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CLASSIFICATION OF FLEXIBLE MANUFACTURING SYSTEMS: EVOLUTION TOWARDS THE AUTOMATED FACTORY

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ABSTRACT

There has been some uncertainty concerning whether a manufacturing system can be termed "flexible." To clarify this confusion, first, eight types of flexibilities are defined and described. Different FMSs contain different amounts of these flexibilities. We found it useful to classify *types* of FMSs with respect to their flexibility. The types define a *range* of flexibility. We observe that an FMS's type is largely defined by its operating characteristics, but also by the versatility of its machine tools and the kind of automated material handling system. Then, an overview of the evolution of an automated factory, as an integrated combination of FMSs of different *types*, is presented. At each stage during the evolution, various components of automation would be implemented modularly as desired. Finally, the (future) interfaces between some of these components are discussed.

1. INTRODUCTION

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 (Stecke [1983]). 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 are labeled as 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 have long set-ups required or no automated part transfer. Others 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, we first define and describe eight types of flexibility in §2.

All FMSs have the *potential* to utilize these flexibilities to a great extent. However, there are some economic, technological, practical, and strategic reasons not to design and/or utilize all of these flexibilities in a particular FMS. For example, some FMSs operate as fixed-route transfer lines, in part because the development of real-time scheduling capabilities are difficult, expensive, and time-consuming.

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. We propose such a classification scheme for FMSs in §3. Next, in §4 we describe stages, in terms of an increasing amount of automation, during the development, evolution, and eventual implementation of a flexible, automated factory. Several of the components, in particular, group technology, computer aided design, and production planning and control are briefly described. Finally, the interfaces, both existing and future, between various automation components are discussed in §5.

2. TYPES OF FLEXIBILITY

Flexibility may be considered to be the most important, yet unquantifiable, aspect of an FMS. However, a considerable degree of ambiguity surrounds this term. In fact, many "FMSs" have only limited flexibility. In this section, alternative meanings of flexibility are defined. Examples or explanations are provided when needed to illustrate a particular type. Measurement and attainability of each are also discussed.

1. *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 setup 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.

2. *Process Flexiblity*:
   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*." *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 centers.

3. *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." 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, of 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*.

4. *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 circumstance 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 (see Stecke and Solberg [1982]), which also allows machine tool redundancy; and also by duplicating operation assignments (see Stecke [1983]). These latter policies provide *actual routing flexibility*. The FMS would then be state-driven by a feedback control policy.

5. *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. 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 labor. Perhaps alternative uses of the FMS could be found. Also, production volumes can vary from week to week, resulting in variable machine and system utilizations. This flexiblity can be *measured* by how small the volumes can be for all part types. 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*.

6. *Expandability 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*.

7. *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).

8. *Production Flexibility*:
   the range of part types that the FMS can produce. This flexiblity 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 of the previous flexibilities are required.

Not all of these flexiblity types are independent. Figure 1 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 nonexistent!) 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, U.K.) include special-purpose, non-CNC machines, such as hobbing and broaching, which also require (relatively) huge setup times.

We next use this classification of flexibilities to help categorize different types of FMSs.

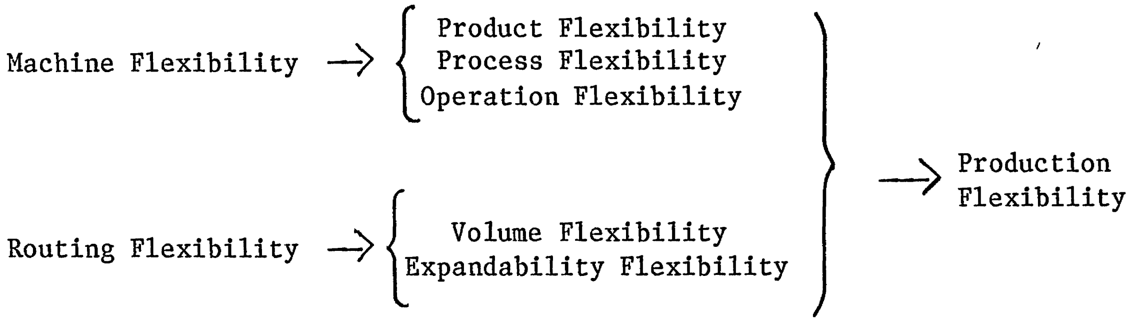

FIGURE 1

Relationships Among Flexibility Types.

