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FLEXIBLE MANUFACTURING SYSTEM HANDBOOK

VOLUME II: DESCRIPTION OF THE TECHNOLOGY

CONTRACT NUMBER: DAAE07-82-C-4040

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by Charles Stark Draper Lab., Inc.
Cambridge, Massachusetts 02139

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U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH AND DEVELOPMENT CENTER
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Flexible Manufacturing Technology is a means to increase productivity for manufacturing environments in the middle ranges of production volume. It is effective for "one of a kind" and true "mass production" quantities. Volumes I through IV of this handbook help determine if a flexible machining system (FMS) will be cost effective for a given application. These volumes explain the configuration and procurement of a FMS, and its impact on the existing organization. The fifth volume of the handbook details the computer programs for the FMS.

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This is the second volume in a five-volume series designed to answer the following questions concerning Flexible Manufacturing Systems (FMS):

- Why an FMS?
- Will an FMS best serve your application?
- What problems might be encountered?
- How do you design an appropriate system?
- What is required to operate a system?

In the series, Volume I is intended to help answer broad policy questions at corporate levels. This volume contains detailed descriptions of the subsystems that make up a typical FMS as well as descriptions of several operational FMSs. Volume III is designed to serve as a detailed guide to planners at corporate and plant levels. Volume IV contains a sample request-for-proposal, a proposal, a glossary of FMS terms, a bibliography, and other technical material. Volume V contains user's manuals for various software packages.

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1.0 DESCRIPTION OF FLEXIBLE MANUFACTURING SYSTEM ELEMENTS

This section describes the major elements of an FMS. It begins with a discussion of the principal physical characteristics of a system, including the central elements, the machining stations, the load/unload stations, control station, and cleaning stations. The material handling systems are next considered, followed by a detailed description of the control system. The multitude of software functions are then explored in depth. Finally, the remaining significant elements of an FMS are addressed. These include fixtures and pallets, tooling, chip handling, deburring, inspection, and requirements for line personnel. To establish a frame of reference, a description of the operation of an entire system is presented in the following subsection.

1.1 DESCRIPTION OF A FLEXIBLE MANUFACTURING SYSTEM

A Flexible Manufacturing System (FMS) can be defined as a "computer-controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one kind of part at low to medium volumes". Figure 1 on page 2 shows a conceptual drawing of an FMS. The definition and the illustration highlight the three essential physical components of an FMS.

- Potentially-independent NC machine tools.
- A conveyance network to move parts and sometimes tools between machines and fixturing stations.
- An overall control network that coordinates the machine tools, the parts-moving elements, and the workpieces.

In most FMS installations, incoming raw workpieces are fixtured onto pallets at a station or group of stations set apart from the machine tools. They then move via the material handling system to queues at the production machines where they will be processed. In properly designed systems, the holding queues are seldom empty, i.e., there is usually a workpiece waiting to be processed when a machine becomes idle. When pallet exchange times are short, machine idle times are quite small. The number of machines in a system typically ranges from 2 to 20 or more. The conveyance system may consist of carousels, conveyors, carts, robots, or a combination of these. But the important aspect of these systems is that the machine, conveyance, and control elements combine to achieve enhanced productivity without sacrificing flexibility.

Perhaps the easiest approach to understanding an FMS is to trace the flow of parts through the system. A typical FMS is capable of random piece-part production within a given part mix. In other words, using simulation and other production analysis techniques, a production part set is determined which utilizes the system capacity. At any given time, any or all of those parts might be found somewhere in the system. If the parts

