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# Classification of flexible manufacturing systems

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*There has been some uncertainty concerning the conditions under which a manufacturing system may be termed 'flexible'. To clarify this confusion eight types of flexibilities are defined and described.*

A FLEXIBLE Manufacturing System (FMS) is an integrated, computer-controlled complex of automated material handling devices and numerically controlled (NC) machine tools that can simultaneously process medium-sized volumes of a variety of part types.<sup>[5]</sup> This new production technology has been designed to attain the efficiency of well-balanced, machine-paced transfer lines, while utilizing the flexibility that job shops have to simultaneously machine multiple part types.

Recently, many new manufacturing facilities have been labelled FMS. This has caused some confusion about what constitutes an FMS. Flexibility and automation are the key conceptual requirements. However, it is the *extent* of automation and the *diversity* of the parts that are important; some systems are termed FMS just because they contain automated material handling. For example, dedicated, fixed, transfer lines or systems containing only automated storage and retrieval are not FMSs. Other systems only contain several (unintegrated) NC or CNC machines. Still other systems use a computer to control the machines, but often require long set-ups or have no automated parts transfer.

Some systems are called flexible because they produce a variety of parts (of very similar type, using fixed automation). In most of these examples, the operating mode is either transfer line-like or based on producing batches of similar part types.

To help clarify the situation, eight types of flexibilities will be defined and described. Examples or explanations are provided when needed to illustrate a particular flexibility type. Measurement and attainability of each are also discussed.

□ *Machine Flexibility*: the ease of making the changes required to produce a given set of part types. *Measurement* of these changes include, for example, the time to replace worn-out or broken cutting tools, the time to change tools in a tool magazine to produce a different subset of the given part types, and the time to assemble or mount the new fixtures required. The set-up time required for a machine tool to switch from one part type to another includes: cutting tool preparation time; part positioning and releasing time; and NC program changeover time. This flexibility can be *attained* by:

- (a) technological progress, such as sophisticated tool-loading and part-loading devices;
- (b) Proper operation assignment, so that there is no need to change the cutting tools that are in the tool magazines, or they are changed less often;
- (c) having the technological capability of bringing both the part and required cutting tools to the machine tool together.

□ *Process Flexibility*: the ability to produce a given set of part types, each possibly using different materials, in several ways. Buzacott [1982] calls this 'job flexibility', which 'relates to the mix of jobs which the system can process.' Gerwin [1982] calls this 'mix flexibility'. *Process flexibility* increases as machine set-up costs decrease. Each part can be machined individually, and not necessarily in batches. This flexibility can be *measured* by the number of part types that can simultaneously be processed without using batches. This flexibility can be *attained* by having:

- (a) *machine flexibility*; and
- (b) multi-purpose, adaptable, CNC

machining centres.

□ *Product Flexibility*: the ability to changeover to produce a new (set of) product(s) very economically and quickly. Mandelbaum [1978] calls this 'action flexibility, the capacity for taking new action to meet new circumstances.' Included in this concept is Gerwin's [1982] 'design-change flexibility'. This flexibility heightens a company's potential responsiveness to competitive and/or market changes. *Product flexibility* can be *measured* by the time required to switch from one part mix to another, not necessarily of the same part types. This flexibility can be *attained* by having:

- (a) an efficient and automated production planning and control system containing:
  - (i) automatic operation assignment procedures; and
  - (ii) automatic pallet distribution calculation capability.
- (b) *machine flexibility*.

□ *Routing Flexibility*: the ability to handle breakdowns and to continue producing the given set of part types. This ability exists if either a part type can be processed via several routes, or, equivalently, each operation can be performed on more than one machine. Note that this flexibility can be:

*Potential*: part routes are fixed, but parts are automatically rerouted when a breakdown occurs;

*Actual*: identical parts are actually processed through different routes, independent of breakdown situations.

