilon + 4\delta$ and $\mu = 2\varepsilon + 4\delta$,

$T_2 = \alpha + \mu + w_1 + w_2$

$= \alpha + \mu + \max\{0, b - \mu\} + \max\{2\varepsilon + 4\delta, a, b\}$

$= \alpha + \max\{\mu, b, a\} = 4\varepsilon + 4\delta + \max\{2\varepsilon + 4\delta, a, b\}$

where,

$w_1 = \max\{0, a - 4\delta - 2\varepsilon - w_2\}$

$w_2 = \max\{0, b - 4\delta - 2\varepsilon\}$
Algorithm: Step 0: Calculate $\mu = 2\epsilon + 4\delta$

Step 1: Calculate $\mu \leq \max \{a, b\}$, then $T_2$ is optimal. Calculate $T_2$ and stop.
   Otherwise go to step 2.

Step 2: If $\mu > \max \{a, b\}$ and $2\delta \leq a + b$, then $T_2$ is optimal. Calculate $T_2$ and stop.
   Otherwise go to step 3.

Step 3: If $\mu > \max \{a, b\}$ and $2\delta > a + b$, then $T_1$ is optimal. Calculate $T_1$ and stop.

Example: Determine the optimal cycle time and corresponding robot sequences in a two-machine robotic cell with the following data:

- Processing time of Machine M1 = 11.00 min
- Processing time of Machine M2 = 09.00 min
- Robot gripper pickup = 0.16 min
- Robot gripper release time = 0.16 min
- Robot move time between the two machines = 0.24 min

Solution:

Step 0: $\mu = 2\epsilon + 4\delta$
   $\mu = 2(0.16) + 4(0.24) = 1.28$ min

Step 1: $\mu \leq \max \{a, b\}$
   $1.28 \leq \max \{11, 9\}$, i.e. $1.28 < 11$. Therefore, $T_2$ is optimal.
   $T_2 = \alpha + \max \{\mu, a, b\}$
   $T_2 = [4\epsilon + 4\delta] + \max \{1.28, 11, 9\} = [4(0.16) + 4(0.24)] + 11$
   $T_2 = 1.6 + 11 = 12.6$ min

The optimal cycle time is 12.6 min and the optimal robot is given by fig (b) as shown in the previous slide.
FMS Scheduling and Control

• Flexible manufacturing systems can differ significantly in complexity.
• Complexity is determined by:
  • The number of machines and the number of parts resident in the system.
  • The complexity of parts and control requirements of the specific equipment.

Example 1: The most simple FMS consists of a processing machine, a load/unload area, and a material handler (a one-machine system is the most simple FMS that can be constructed).

Operation of this system consists of loading the part/parts that move down a conveyor to the machine.
Once the part is loaded onto the machine, the robot is retracted to a "safe position" and the machining begins.
For a single part is to be processed in the system, a minimum number of switches and sensors required are:
  • Parts on the conveyor all have to be oriented in the same way.
  • Robot can pick up the part and deliver it to the NC machine in the same orientation.
  • Proximity switch or micro-switch is required at the end of the conveyor to detect when a part is resident, and on the machine for the same purpose.

A simple programmable logic controller can easily control this system.
The logic for the system is as follows:

1. If a part is resident at the end of the conveyor (switch 1 is on) and no part is on the NC machine (switch 2 is off), then pick up the part on the conveyor and move it to the NC machine and retract the robot to a safe point (run robot program 1). After the program is complete and switch 2 senses that the part is correctly positioned, start the NC machine (turn on relay M). While the machine is running, a switch signal from the NC machine, switch #2, will be ON.

2. If switch 11 is off and switch #2 is on (the NC machine has completed processing a part), take the part off the NC machine and move it to the output bin (run robot program 2).
Add little complexity: Example 2

If the same system were to be used to process a variety of parts, several changes in the control would be required.

- Either several robot programs for handling the parts would be necessary or a common part pallet would be necessary for gripping the part.
- For simplicity, it's assumed that a common pallet is used to fixture all parts.
- Need to detect which part is resident at each station.

Part identification is usually performed by a bar-code reader or by using a set of switches that each pallet will trigger. Each pallet type (and sometimes each pallet) then can be identified by the combination of switches that are active.

For instance, sixteen part types could be identified using four 2-state switches ($2^4$). These switches are numbered 31-34 (Diagram of Robot, machine and conveyor).

Variety of different part programs have to be executed to machine each different part type.

The PLC ladder logic indicates which program should be run in CNC machine.
The system consists of two CNC machines, a robot, a load station, and an output bin. Parts enter the system on a conveyor in a pre-specified order that cannot be altered once the parts are on the conveyor.