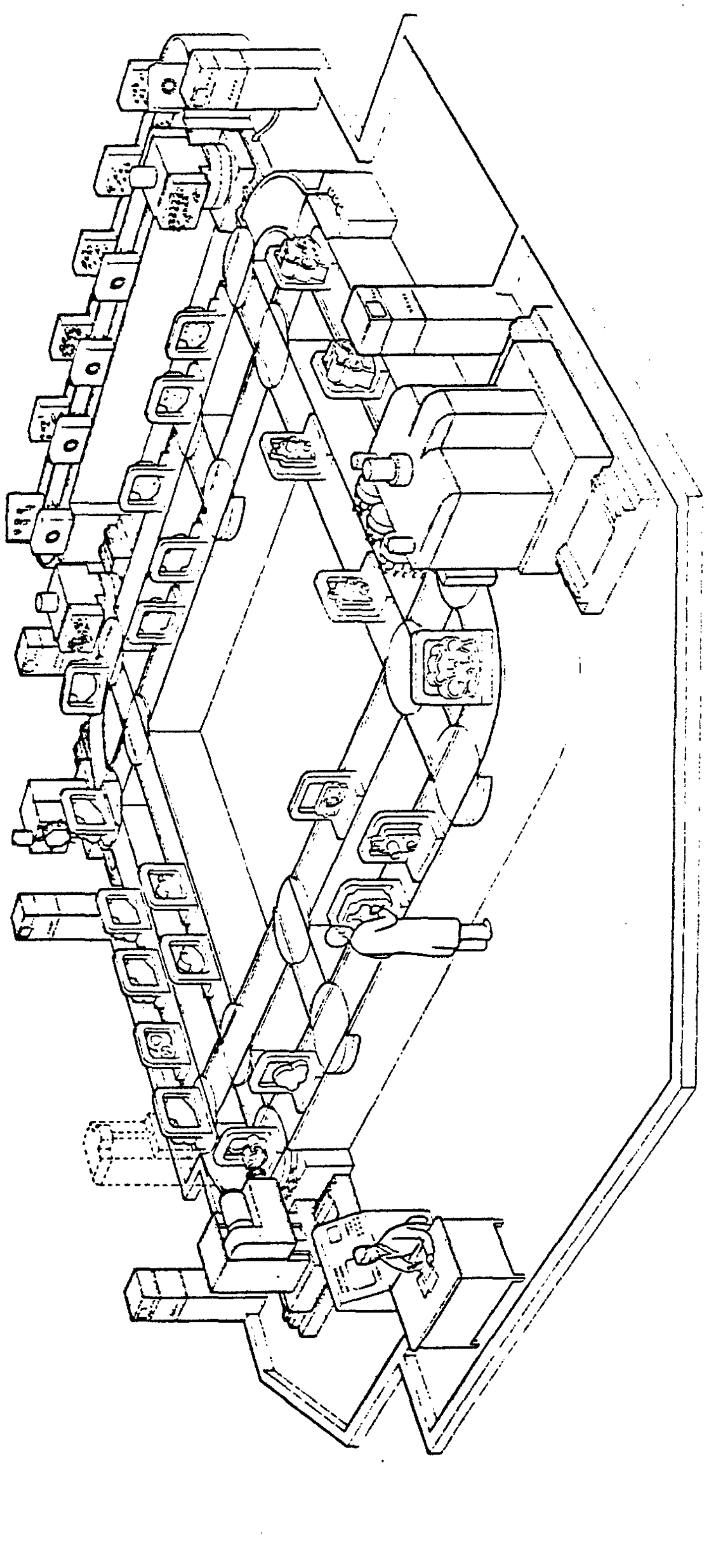


Figure 1. Conceptual Drawing of an FMS

require many tools, it may not be possible to have all of them in the system at one time because of limited in-system tool storage capacity. In this case, the part set will be divided into groups, called batches, the required tooling for each of which will fit in the FMS. For each batch, each machine will be tooled to process specific parts. Thus, not all parts will go to all machines - each part will be allocated to one or more specific machines to process it. Where possible, alternate machines are specified to perform each operation on each part type. For example, if there are three part types, A, B, and C, each of which must go to two different machine groups, M1 and M2, and there are two machines in each group M11, M12 and M21, M22, the allocation and routing might look like the following:

Part A and Part B go to M11, then M22.
Part C goes to M12 and M21.

In this situation, machines M12 and M21 will machine only Part C, unless something is wrong with M11 or extra time is available on M12, in which case Part A might also be machined on machine M12. When Part A and Part C are both competing for machine M12, the FMS computer will determine which part is further behind schedule and allow that part to use M12. (Note, it is assumed that machines within each group are tooled identically.)

Part flow begins at the load/unload station, where the raw castings and fixtures are kept. The FMS control computer keeps track of the status of every part and machine in the system. It continually tries to achieve the production targets for each part type and in doing so tries to keep all the machines busy. In selecting parts to be sent into the system, it chooses part types which are the most behind in their production goals, and for which there are currently empty fixture/pallets or load stations. If an appropriate pallet/fixture combination and a workpiece are available at the load station, the loader will get a message at his computer terminal to load that part on its pallet. He will then enter the part number and pallet code into the terminal, and the computer will send a transporter (e.g., a cart) to the load station to move the pallet. The transporter is next sent to the machine.