3. CLASSIFICATION OF FLEXIBLE MANUFACTURING SYSTEMS

Towards a classification of flexible manufacturing systems, Groover [1980] divides 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, we note that all FMSs are different in terms of the amounts of the flexibilities that they utilize. In this section, we provide a classification of FMSs according to their inherent, overall flexibility. We will define four general *types* of FMS.

The following standards are provided based on FMS components, which we shall use 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

3. Storage areas for in-process inventory:
    - Central buffer storage
    - Decentralized 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, our classification scheme will include the flexible assembly system (FAS). We begin by defining the simplest components, or modules, that can be considered during the construction of an FMS.

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 application is in assembly.

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

The types of FMS are now described. They 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 it 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-with-feedback, priority rule.

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 subrange 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, U.S.A.).

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 retooling and manually inputting the appropriate command to the computer, to reroute parts to the capable machine tool. This takes more time than the automatic rerouting available to a Type II FMS.

Type IV FMS: Flexible Transfer Multi-Line

The fourth FMS type consists of duplicate Type III FMSs. 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 tries 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 subgroups of flexiblity. 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 assembly 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 tools may differ. What really defines the flexibility of an installation is how it is run. The level of desired flexibility is an important decision in the development and implementation of an FMS.

4. EVOLUTION OF AN AUTOMATED FACTORY

One general approach to modularly develop, plan, construct, and eventually implement an automated factory (AF) is provided in Figure 2. Beginning with an NC machine tool, for example, when the automated functions that are listed in Figure 2 are included (such as an automatic load and unload under CNC control capability), an FMC is the result. Then, integrating several FMCs, each possibly containing a different type of CNC machine tool, with some of the additional automated features in Figure 2, provides an FMS. The present state of the technology does not allow the automatic integration of an FMS and an FAS. Future systems should. The eventual connections and interfaces between several FMSs, FASs, with a group technology (GT) system and a computer aided design (CAD) system can provide a totally automated factory. Short descriptions of some of these other components of an automated factory, such as CAD, GT, and production planning and control are in order.

Computer Aided Design

Computer aided design (CAD) is both product and process related. First, the geometry of a particular part type is captured at a computer terminal and input into an engineering data base. Analytical software is used to analyze the part type design. Then, computer aided process planning (CAPP) is used to define the operations of the part type. Finally, NC part programming provides the software instructions to run the CNC machine tools that manufacture the part type. The source instructions of the NC part program provide the interface (via a post processor that is unique to the machine) between the part type geometry and its desired material, and the CNC machine tool that cuts the part.

Group Technology

Group technology (GT) is another design tool that is also both product and process related. First, all part types are classified and coded according to their characteristics, such as size, volume, weight, shape, material, cost, and machine tool required. This information is used to group similar part types together. This data can also be used to standardize processes and materials for similar part types and hence reduce the number of part types in the data base. Next, a cell of machine tools is chosen that is dedicated to produce that family of part types. GT is mostly applicable to a product-driven industry, rather than a process-driven.

During the design of an FMS, occasionally GT has been used to help identify the appropriate families of part types to produce. This initial choice impacts the number and types of machine tools in the FMS. As part type requirements change and new part types are designed to be machined by the FMS, additional and appropriate machine tools can then be added to the FMS.

