WE ARE GOING TO LEARN IN THIS FMS CHAPTER

1. What is a Flexible Manufacturing System?
2. FMS Components
3. FMS Applications and Benefits
4. FMS Planning and Implementation Issues
5. Quantitative Analysis of Flexible Manufacturing Systems
Where to Apply FMS Technology

- The plant presently either:
  - Produces parts in batches or
  - Uses manned Group Technology cells and management wants to automate the cells
- It must be possible to group a portion of the parts made in the plant into part families
  - The part similarities allow them to be processed on the FMS workstations
- Parts and products are in the mid-volume, mid-variety production

Flexible Manufacturing System - Defined

A highly automated GT machine cell, consisting of a group of processing stations (usually CNC machine tools), interconnected by an automated material handling and storage system, and controlled by an integrated computer system
- The FMS relies on the principles of GT
  - No manufacturing system can produce an unlimited range of products
  - An FMS is capable of producing a single part family or a limited range of part families
GENERAL FLEXIBILITY TESTS to call automated systems as FMS

To qualify as being flexible, a manufacturing system should satisfy the following criteria (“yes” answer for each question):

1. Can it process different part styles in a non-batch mode?
2. Can it accept changes in production schedule?
3. Can it respond gracefully to equipment malfunctions and breakdowns?
4. Can it accommodate introduction of new part designs?

A robotic 2 machine 1 Robot CELL

Is this simple FMS with two machine tools and robot FLEXIBLE? WHAT KIND OF SPECIFIC QUESTIONS CAN BE ASKED?
SPECIFIC QUESTIONS FOR FLEXIBILITY TESTS

1. Part variety test
   • Can it machine different part configurations in a mix rather than in batches?
2. Schedule change test
   • Can production schedule and part mix be changed?
3. Error recovery test
   • Can it operate if one machine breaks down?
     • Example: while repairs are being made on the broken machine, can its work be temporarily reassigned to the other machine?
4. New part test
   • As new part designs are developed, can NC part programs be written off-line and then downloaded to the system for execution?

Definitions of FLEXIBILITY

<table>
<thead>
<tr>
<th>Flexibility Type</th>
<th>Definition</th>
<th>Depends on Factors Such As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine flexibility</td>
<td>Capability to adapt a given machine (workstation) in the system to a wide range of production operations and part styles. The greater the range of operations and part styles, the greater the machine flexibility.</td>
<td>Setup or changeover time. Ease of machine reprogramming (ease with which part programs can be downloaded to machines). Machine flexibility of individual stations.</td>
</tr>
<tr>
<td>Production flexibility</td>
<td>The range or universe of part styles that can be produced on the system.</td>
<td>Machine flexibility of individual stations. Range of machine flexibilities of all stations in the system.</td>
</tr>
<tr>
<td>Mix flexibility</td>
<td>Ability to change the product mix while maintaining the same total production quantity, that is, producing the same parts only in different proportions.</td>
<td>Similarity of parts in the mix. Relative work content times of parts produced. Machine flexibility.</td>
</tr>
<tr>
<td>Product flexibility</td>
<td>Ease with which design changes can be accommodated. Ease with which new products can be introduced.</td>
<td>How closely the new part design matches the existing part family. Off-line part program preparation. Machine flexibility.</td>
</tr>
<tr>
<td>Volume flexibility</td>
<td>Ability to economically produce parts in high and low total quantities of production, given the fixed investment in the system.</td>
<td>Level of manual labor performing production. Amount invested in capital equipment.</td>
</tr>
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<td>Expansion flexibility</td>
<td>Ease with which the system can be expanded to increase total production quantities.</td>
<td>Expense of adding workstations. Ease with which layout can be expanded. Type of part handling system used. Ease with which properly trained workers can be added.</td>
</tr>
</tbody>
</table>
Types of FMS

- Kinds of operations
  - Processing vs. assembly
  - Type of processing
    - If machining, rotational vs. non-rotational
- Number of machines (workstations):
  1. **Single machine cell** \((n = 1)\)
  2. **Flexible manufacturing cell** \((n = 2 \text{ or } 3)\)
  3. **Flexible manufacturing system** \((n = 4 \text{ or more})\)