**Example 3**: Single part routing is assumed for this system.

The control logic for the system is summarized as follows:

1. If a part is at the end of the conveyor (switch 1 is on) and no part is on machine 1 (switch 11 is off), move the part from the conveyor to the machine (run robot program 1).
2. If a part is finished at machine 1 (switch 11 is on and switch 12 is off) and machine 2 is empty (switch 21 is off), move the part from machine 1 to machine 2.
3. If the part on machine 2 is complete (switch 21 is on and switch 22 is off), remove the part from the machine and place it in the output bin.
Example 4: A two-machine two-part FMS.

Case-I. If two parts are allowed to enter the system in a random order (but 2\textsuperscript{nd} part is processed after finishing the 1\textsuperscript{st} part):
Part identification is necessary.

If the parts are of different size, different robot programs may be required unless the parts are on a common-size pallet fixture (assumed in this case).

Two state switches are required on each machine: one to detect if a part is on the machine and one to determine whether it is part 1 or 2.

If all part 1's are in the system, the control of the system is the same as it was previously.

If all part 2's are in the system, a similar control is required, changing the routing from machine 1 to machine 2 and vice versa.

Case-II. If the parts are allowed to be mixed in the system. Consider this case:

Part 1 is in the system and at machine 1 and part 2 is at the load point on the conveyor. Then if , part 2 is moved to machine 2 and processing begins, system "locks" or "deadlocks."
Part 1 must be moved to machine 2, which is occupied by part 2. When part 2 is complete, it must be moved to machine 1, which is also occupied.
Deadlocking

Deadlocking can occur in an operational FMSs. It can only be overcome by human intervention. In order to eliminate dead-locking, one of two fixes are required:
1. A queuing station is required or,
2. Both/multiple parts are not allowed in the system at the same time.

In order to eliminate deadlocking by adding queueing stations:
- If n parts are allowed in the system, then n - 1 queueing stations will be required to ensure that blocking does not occur.
- Part routing can significantly reduce this number, may be to zero.

For the system with a queueing station, logic is:
1. If part 1 is on machine 1 and part 2 is at the load position on the conveyor, then load a part from the conveyor to machine 2.
2. If part 2 is on machine 2 and part 1 is on the load position on the conveyor, then load a part from the conveyor to machine 1.
Network graph of a 2-machine 2-part FMS-system flow.
(a) Part 1 at machine 1 and part 2 at machine 2.
(b) Part 1 at machine 1 and part 2 at machine 2 and a queue.

The processing times are given as part of the figure, gantt chart.

Assumed that 1 min of handling time is required for each robot operation. Also, assumed that parts are batched in groups of 2, that is, two part 1's are followed by two part 2's, and so on.

Completion of five parts requires 44 time units given the control strategy and the additional queueing station.

Indication of, when locking can occur is that the network graph of the system forms a closed graph.

Whenever a closed circuit of arcs occurs on the network, a potential for locking occurs.

When an additional queueing station is added to the system, the continuity of the circuit is broken.

Gantt chart for the 2 m/c 2 part FMS: ‘1’ / ‘2’ indicates that part 1 / part 2 is being processed, handled, or queued, respectively.

Assumed that 1 min of handling time is required for each robot operation. Also, assumed that parts are batched in groups of 2, that is, two part 1's are followed by two part 2's, and so on.

Completion of five parts requires 44 time units given the control strategy and the additional queueing station.

Indication of, when locking can occur is that the network graph of the system forms a closed graph.

Whenever a closed circuit of arcs occurs on the network, a potential for locking occurs.

When an additional queueing station is added to the system, the continuity of the circuit is broken.
Flow Systems

FMSs are also designed to produce part families that produce a flow-system environment rather than a job-shop environment.

A flow system constrains the flow and control of the system significantly.
- All parts must follow the same routing.
- The machines need not perform an operation on all parts, but all parts must visit all machines.

The logic control of the system:
1. If a part is at the load station and machine 1 is idle, move the part to machine 1.
2. If a part is resident at machine m and complete and machine m + 1 is idle, move the part to machine m + 1.
3. If a part is at a machine and unprocessed, process that part.
4. If a part is at the last machine and complete, move it to the unload station.

Example. The 3 machine system (figure), parts enter the system at the load station and are then moved to the first NC machine by robot 1.

Robot 2 then moves the part from machine 1 to machine 2, and so forth.
Complex control FMSs

A 3-machine FMS
Robot handling times

### Part Routings

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Routing</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L→1→2→3→U</td>
<td>0→4→5→3→0</td>
</tr>
<tr>
<td>2</td>
<td>L→3→2→U</td>
<td>0→6→3→0</td>
</tr>
<tr>
<td>3</td>
<td>L→2→1→2→U</td>
<td>0→3→4→4→0</td>
</tr>
<tr>
<td>4</td>
<td>L→1→3→2→U</td>
<td>0→2→5→2→0</td>
</tr>
<tr>
<td>5</td>
<td>L→3→U</td>
<td>0→7→0</td>
</tr>
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</table>

