Ch 19
Flexible Manufacturing Systems (FMS)

Sections:
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 GT 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 range.

©2008 Pearson Education, Inc., Upper Saddle River, NJ. All rights reserved. This material is protected under all copyright laws as they currently exist. No portion of this material may be reproduced in any form or by any means, without permission in writing from the publisher. For the exclusive use of adopters of the book Automation, Production Systems, and Computer-Integrated Manufacturing, Third Edition, by Mikell P. Groover.
Flexible Manufacturing System (FMS) - Defined

FMS is 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 reason the FMS is called flexible is that it is capable of processing a variety of different part styles simultaneously at the various workstations, and the mix of part styles and quantities of production can be adjusted in response to changing demand patterns.

- 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.
Flexibility Tests in an Automated Manufacturing System

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? (Part variety test.)
2. Can it accept changes in production schedule? (Schedule change test.)
1. Can it respond gracefully to equipment malfunctions and breakdowns? (Error recovery test.)
2. Can it accommodate introduction of new part designs? (New part test.)

The most important criteria are (1) and (2). Criteria (3) and (4) are softer and can be implemented at various levels.

In fact, introduction of new part designs is not a consideration in some flexible manufacturing systems; such systems are designed to produce a part family whose members are all known in advance.
Automated Manufacturing Cell

Automated manufacturing cell with two machine tools and a robot. Is it a flexible cell?

Is the Robotic Work Cell Flexible?

1. **Part variety test**
   - Can it machine different part configurations in a mix rather than in batches? (If yes $\sqrt{\text{✓}}$

2. **Schedule change test**
   - Can production schedule and part mix be changed? (If yes $\rightarrow \sqrt{\text{✓}}$)
Is the Robotic Work Cell Flexible?

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? (If yes $\checkmark$)

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? (If yes $\checkmark$)

(This capability requires the new part to be within the part family intended for the FMS, so that the tooling used by the CNC machines as well as the end effector of the robot are suited to the new part design.)

Types of FMS

- Kinds of operations
  - Processing or assembly
- Type of processing
  - If machining, rotational or non-rotational
- Number of machines ($n$) (workstations):
  1. Single machine manufacturing cell ($n = 1$)
  2. Flexible manufacturing cell ($n = 2$ or $3$)
  3. Flexible manufacturing system ($n = 4$ or more)
A single machine cell consists of one CNC machining center combined with a parts storage system for unattended operation.

Completed parts are periodically unloaded from the parts storage unit, and raw workparts are loaded into it.

The cell can be designed to operate in a batch mode, a flexible mode, or a combination of the two.

When operated in a batch mode, the machine processes parts of a single style in specified lot sizes and is then changed over to process a batch of the next part style.
Single-Machine Manufacturing Cell

- When operated in a flexible mode, the system satisfies three of the four flexibility tests.
  
  It is capable of
  
  (1) processing different part styles,
  (2) responding to changes in production schedule, and
  (4) accepting new part introductions.

  Criterion (3), error recovery, cannot be satisfied because if the single machine breaks down, production stops.
Flexible Manufacturing Cell

A flexible manufacturing cell consists of two or three processing workstations (typically CNC machining centers or turning centers) plus a parts handling system.

- The parts handling system is connected to a load/unload station.
- The handling system usually includes a limited parts storage capacity.
- A flexible manufacturing cell satisfies the four flexibility tests discussed previously.
A two-machine flexible manufacturing cell for machining
(photo courtesy of Cincinnati Milacron)

A five-machine flexible manufacturing cell for machining
(photo courtesy of Cincinnati Milacron)
Flexible Manufacturing System (FMS)

- A flexible manufacturing system has four or more processing stations connected mechanically by a common parts handling system and electronically by a distributed computer system.
- Thus, an important distinction between a FMS and a FMC is in the number of machines: a FMC has two or three machines, while a FMS has four or more.