Once at the queue in front of the machine, the computer actuates the transfer mechanism in the queue (usually called a shuttle) and the pallet is shifted from the transporter onto the shuttle. The transporter is then free and will leave when a new move request is assigned. The part and pallet wait until the part currently being machined is completed, and then the two parts and their pallets exchange positions. As the new part and pallet are moved onto the machine, the proper NC part program is downloaded to the machine controller from the FMS control computer. After completing the downloading, machining begins.

The finished part now on the shuttle waits for the computer to send a free transporter to collect it and carry it to its next destination. If, for some reason, the part cannot go to that destination, the computer checks its files for alternative destinations. If one exists, the computer decides if conditions in the FMS (backlog, availability, lateness) warrant sending the part to that destination. If it does not, the part either circulates around the system on the transporter until the destination is available, or the transporter unloads it at some intermediate or storage queue, and retrieves it when the destination is available. The last destination is usually the load station, now functioning as an unload station where the part is removed from the pallet and replaced by a new part, or the pallet is stored until needed.

The computer controls the cycles just described for all parts and all machines in the system, performing scheduling, dispatching, and traffic coordination functions. It also collects statistics and other manufacturing information from each station for reporting purposes.

The conceptual FMS drawing (Figure 1 on page 2) illustrates many of the features just discussed. The control computer is on the left. The material handling system is a conveyor. The pallets and parts are being carried to their destinations, which might be a machining center or an inspection machine. The two machines in the upper right-hand side of the figure are head changers. These machines share a number of fixed-pattern, multiple-spindle drilling/tapping heads which circulate on a separate conveyor. This type of more dedicated equipment is sometimes integrated into an FMS to increase productivity. The manual load/unload station is shown opposite the computer control console.

1.2 WORK STATIONS

1.2.1 Machining Stations

The capabilities of an FMS are uniquely identified by the machines it contains and, therefore, it is appropriate to initiate a discussion of such systems with a description of the variety of machines that can be employed. In general, horizontal-spindle machining centers are the key metal-removing machines in FMSs, although any particular line may employ a variety of special-purpose machines to support these basic machines. Examples would be multiple-spindle machines (such as head changers) to most economically produce hole patterns, and special, single-purpose machines to accomplish machining operations not performed by machining centers, such as broaching, planing, hobbing, turning, and perhaps even grinding.

The class of parts to be produced on an FMS usually determines the type of machine or mix of types of machines to be included in that FMS. Presently, FMS technology, with respect to prismatic parts, is more mature than that for rotational parts. The usual choices of machines for prismatic parts are between various brands of vertical and horizontal machining centers and special-purpose machines, such as head changers and head indexers.

To accommodate a mix of strictly prismatic parts with other prismatic parts requiring large bores or circular bearing surfaces, vertical turret lathes (VTL) can be used. Rotational parts having a length-to-diameter ratio of less than two, such as disks, hubs, or wheels with considerable milling, drilling and/or tapping, are usually candidates for inclusion in a prismatic-part part type FMS. A mix of machining centers and VTLs will usually require more fixtures per part, especially when VTLs are combined with horizontal machining centers, because the rotational axes of the two machine types are different. This can be overcome through using tilting rotary tables on the horizontal machines, though not without problems. Adding a tilting rotary table to a standard machining center greatly increases its cost (it is now a five-axis machine). Also the pallet, fixture and part are cantilevered off the table, aggravating accuracy problems due to droop as well as aggravating wear and failure mechanisms.

FMS technology with respect to strictly rotational parts - bars and shafts - is still in its infancy, particularly in the U.S. Standard CNC lathes with both bar and chucking ability can be integrated to form a rotational FMS (the material handling schemes will be discussed later), but currently this concept only exists on a smaller scale in flexible manufacturing cells.

Machining centers can be basic horizontal or vertical three-axis machines that process just one side of a piece-part (or could do some limited machining on some adjacent faces). This approach normally requires multiple fixturing passes to complete the manufacture of each piece-part. Each pass is treated by a separate part program and may be machined on the same mill or a different one, depending upon the work schedule and tool complement of each machine on the line. With the addition of one or two axes to horizontal machining centers -- pallet rotation (usually the fourth axis) and/or head tilt (usually the fifth axis) -- greater piece-part access is gained. Typically, three and often four sides of a part can be placed normal to the spindle axis with pallet rotation, affording more machining time per setup. To obtain the same part access with a vertical machining center, a tilting rotary table must be added to the basic machine. (Again, this is now a five-axis machine with the associated potential problems.) Aside from the increased cost, this concept works well for small pallets and parts.