**System status**

<table>
<thead>
<tr>
<th>Robot</th>
<th>Machine 1</th>
<th>Machine 2</th>
<th>Machine 3</th>
<th>Load</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$L \rightarrow \mathcal{M}_1$</td>
</tr>
<tr>
<td>$\mathcal{M}_1$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$\mathcal{M}_1 \rightarrow L$</td>
</tr>
<tr>
<td>$\mathcal{M}_2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$\mathcal{M}_2 \rightarrow L$</td>
</tr>
<tr>
<td>$\mathcal{M}_3$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$\mathcal{M}_3 \rightarrow L$</td>
</tr>
<tr>
<td>L</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Wait</td>
</tr>
<tr>
<td>L</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$L \rightarrow \mathcal{M}_1$</td>
</tr>
<tr>
<td>L</td>
<td>3.2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Wait</td>
</tr>
<tr>
<td>$\mathcal{M}_3$</td>
<td>3.2</td>
<td>1.2(^c)</td>
<td>1.3</td>
<td>4</td>
<td>$\mathcal{M}_3 \rightarrow \mathcal{M}_2$</td>
</tr>
</tbody>
</table>

\(^a\)L denotes that the robot is currently directed at the load station.  
\(^b\)$M_1 = \text{machine 1, } M_2 = \text{machine 2; } M_3 = \text{machine 3}$.  
\(^c\)Underlined entries indicate that the operation is complete.  
\(^c\)1,2 indicates that part 1, operation 2 is currently being performed at that station.
General Shop-Floor Control Problem

A shop consists of several pieces of manufacturing equipment that are used to process, transport, and store items. An item can be a part, raw material, a tool, a fixture, or any other object that moves through the shop.

The equipment includes NC machine tools, robots, conveyors, automated guided vehicles, automated storage systems, and so on. Set of other items might be required (e.g., specific cutting tools or fixtures).

Between processing tasks, some or all of these items must be transported between the different pieces of equipment.

*Input/output diagram for the general shop-floor control problem.*

Figure shows the shop-floor control system (SFCS) as a black-box entity that receives inputs from an external (business) system/s and generates the device-specific instructions necessary to enact the individual manufacturing tasks.

Primary inputs to the SFCS are the production requirements, which describe the parts to be manufactured, and the resources, which describe the shared resources (items) to be used by the equipment within the shop.
A sample bracket.

Manufacturing system to illustrate control

General Shop-Floor Control Problem

Precedence graph for a sample bracket. Operation task and resource summary for bracket arranged by feature

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
<th>Feature</th>
<th>Feature spec.</th>
<th>Time (est.)</th>
<th>Tooling</th>
<th>Machine</th>
<th>Fixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Side mill</td>
<td>Locate surf. A</td>
<td>Mill face A</td>
<td>0.6 min</td>
<td>1.0” end mill</td>
<td>Mach. Ctr.</td>
<td>Fxt #1</td>
</tr>
<tr>
<td>2</td>
<td>Side mill</td>
<td>Locate surf. B</td>
<td>Mill face B</td>
<td>0.35 min</td>
<td>1.0” end mill</td>
<td>Mach. Ctr.</td>
<td>Fxt #1</td>
</tr>
<tr>
<td>3</td>
<td>Twist drill</td>
<td>Hole #1</td>
<td>Rough drill hole #1</td>
<td>0.33 min</td>
<td>0.3595” drill</td>
<td>Mach. Ctr.</td>
<td>Fxt #2</td>
</tr>
<tr>
<td>5</td>
<td>Ream</td>
<td>Hole #1</td>
<td>Finish hole #1</td>
<td>0.25 min</td>
<td>0.375” ream</td>
<td>Mach. Ctr.</td>
<td>Fxt #2</td>
</tr>
<tr>
<td>5a</td>
<td>Bore</td>
<td>Hole #1</td>
<td>Finish hole #1</td>
<td>0.34 min</td>
<td>0.375”bore</td>
<td>Mach. Ctr.</td>
<td>Fxt #3</td>
</tr>
<tr>
<td>4</td>
<td>Twist drill</td>
<td>Hole #2</td>
<td>Rough drill hole #2</td>
<td>0.33 min</td>
<td>0.3595” drill</td>
<td>Mach. Ctr.</td>
<td>Fxt #3</td>
</tr>
<tr>
<td>6</td>
<td>Ream</td>
<td>Hole #2</td>
<td>Finish hole #2</td>
<td>0.25 min</td>
<td>0.375” ream</td>
<td>Mach. Ctr.</td>
<td>Fxt #3</td>
</tr>
<tr>
<td>6a</td>
<td>Bore</td>
<td>Hole #2</td>
<td>Finish hole #2</td>
<td>0.34 min</td>
<td>0.375”bore</td>
<td>Mach. Ctr.</td>
<td>Fxt #3</td>
</tr>
<tr>
<td>7</td>
<td>Slot mill</td>
<td>Slot #1</td>
<td>Mill slot #1</td>
<td>0.76 min</td>
<td>0.5” end mill</td>
<td>Mach. Ctr.</td>
<td>Fxt #1</td>
</tr>
</tbody>
</table>