Flexible Manufacturing Cell (FMC)
Flexible Manufacturing System (FMS)

- There are usually other differences as well. One is that the FMS generally includes non-processing workstations that support production but do not directly participate in it. These other stations include part/pallet washing stations, coordinate measuring machines, and so on.
- Another difference is that the computer control system of a FMS is generally larger and more sophisticated, often including functions not always found in a cell, such as diagnostic and tool monitoring.
- These additional functions are needed more in a FMS than in a FMC because the FMS is more complex.
Features of the Three Categories

- We have defined the dividing line that separates a FMS from a FMC to be four machines.
- It should be noted that not all practitioners would agree with that dividing line; some might prefer a higher value while a few would prefer a lower number.
- Also, the distinction between cell and system seems to apply only to flexible manufacturing system that are automated.
- The manned counterparts of these systems discussed in the previous chapter arc always referred to as cells, no matter how many workstations are included.
Features of the Three Categories - Flexibility

Another way to classify flexible manufacturing systems is according to the level of flexibility designed into the system. This method of classification can be applied to systems with any number of workstations, but its application seems most common with FMCs and FMSs.

<table>
<thead>
<tr>
<th>ASLE 19.1 Flexibility Criteria Applied to the Three Types of Manufacturing Cells and Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexibility Criteria (Tests of Flexibility)</strong></td>
</tr>
<tr>
<td><strong>System type</strong></td>
</tr>
<tr>
<td>Single machine cell</td>
</tr>
<tr>
<td>Flexible manufacturing cell (FMC)</td>
</tr>
<tr>
<td>Flexible manufacturing system (FMS)</td>
</tr>
</tbody>
</table>

FMS Types – Classification based on 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.
Dedicated vs. Random-Order FMSs

Figure 19.5 Comparison of dedicated and random-order FMS types.

<table>
<thead>
<tr>
<th>System type</th>
<th>Flexibility Criteria (Tests of Flexibility)</th>
</tr>
</thead>
</table>
FMS Components

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

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
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

AGV – Automated Guided Vehicle

FMS Open Field Layout - FMS at Chance-Vought Aircraft
Robot-Centered Cell

- **Suited to the handling of rotational parts and turning operations**

![Diagram of a robot-centered cell]

---

Material Handling Equipment for FMS Layouts

**TABLE 19.3** Material Handling Equipment Typically Used as the Primary Handling System for the Five FMS Layouts

<table>
<thead>
<tr>
<th>Layout Configuration</th>
<th>Typical Material Handling System</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-line layout</td>
<td>In-line transfer system (Section 16.1.2)</td>
</tr>
<tr>
<td></td>
<td>Conveyor system (Section 10.2.4)</td>
</tr>
<tr>
<td></td>
<td>Rail-guided vehicle system (Section 10.2.3)</td>
</tr>
<tr>
<td>Loop layout</td>
<td>Conveyor system (Section 10.2.4)</td>
</tr>
<tr>
<td></td>
<td>In-floor towline carts (Section 10.2.4)</td>
</tr>
<tr>
<td>Ladder layout</td>
<td>Conveyor system (Section 10.2.4)</td>
</tr>
<tr>
<td></td>
<td>Automated guided vehicle system (Section 10.2.2)</td>
</tr>
<tr>
<td></td>
<td>Rail-guided vehicle system (Section 10.2.3)</td>
</tr>
<tr>
<td>Open field layout</td>
<td>Automated guided vehicle system (Section 10.2.2)</td>
</tr>
<tr>
<td></td>
<td>In-floor towline carts (Section 10.2.4)</td>
</tr>
<tr>
<td>Robot-centered layout</td>
<td>Industrial robot (Chapter 8)</td>
</tr>
</tbody>
</table>
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
FMS Computer Functions

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

---

FMS Computer Functions - Performance monitoring and reporting

**TABLE 19.4** Typical FMS Performance Reports

<table>
<thead>
<tr>
<th>Type of Report</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>Summary of the uptime proportion (reliability) of the workstations. Details such as reasons for downtime are included to identify recurring problem areas.</td>
</tr>
<tr>
<td>Utilization</td>
<td>Summary of utilization of each workstation as well as the average utilization of the FMS for specified periods (days, weeks, months).</td>
</tr>
<tr>
<td>Production</td>
<td>Daily and weekly quantities of different parts produced by the FMS. Comparison of actual quantities against the production schedule.</td>
</tr>
<tr>
<td>Tooling</td>
<td>Information on various aspects of tool control, such as a listing of tools at each workstation and tool life status.</td>
</tr>
<tr>
<td>Status</td>
<td>Instantaneous “snapshot” of the present condition of the FMS. Line supervision can request this report at any time to learn the current status of system operating parameters (e.g., trouble spots, utilization, availability, cumulative piece counts, and tooling).</td>
</tr>
</tbody>
</table>
Duties Performed by Human Labor