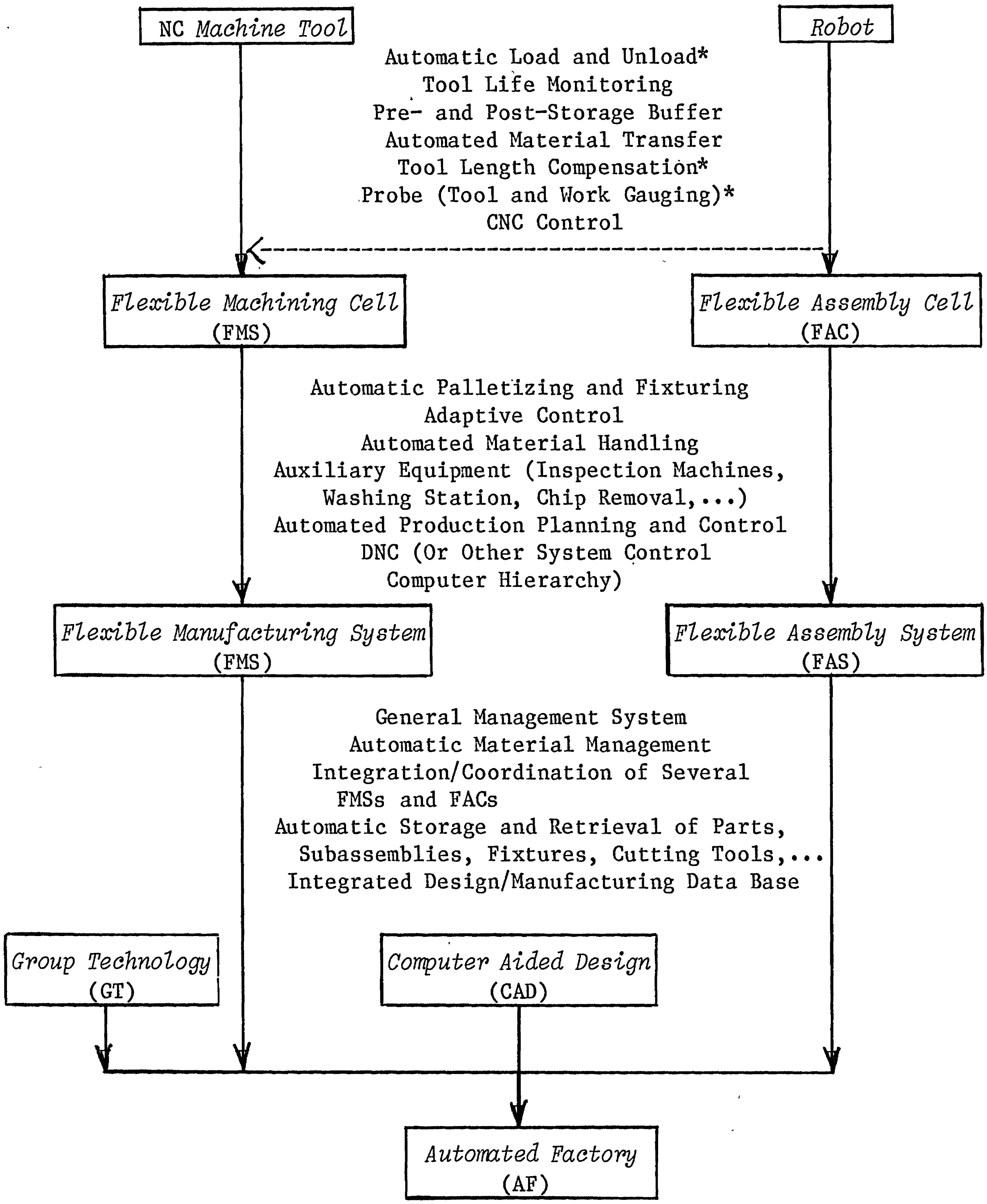

FIGURE 2

Modular Evolution to an Automated Factory.

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*These features apply mainly to NC machine tools, rather than to robots.

Automated Production Planning and Control

Some properties and constraints of FMSs are similar to those of flow and job shops, while others are different. This technology creates the need to develop new and appropriate planning and control procedures that take advantage of the system's capabilities for higher production rates (Stecke [1983]).

A complete discussion of FMS planning and control functions is beyond the scope of this paper. However, since there has been much recent research concerning planning and control models for FMSs, a bibliography of this research is provided.

Flexible with Conventional Systems

As an older machine tool wears out, there has been a tendency to replace it with NC. Of course, conventional manufacturing systems or lines within a plant will not disappear. Future research must also address the problem of interfacing automated with conventional systems. In addition, there will always be situations that one does not want to automate.

5. INTERFACES BETWEEN VARIOUS COMPONENTS OF AUTOMATION

Some of the interfaces between the various modular components and requirements given in Figure 2 exist, while others do not yet. Recall that the NC part program is an interface between CAD and FMS. However, the automatic generation of part programs is not yet widely available. Another interface is the automatic linkage between an MRP-type output--a pick list, say--and the computer that controls the automatic storage and retrieval system or the automated warehouse.

There is no interface yet between GT and MRP-type output. Robotics is still a stand alone application via the FAC and FAS. Robots cannot yet be linked to a central engineering data base from the part type geometry provided by a CAD system.

All of manufacturing involves transmitting, sorting, analyzing, and modifying data. Parts are a manifestation of data. Data is a useful corporate resource.

There are different design/engineering CAD *data bases*. Current research is investigating the problems concerning how to communicate between them. The state-of-the-art integrates CAD's geometric engineering data with the alphanumeric manufacturing information that is already in a business data base.

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