Three Types of FMS with respect to number of machines

A single-machine CNC machining cell (in Cincinnati Milacron)
2. Flexible Manufacturing Cell

A two-machine flexible manufacturing cell for machining (in Cincinnati Milacron)
The DIFFERENCE Between Flexible Manufacturing System (FMS) and Flexible Manufacturing Cell (FMC)

3. A five-machine flexible manufacturing system for machining (in Cincinnati Milacron)
FMS Types according to Level of Flexibility

1. Dedicated FMS
   - Designed to produce a limited variety of part styles
   - The complete universe of parts to be made on the system is known in advance
   - Part family likely based on product commonality rather than geometric similarity

2. Random-order FMS
   - Appropriate for large part families
   - New part designs will be introduced
   - Production schedule is subject to daily changes
FMS Components

1. Workstations
2. Material handling and storage system
3. Computer control system
4. Human labor

WHAT DO YOU THINK?

What kind of properties of FMS components must have?

The basic processing (PROCESSING WORKSTATIONS) in the system must be automated. Because automation must be programmable in order to accommodate a variety of product-processing requirements, easily alterable as well as versatile machines must perform the basic processing. For this reason, CNC turning centers, CNC machining centers, and robotic workstations comprise the majority of equipment in these systems. These machines are not only capable of being easily reprogrammed, but are also capable of accommodating a variety of tooling via a tool changer and tool-storage system. It is not unusual for a CNC machining center to contain 60 or more tools (mills, drills, boring tools, and so on), and for a CNC turning center to contain 12 or more tools (right-hand turning tools, left-hand turning tools, boring bars, drills, and so on). The automatic tool changer and storage capabilities of NC machines make them natural choices for material processing workstations.

Parts must also be moved between processing stations automatically. The selection of the type of MATERIAL HANDLING SYSTEM is a function of several system features. The material-handling system, first, must be able to accommodate the load and bulk of the part and perhaps the part fixture. Large, heavy parts require large, powerful handling systems such as roller conveyors, guided vehicles, or track-driven vehicle systems. The number of machines to be included in the system and the layout of the machines also present another design consideration. If a single mate-rial handler is to move parts to all the machines in the system, then the work envelope of the handler must be at least as large as the physical system. A robot is normally only capable of addressing one or two machines and a load-and-unload station. A conveyor or automatic guided vehicle (AGV) system can be expanded to include miles of factory floor.
WHAT DO YOU THINK?

What kind of properties of FMS components must have?

The transfer system is sometimes designed to accommodate some sort of Pallet Fixture. Workparts are attached to the pallet fixtures and the pallets are transferred between stations, carrying the part through its sequence of operations. The pallet fixture is designed so that it can be conveniently moved, located, and clamped in position at successive stations. Since the part is accurately located in the fixture, it is therefore correctly positioned for each operation.

One of the commonly neglected aspects of an FMS is the Fixturing used. Because fixtures are part of the tooling of the system, one could argue that they should also be standard for the system. Work on creating "flexible fixtures" that could be used to support a variety of components has only recently begun. One unique aspect of many FMSs is that the part is also moved about the system in the fixture (or pallet fixture). Fixtures are made to the same dimensions so that the material-handling system can be specialized to handle a single geometry. Parts are located precisely on the fixture and moved from one station to another on the fixture. Fixtures of this type are usually called pallet fixtures, or pallets. Many of the pallet fixtures employed today have standard "T-slots" cut in them, and use standard fixture kits to create the part-locating and -holding environment needed for machining.

The other method of workpart location and fixturing does not use pallets. With this method, the workparts themselves are indexed from station to station. When a part arrives at a station, it is automatically clamped in position for the operation. The obvious benefit of this transfer method is that it avoids the cost of pallet fixtures.

Versatility is the key to most FMSs, and as such, the Tooling used in the system must be capable of supporting a variety of products or parts. The use of special forming tools in an FMS is not typical in practice. The contours obtained by using forming tools can usually be obtained through a contour-control NC system and a standard mill.

1. Workstations

- **Load and unload station(s)**
  - Factory interface with FMS
  - Manual or automated
  - Includes communication interface with worker to specify parts to load, fixtures needed, etc.