The main, applicable circumstances occurs when a system component, such as a machine tool, breaks down. This flexibility can be *measured* by the robustness of the FMS when breakdowns occur: the production rate does not decrease dramatically and parts

continue to be processed. This flexibility can be *attained* by allowing for automated and automatic rerouting of parts (*potential routing flexibility*), by pooling machines into machine groups,<sup>[6]</sup> which also allows machine tool redundancy; and also by duplicating operation assignments.<sup>[5]</sup> These latter policies provide *actual routing flexibility*. The FMS would then be state-driven by a feedback control policy.

□ *Volume Flexibility*: the ability to operate an FMS profitably at different production volumes. A higher level of automation increases this flexibility, partly as a result of both lower machine set-up costs and lower variable costs such as direct labour costs. If it is not economical to run a particular system at its usual volume, say during a decrease in market demand or a recession, then there are less personnel problems concerning the idling of labour. Perhaps alternative uses of the FMS could be found. Also, production volumes can vary from week to week, resulting in variable machine and system utilisations. This flexibility can be *measured* by how small the volumes can be for all part types with the system still being run profitably. The lower the volume is, the more *volume-flexible* the system must be. This flexibility can be *attained* by having:

- (a) multipurpose machines; and
- (b) a layout that is not dedicated to a particular process; and
- (c) a sophisticated, automated materials handling system, such as (possibly intelligent) carts, and not fixed-route conveyors; and
- (d) *routing flexibility*.

□ *Expansion Flexibility*: the capability of building a system, and expanding it as needed, easily and *modularly*. This is not possible with most assembly and transfer lines. This flexibility can be *measured* according to how large the FMS can become. This flexibility is *attained* by having:

- (a) a non-dedicated, non-process-driven layout; and
- (b) a flexible materials handling system consisting of, say, wire-guided carts; and
- (c) modular, flexible machining cells with pallet changers; and
- (d) *routing flexibility*.

□ *Operation Flexibility*: the ability to interchange the ordering of several operations for each part type. There is usually some required partial precedence structure for a particular

part type. However, for some operations, their respective ordering is arbitrary. Some process planner has usually determined a *fixed* ordering of all operations, each on a particular machine (type). However, keeping the routing options open and not pre-determining either the 'next' operation or the 'next' machine increases the flexibility to make these decisions in real-time. These decisions should depend on the current system state (which machine tools are currently idle, busy, or bottleneck).

□ *Production Flexibility*: the universe of part types that the FMS can produce. This flexibility is measured by the level of existing technology. It is *attained* by increasing the level of technology and the versatility of the machine tools. The capabilities of all the previous flexibilities are required.

Not all of these flexibility types are independent. The Figure displays the relationships between the different flexibilities. The arrows signify 'necessary for'. An ideal FMS would possess all of the defined flexibilities. However, the cost of the latest in hardware and the most sophisticated (and at present non-existent!) software to plan and control adequately would be quite high on some of these measures and low on others. For instance, processing a particular group of products may be made possible through the use of head indexers having multiple-spindle heads. However, they hinder both adding new part types to the mix and introducing new part numbers, since retooling costs are high and changeover time can be a day. Also, some flexible systems (such as the SCAMP system in Colchester, UK) include special-purpose, non-CNC machines, such as hobbing and broaching, which also require (relatively) huge set-up times.

This classification of flexibilities can help categorize different types of FMS.

The *level of automation* helps to determine the amount of available flexibility. Because of the different choices of various flexibility levels, there are different types of FMSs. It is, therefore, useful to classify these systems in terms of their overall flexibility.