- 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

FMS Applications

- Machining – most common application of FMS technology
- Assembly
- Inspection
- Sheet metal processing (punching, shearing, bending, and forming)
- Forging
EXAMPLE 19.1
Vought Aerospace FMS

- A flexible manufacturing system installed at Vought Aerospace in Dallas, Texas, by Cincinnati Milacron is used to machine approximately 600 different aircraft components.
- The FMS consists of eight CNC horizontal machining centers plus inspection modules.
- Part handling is accomplished by an automated guided vehicle system using four vehicles.

LOADING AND UNLOADING OF THE SYSTEM IS DONE AT TWO STATIONS.
These load/unload stations consist of storage carousels that permit parts to be stored on pallets for subsequent transfer to the machining stations by the AGVS. The system is capable of processing a sequence of single, one-of-a-kind parts in a continuous mode, so a complete set of components for one aircraft may be made efficiently without batching.
EXAMPLE 19.2
Flexible Fabricating System (FFS)

- The term **Flexible Fabricating System (FFS)** is sometimes used in connection with systems that perform sheet-metal pressworking operations.
- The system is designed to unload sheet-metal stock from the **Automated Storage/Retrieval System (AS/RS)**, move the stock by rail-guided cart to the CNC punch press operations, and then move the finished parts back to the AS/RS, all under computer control.
Flexible automation concepts can be applied to assembly operations. Although some examples have included industrial robots to perform the assembly tasks, the following example illustrates a flexible assembly system that makes minimal use of industrial robots.

An FMS for assembly, installed by Allen-Bradley Company “flexible automated assembly line” produces motor starters in 125 model styles.
EXAMPLE 19.3
Assembly FMS at Allen-Bradley

The line boasts a one-day manufacturing lead time on lot sizes as low as one and production rates of 600 units per hour.

The system consists of 26 workstations that perform all assembly, subassembly, testing, and packaging.

The stations are linear and rotary indexing assembly machines with pick-and-place robots performing certain handling functions between the machines.

Each step in the process uses 100% automated testing to ensure very high quality levels.

The flexible assembly line is controlled by a system of Allen-Bradley programmable logic controllers.

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
FMS Benefits

- 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
FMS Planning and Design Issues

- **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
FMS Operational Issues

- 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 Flexible Manufacturing Systems

- 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
Quantitative Analysis of Flexible Manufacturing Systems

- **Deterministic models** are useful in obtaining starting estimates of system performance, but do not permit evaluation of operating characteristics such as the build-up of queues and other dynamics that can impair system performance.

- Consequently, deterministic models tend to overestimate FMS performance.

- On the other hand, if actual system performance is much lower than the estimates provided by these models, it may be a sign of either poor system design or poor management of FMS operations.

- **Queuing models** can be used to describe some of the dynamics not accounted for in deterministic approaches.

- These models are based on the mathematical theory of queues.

- They permit the inclusion of queues, but only in a general way and for relatively simple system configurations.

- The performance measures that are calculated are usually average values for steady-state operation of the system.

- Probably the most well known of the FMS queuing models is CAN-Q.

---


[26] Solberg, J. J., “CAN-Q User's Guide,” Report No. 9 (Revised), NSF Grant No. APR74-15236, Purdue University, School of Industrial Engineering, West Lafayette, IN, 1980.
Bottleneck Model

- Important aspects of FMS performance can be mathematically described by a deterministic model called the bottleneck model, developed by Solberg.
- Although it has the limitations of a deterministic approach, the bottleneck model is simple and intuitive. It can be used to provide starting estimates of IMS design parameters such as production rate, number of workstations, and similar measures.


We have simplified Solberg’s model somewhat and adapted the notation and performance measures to be consistent with our discussion in this chapter.)

Bottleneck Model

- The term bottleneck refers to the fact that the output of the production system has an upper limit, given that the product mix flowing through the system is fixed.
- The model can be applied to any production system that possesses this bottleneck feature, for example, a manually operated machine cell or a production job shop.
- It is not limited to flexible manufacturing systems.
What the Equations Tell Us

- 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 (machines, ...) 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.

WIP : Work-in-Process (Number of parts in the system),
MLT : Manufacturing Lead Time.