- **CNC machine tools in a machining type system**
  - CNC machining centers
  - Milling machine modules
  - Turning modules

- **Assembly machines**
2. Material Handling and Storage

Functions:

• Random, independent movement of parts between stations
• Capability to handle a variety of part styles
  • Standard pallet fixture base
  • Workholding fixture can be adapted
• Temporary storage
• Convenient access for loading and unloading
• Compatibility with computer control

Material Handling Equipment

• Primary handling system establishes basic FMS layout
• Secondary handling system - functions:
  • Transfers work from primary handling system to workstations
  • Position and locate part with sufficient accuracy and repeatability for the operation
  • Reorient part to present correct surface for processing
  • Buffer storage to maximize machine utilization
Five Types of FMS Layouts

- The layout of the FMS is established by the material handling system
- Five basic types of FMS layouts
  1. In-line
  2. Loop
  3. Ladder
  4. Open field
  5. Robot-centered cell

FMS In-Line Layout

- Straight line flow, well-defined processing sequence similar for all work units
- Work flow is from left to right through the same workstations
- No secondary handling system
FMS In-Line Layout

- Linear transfer system with secondary parts handling system at each workstation to facilitate flow in two directions.

FMS Loop Layout

- One direction flow, but variations in processing sequence possible for different part types.
- Secondary handling system at each workstation.
FMS Rectangular Layout

- Rectangular layout allows recirculation of pallets back to the first station in the sequence after unloading at the final station

FMS Ladder Layout

- Loop with rungs to allow greater variation in processing sequence
FMS Open Field Layout

- Multiple loops and ladders, suitable for large part families

Robot-Centered Cell

- Suited to the handling of rotational parts and turning operations
FMS Computer Functions

1. Workstation control
   • Individual stations require controls, usually computerized
2. Distribution of control instructions to workstations
   • Central intelligence required to coordinate processing at individual stations
3. Production control
   • Product mix, machine scheduling, and other planning functions
4. Traffic control
   • Management of the primary handling system to move parts between workstations
5. Shuttle control
   • Coordination of secondary handling system with primary handling system
6. Workpiece monitoring
   • Monitoring the status of each part in the system
7. Tool control
   • Tool location
     • Keeping track of each tool in the system
   • Tool life monitoring
     • Monitoring usage of each cutting tool and determining when to replace worn tools
8. Performance monitoring and reporting
   • Availability, utilization, production piece counts, etc.
9. Diagnostics
   • Diagnose malfunction causes and recommend repairs

Duties Performed by Human Labor

WHAT DOES A HUMAN DO IN FMS THEN?

• Loading and unloading parts from the system
• Changing and setting cutting tools
• Maintenance and repair of equipment
• NC part programming
• Programming and operating the computer system
• Overall management of the system
IN SUMMARY
FMS COMPONENTS

• Workstations
  • Load/Unload Stations
  • Machining Stations (CNC machining centers)
  • Other Processing Stations (Punching, shearing, bending etc.)
  • Assembly
  • Other Stations (QC, inspection etc.)

• Material Handling and Storage Systems
  • Movement of workparts
  • Handling workparts
  • Temporary storage
  • Access for loading/unloading workparts
  • Compatible with computer control

• Computer Control System
  • Workstation control
  • Distribution of control instructions
  • Production control
  • Traffic control
  • Shuttle control
  • Workpart monitoring
  • Tool control
  • Performance monitoring and reporting
  • Diagnostics

• Human resources
  • Loading raw material into the system
  • Unloading finished parts from the system
  • Changing and setting tools
  • Equipment maintenance and repair
  • NC part programming
  • Control system programming
  • Overall management

FMS Applications

• Machining – most common application of FMS technology
• Assembly
• Inspection
• Sheet metal processing (punching, shearing, bending, and forming)
• Forging
A robot-tended FMS system. This FMS is designed for cylindrical parts and can be the basis for thoughtful, progressive flexible automation. The two Milacron two-axis CNC step grinding machines are positioned back to back and offset. This allows full access to the front of each machine, and enables one stand-alone Milacron Robot to automate loading and unloading of parts from a conveyor. Hydraulic footstocks are automatically actuated. This, and in-process gauging, makes the cell ideal for unattended operation during "lights out" shifts.