Towards a classification of flexible manufacturing systems, Groover [1980] divided FMSs into two distinct types:

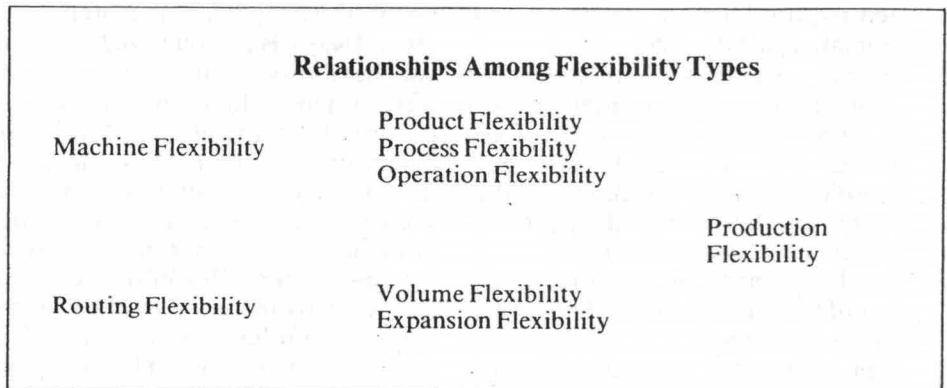
- (i) Dedicated FMS;
- (ii) Random FMS.

A dedicated system machines a fixed set of part types with well-defined manufacturing requirements over a known time horizon. The 'random FMS', on the other hand, machines a greater variety of parts in random sequence.

In addition to these basic, extreme types of FMSs, all FMSs are different in terms of the amounts of the flexibilities that they utilize. In this section, a classification of FMSs according to their inherent, overall flexibility is provided. Four general *types* of FMS will be defined.

The following standards are provided based on FMS components, which will be used to describe and classify the different types of FMSs:

1. Machine tools:
  - General-purpose or specialized
  - Automatic tool changing capabilities (increase flexibility)
  - Regarding tool magazines, their capacity, removability, and tool-changing needs (affect the flexibility).
2. Materials handling system:
  - Types include: conveyor or one-way carousel; tow-line with carts; network of wire-guided carts; stand-alone robot carts
  - Part movement equipment: palletized and/or fixtured
  - Tool transportation system: manual; or, automatically, with parts.



*Relationship among types of flexibility.*



3. Storage areas for in-process inventory:

- Central buffer storage
- Decentralised buffer at each machine tool
- Local storage.

4. Computer control:

- Distribution of decisions
- Architecture of the information system
- Types of decisions: input sequence; priority rules; part to cart assignment; cart traffic regulation
- Control of part mix: through periodic input; through a feedback-based priority rule.

These 'flexibility' standards for the physical FMS components are used to clarify differences and similarities between the FMS types.

Although not typically considered FMS, this classification scheme will include the flexible assembly system (FAS).

The simplest possible component of an FMS or FAS is a flexible assembly cell (FAC). It consists of one or more robots and peripheral equipment, such as an input/output buffer and automated material handling. To date, only about 6% of robot applications are in assembly.

A flexible assembly system (FAS) consists of two or more FACs. In the future, as the technology develops to allow the interface between manufacturing and assembly, an FAS could also be a component of a flexible system.

The types of FMS described, are categorized according to the extent of use of their flexibilities. The classification of a particular FMS usually results basically from its mode of operation as well as the properties of the four components described above.

#### ■ Type I FMS: Flexible Machining Cell

The simplest, hence most flexible (especially with respect to five of the flexibilities) type of FMS is a flexible machining cell (FMC). It consists of one general-purpose CNC machine tool, interfaced with automated material handling which provides raw castings or semi-finished parts from an input buffer for machining, loads and unloads the machine tool, and transports the finished workpiece to an output buffer for eventual removal to its next destination. An articulated arm, robot, or pallet changer is sometimes used to load and unload. Storage includes the raw castings area, the input and output buffers of the

machine tools, and the finished parts area.

Since an FMC contains only one metal-cutting machine tool, one might question its being called a system. However, it has all of the components of an FMS. Also, it is actually an FMS component itself. With one machine tool, it is the smallest, most trivial FMS.

#### ■ Type II FMS: Flexible Machining System

The second type of FMS can have the following features: It can have real-time, on-line control of part production. It should allow several routes for parts, with small volume production of each, and consists of FMCs of different types of general-purpose, metal-removing machine tools. Real-time control capabilities can automatically allow multiple routes for parts, which complicate scheduling software. Because of real-time control, however, the actual scheduling might be easier. For example, the scheduling rule might be to route randomly, or route to the nearest free machine tool of the correct machine type. The scheduling rule could be some appropriate, system-dependent, dynamic priority rule with feedback.