FMS at Chance-Vought Aircraft (in Cincinnati Milacron)
FMS for Sheet Metal Fabrication

FMS Benefits

- Increased machine utilization
  - Reasons:
    - 24 hour operation likely to justify investment
    - Automatic tool changing
    - Automatic pallet changing at stations
    - Queues of parts at stations to maximize utilization
    - Dynamic scheduling of production to account for changes in demand
- Fewer machines required
- Reduction in factory floor space required
- Greater responsiveness to change
- Reduced inventory requirements
  - Different parts produced continuously rather than in batches
- Lower manufacturing lead times
- Reduced labor requirements
- Higher productivity
- Opportunity for unattended production
  - Machines run overnight ("lights out operation")
FMS Planning and Design Issues

- Part family considerations
  - Defining the part family of families to be processed
    - Based on part similarity
    - Based on product commonality
- Processing requirements
  - Determine types of processing equipment required
- Physical characteristics of workparts
  - Size and weight determine size of processing equipment and material handling equipment
- Production volume
  - Annual quantities determined number of machines required
- Types of workstations
- Variations in process routings
- Work-in-process and storage capacity
- Tooling
- Pallet fixtures

FMS Operational Issues

- Scheduling and dispatching
  - Launching parts into the system at appropriate times
- Machine loading
  - Deciding what operations and associated tooling at each workstation
- Part routing
  - Selecting routes to be followed by each part
- Part grouping
  - Which parts should be on the system at one time
- Tool management
  - When to change tools
- Pallet and fixture allocation
  - Limits on fixture types may limit part types that can be processed
Quantitative Analysis of FMS

- FMS analysis techniques:
  1. Deterministic models
  2. Queueing models
  3. Discrete event simulation
  4. Other approaches, including heuristics

- Deterministic models
  1. **Bottleneck model** - estimates of production rate, utilization, and other measures for a given product mix
  2. **Extended bottleneck model** - adds work-in-process feature to basic model

**BOTTLENECK MODEL**

- Calculates maximum production rate for the FMS (gives an upper limit at fixed part mix ratios)
  \[ p_j = \text{Fraction of the total system output that is of style } j \]
  \[ j = 1, 2, \ldots, P \] (\( P \) = Total number of different part styles)
  \[ \sum_{j=1}^{P} p_j = 1 \]

  \( s_i = \text{Number of servers (machines/human operators) at workstation } i \)
  \( i = 1, 2, \ldots, n \) (\( n \) = Total number of workstations)

  \( t_{ijk} = \text{Process time of operation } k \text{ of product } j \text{ at station } i \)

  \( s_{n+1} = \text{Number of carriers in handling system} \)
  (\( n+1 \) = Material handling workstation)

  \( t_{n+1} = \text{Mean transportation required to move a part from one station to the next} \)

  \( f_{ijk} = \text{Operation frequency of operation } k \text{ of product } j \text{ at station } i \)
BOTTLENECK MODEL

- Workload of station $i$

\[
WL_i = \sum_j \sum_k t_{ijk} f_{ijk} p_j
\]

- Workload for material handling system

\[
WL_{n+1} = n_t t_{n+1} \\
n_t = \sum_i \sum_j \sum_k f_{ijk} p_j - 1
\]

$t_{n+1}$ = Mean transportation time per move

$n_t$ = Mean number of transports

BOTTLENECK MODEL

- Production rate for all parts

\[
R^*_p = \frac{s^*}{WL^*}
\]

$R^*_p$ = Maximum production rate of all parts

$s^*$ = Number of servers at the bottleneck station

$WL^*$ = Workload at the bottleneck station

- Individual part production rate

\[
R^*_{pj} = p_j \frac{s^*}{WL^*}
\]

- Mean utilization of each station

\[
U_i = \frac{WL_i}{s_i} \geq \frac{WL_i}{s_i} \frac{s^*}{WL^*}
\]

$U_i$ = Utilization of station $i$
BOTTLENECK MODEL

- Average station utilization
  \[ \bar{U} = \frac{\sum_{i=1}^{n} U_i}{n+1} \]

- Overall FMS utilization
  \[ \bar{U}_s = \frac{\sum_{i=1}^{n} s_i U_i}{\sum_{i=1}^{n} s_i} \]

- Number of busy servers at each station
  \[ BS_i = WL_i \left\lceil \frac{s_i}{WL} \right\rceil = WL_i \frac{s_i}{WL} \]

EXTENDED BOTTLENECK MODEL

- Keeps the numbers of parts at a fixed number
  - Assumes a closed queuing network in which there is always a certain number of workparts in the FMS (N)
  - N is a constant value: whenever a part exits the system a new part enters.
  - If N is a very small number then the machines will starve the production rate of the system will be less then \( R^* \). If N is a very large number then \( R^* \) is a good estimate.
  - \( WIP = N \) (Number of parts in the system)

\[ MLT = \sum_{i=1}^{n} WL_i + WL_{n+1} + T_w \]

\( T_w = \) Mean waiting time of a part due to the queues in the system
EXTENDED BOTTLENECK MODEL

• If \( N \) is a very small number then \( MLT \) will be small (no waits). If \( N \) is a very large number then \( MLT \) will be large too (more waits).

• Correlation between \( N \) and \( MLT \) \( N = R_p(MLT) \)

\[
\begin{align*}
\text{Case 1: } & N < N^* = R_p^* \left( \sum_{i=1}^{n} WL_i + WL_{i+1} \right) \\
MLT_1 &= \sum_{i=1}^{n} WL_i + WL_{i+1} \\
R_p &= \frac{N}{MLT_1} \\
R_p &= p_t R_p \\
T_w &= 0 \\
T_w &= MLT_2 - \left( \sum_{i=1}^{n} WL_i + WL_{i+1} \right)
\end{align*}
\]

\[
\begin{align*}
\text{Case 2: } & N = N^* = R_p^* \left( \sum_{i=1}^{n} WL_i + WL_{i+1} \right) \\
R_p^* &= \frac{s^*}{WL^*} \\
R_p^* &= p_t R_p^* \\
MLT_2 &= \frac{N}{R_p^*} \\
T_w &= MLT_2 - \left( \sum_{i=1}^{n} WL_i + WL_{i+1} \right)
\end{align*}
\]

• Example 16.10

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**Figure 16.16** General behavior of the extended bottleneck model: (a) manufacturing lead time \( MLT \) as a function of \( N \) and (b) production rate \( R_p \) as a function of \( N \).
EXTENDED BOTTLENECK MODEL

• Sizing the FMS
  • Size of FMS : Number of workstations and servers
    \[ s_i = \min \text{int} \geq R_p \sum L_i \]

• Remarks:
  • Production rate of an FMS is limited to the production rate of the bottleneck station (with maximum workload per server)
  • If product ratio is relaxed (less variety) the utilization of the non-bottleneck stations can be increased as well as production rate of the FMS
  • Number to parts in the system should be greater than the number of servers. A ratio of 2 parts/server is optimum
  • If WIP is too low then production rate is impaired
  • If WIP is too high than production rate will remain the same but MLT will increase

What the Equations of Bottleneck Models Tell

• For a given part mix, the total production rate is ultimately limited by the bottleneck station
• If part mix ratios can be relaxed, it may be possible to increase total FMS production rate by increasing the utilization of non-bottleneck stations
• As a first approximation, bottleneck model can be used to estimate the number of servers of each type to achieve a specified overall production rate
• The number of parts in the FMS at any one time should be greater than the number of servers (processing machines) in the system
  • Ratio of two parts per server is probably optimum
  • Parts must be distributed throughout the FMS, especially in front of the bottleneck station
  • If WIP is too low, production rate is impaired
  • IF WIP is too high, MLT increases
The most simple FMS consists of a single 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(s) 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. Although this is a very simple system, it illustrates several interesting design and control decisions that must be considered. If only a single part type is to be processed in the system, a minimum number of switches and sensors are necessary for the system. One requirement of the system is that the parts on the conveyor all have to be oriented in the same way. This is required so that the robot can pick up the part and deliver it to the NC machine in the same orientation every time. A proximity switch or microswitch is required at the end of the conveyor to detect when a part is resident, and on the machine for the same purpose.