Sometimes, dedicated, special-purpose machines tools, such as multiple-spindle head changers, are used in an FMS to increase production. The machine tools are unordered in a process-independent layout. It is the part types that are to be processed by an FMS which define the necessary, required machine tools.

A Type II FMS is highly *machine-flexible*, *process-flexible*, and *product-flexible*. It is also highly *routing-flexible*, since it can easily and automatically cope with machine tool or other breakdowns if machines are grouped or operation assignments are duplicated.

Within the Type II category, the various kinds of material handling provide a sub-range of flexibility. In order of increasing flexibility, various material handling systems include: power roller conveyors, overhead conveyors, shuttle conveyors, in-floor tow line conveyors, and wire-guided carts. Some examples include:

- (i) a network of carts and decentralized storage areas, for shorter processing times (Renault Machines Outils, in Boutheon, France);
- (ii) a tow line with carts and centralized storage areas, for longer processing times (Sundstrand/

Caterpillar DNC Line, in Peoria, Illinois, USA).

#### ■ Type III FMS: Flexible Transfer Line

The third type of FMS has the following features. For all part types, each operation is assigned to, and performed on, only one machine. This results in a *fixed route* for each part through the system. The layout is process-driven and hence ordered. The material handling system is usually a carousel or conveyor. The storage area is local, usually between each machine. In addition to general-purpose machines, it can contain special-purpose machines, robots, and some dedicated equipment. Scheduling, to balance machine workloads, is easier. In fact, a Type III FMS is easier to manage because it operates similarly to a dedicated transfer line. The computer control is more simple and a periodic input of parts is realistic. Once set up, it is easy to run and to be efficient. The difference is that it is set up often and relatively quickly.

A Type III FMS is less *Process-flexible* and less capable of automatically handling breakdowns. However, the system can adapt by re-tooling and manually inputting the appropriate command to the computer, to re-route parts to the capable machine tool. This takes more time than the automatic re-routing available to a Type II FMS.

#### ■ Type IV FMS: Flexible Transfer Multi-Line

The fourth FMS type consists of multiple Type III FMSs that are interconnected. This duplication does *not* increase *process flexibility*. Similar to a Type III FMS, scheduling and control are relatively easy, once the system is set up. The main advantage is the redundancy that it provides in a breakdown situation, to increase its *routing-flexibility*. It attempts to achieve the best of both FMS Types II and III.

### Flexibility range

All things being equal, a Type II FMS is operated 'flexibly', while a Type III FMS is operated in a much more 'fixed' manner. These types provide the extremes, say, the *bounds* on flexibility. There is, of course, a whole range of flexibilities between the two general types. However, these smaller variations in flexibility are defined by the versatilities and capabilities of the machine tools, which are dictated by the particular

FMS application, i.e., the part types to be machined. The types of material handling system also provides sub-groups of flexibility. The overall flexibility, however, is defined by an FMS's *mode of operation*.

In general, the FMSs of the United States and the Federal Republic of Germany tend to be more like the Type II FMS, while those of Japan are more similar to Type III. The second floor of Fanuc's Fuji complex, consisting of four flexible transfer lines, is an example of an operating Type IV FMS. It consists of several identical FACs, which are not all identically tooled. Parts do have fixed routes, but if an assembly cell is down, the parts requiring it are automatically able to be routed to another assembly cell, which contains the correct tooling. The first floor of this Fanuc plant, the Motor Manufacturing Division, is a good example of Type II.

All FMSs consist of similar components. The numbers and types of machine tool may differ. What really defines the flexibility of an installation is how it is run. The level of desired flexibility is an important strategic decision in the development and implementation of an FMS. This paper has provided a framework for such strategic decisions.

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