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 M1). 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).

The ladder logic for this system is as follows:

A Gantt chart of the flow:
Inherent in the figure is that there is always a part available at the load station and that there are no machine breakdowns.
**COMPUTER CONTROL OF FLEXIBLE MANUFACTURING SYSTEMS: FMS Scheduling and Control**

How do we identify different part types?

For the sake of illustration, we assume that a common pallet is used to fixture all parts. It also will be necessary 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, if four optical switches are used for this process and the switches are off when light is unobstructed, then one pallet could have four tabs used to obstruct the light and this pallet would be identified by four closed (on) switches. Sixteen part types could be identified using four 2-state switches ($2^4$). For each different part type a different part program has to be executed to machine. The programmable logic controller ladder logic inspects each switch setting and indicates which program should be run. This logic is as follows:

<table>
<thead>
<tr>
<th>Part 1 is on the machine.</th>
<th>Run part program 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 2 is on the machine.</td>
<td>Run part program 2.</td>
</tr>
<tr>
<td>Part 16 is on the machine.</td>
<td>Run part program 16.</td>
</tr>
</tbody>
</table>

**COMPUTER CONTROL OF FLEXIBLE MANUFACTURING SYSTEMS: FMS Scheduling and Control—More Than One Machine (Two)**

As more machines are added, the difficulty of controlling the system increases dramatically, unless a single part type is used in the system at any time. The system consists of two CNC machines, a robot, a load station, and an output bin. In this example, a single part type enters the system on a conveyor in a prespecified order that cannot be altered once the parts are on the conveyor.
COMPUTER CONTROL OF FLEXIBLE MANUFACTURING SYSTEMS: FMS Scheduling and Control—MORE THAN ONE MACHINE (TWO)

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.

---

**Diagram:**

1. **R₁**
   - 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 machine 1.

2. **R₂**
   - 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. **R₃**
   - 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.

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COMPUTER CONTROL OF FLEXIBLE MANUFACTURING SYSTEMS: FMS Scheduling and Control—TWO MACHINES AND TWO PART TYPES

If two parts are allowed to enter the system in a random order, the control of the system is increased significantly. The first characteristic of the system that is noted is that part identification is necessary. Again, if the parts are of different size, different robot programs may be required unless the parts are on a common-size pallet fixture. 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.
However, if the parts are allowed to be *mixed* in the system, some interesting phenomena take place. If part 1 is in the system and at machine 1 and part 2 is at the load point on the conveyor, part 2 can be moved to machine 2 and processing can begin. However, once this move is made, the 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* occurs in many operational FMSs and can only be remedied by human intervention. In order to eliminate dead-locking, one of two fixes are required: (1) **either a queuing station is necessary** or (2) **both parts are not allowed in the system at the same time.**

In general, in order to eliminate deadlocking by adding queuing stations and if *n* parts are allowed in the system, then *n*-1 queuing stations will be required to ensure that blocking does not occur. Part routing can reduce this number to zero; however, under the most severe routing conditions, *n*-1 queuing stations are necessary. Care should be taken before a system designer arbitrarily adds queuing stations to the system, because if many different parts are allowed to enter a complex system, then the material handling system can dedicate a significant portion of its time to simply moving parts to and from these queuing stations and tie up the system.

**AN EXAMPLE FOR CONTROL POLICY TO PREVENT DEADLOCKING:**

Use a queuing station.

Network graph of a two-machine two-part FMS-system flow.

(a) Part 1 at machine 1 and part 2 at machine 2 (DEADLOCKING),
(b) Part 1 at machine 1 and part 2 at machine 2 and a queue
   - Move part 2 at machine 2 to queue.
   - Move part 1 at machine 1 to machine 2.
   - Move part 2 at queue to machine 1.

The Gantt chart assumes that parts are batched in groups of 2, that is, two part 1’s are followed by two part 2’s, and so on.
AN EXAMPLE FOR CONTROL POLICY TO PREVENT DEADLOCKING:

Do not allow both parts at the system at the same time

WHEN THERE IS ONE TYPE DO NOT LET THE OTHER PART TYPE(S) IN.

-- This policy may force us to increase the batch size to increase the utilizations of the machines.