The opportunity to mount more than one workpiece on a pallet/fixture is an adjunct to this multiaxis capability. This may provide some improvement in the throughput of a particular FMS. The fifth axis is normally reserved for special machining requirements in nonorthogonal planes or to solve special reach problems. There are examples in the field of specialized five-axis machines where the tilt head can be used only with the spindle horizontal or vertical. This lowers the cost compared to a machine with full control, while providing for some special machining needs.

The family of parts to be produced on an FMS dictates the power, size envelope, and accuracy required of the machining centers. It is not uncommon to adopt a mix of machines for a line to cover a range of accuracies. However, if, for example, a single high-precision machine is used to achieve special bore tolerances, the entire line operation depends upon the up time of this machine since there is no provision for functional redundancy. It may be better to produce these high-precision bores off-line. From a scheduling standpoint, it is most efficient to provide full redundancy by using identical models for all machines. However, the dictates of the piece-parts may necessarily compromise this ideal.

In addition to power, envelope, and accuracy requirements, the choice of machining centers for an FMS may be further limited by consideration of interfaces with the material handling system. Stand-alone machines that have pallet exchangers as options may be better suited to this interfacing task than those not offering this option.

All FMS machining centers have tool storage capabilities, either in the form of a drum or tool chain. Tooling requirements for the piece-part variety of an FMS usually put extreme demands on storage capacity. It is not uncommon to need more than 100 pockets in a tool-changer magazine. This capacity, coupled with the weights of some tools, in particular large boring bars or face mills, requires some attention to be paid to the reliability of the tool transport and exchange mechanisms.

Vertical turret lathes must be equipped with pallet shuttles before they can be integrated into an FMS. External turning, facing, and boring operations can all be performed on a VTL with little need for a tool changer -- usually a four- to six-tool block-indexable turret with dedicated tools is more than enough to complete the necessary turning work content. Tool changers are available, however, if there is a need for a variety of different turning and grooving tools.

Pallets, coolants, and chip handling systems, while essential elements of the machining center, are discussed separately. "MACHINE CHARACTERISTICS DATA BASE" on page 37 contains an extensive listing of the characteristics of available machines from a variety of vendors.

1.2.2 Load/Unload Stations

The principal requirements of a load/unload station include a clean support for the pallet in a position accessible to the material handling system, pallet maneuverability (or access around it) to permit the loader to remove and load piece-parts, often washing facilities to flush residual chips and obtain clean mounting points for new workpieces, and a computer terminal for operator communication with the FMS control computer.

Normally, the pallet support would be a hydraulically operated table that works in conjunction with the material handling system (MHS) to transport the pallet from the conveyance to a stationary point for loading and unloading. This should incorporate protection for the precision coupling mechanism on the pallet to prevent chips or other foreign materials from lodging in it, which would destroy orientation accuracy.

Piece-part handling equipment will be in the form of overhead cranes or forklift trucks for most parts, since they usually are too heavy to lift manually. At Niigata Engineering Company, Limited (Japan), parts are being fixtured on pallets automatically, but in general, a person is at the load/unload station to operate the overhead crane, etc. Raw and finished piece-part storage must be located close to the load stations to minimize the complexity of a crane system. This handling system must orient the piece-part to mate quickly with the fixture.

During or after the unload sequence, residual chips must be cleared from the fixture/pallet. This is greatly facilitated by having these stations on a raised, open-grid platform where chips can be flushed through to a recirculating coolant trough. Any spray hoses at these stations would be supplied with coolant rather than water to prevent dilution of the coolant.

By incorporating a status-update console at the load station, and by having a multiplicity of load stations, the line and loaders can achieve some independence, enabling the system to achieve high utilization rates. While loading or unloading at one station, a HOLD status is initiated to prevent the MHS from retrieving a pallet from that station. Upon completion of reload, a GO status is initiated so the computer can send a signal to the MHS to exchange a new pallet for the completed pallet. Redundant load stations (having the same fixturing on pallets) prevent the line from being paced by the loaders and give the loaders some freedom to vary their work pace.

1.2.3 Control Station

Although the mainframe computer may be remote from the immediate FMS area, several levels of communication must be available to permit operation and control of the line. Much of this communication takes the form of status reports for each of the machines, the MHS, and the load/unload stations. Each machine would have its own NC console with display (usually a cathode ray tube (CRT)) showing machining sequence data.

A central control station would display more general data from each machine, such as piece-part identification, operation status (awaiting part, machining time remaining in cycle, etc.), together with specific line information pertaining to scheduling, raw part management, tooling status and forthcoming changes, part-program status, pallet status, etc. Manual intervention can be achieved through this control station to rectify specific problems with machines, tooling, the MHS, or piece-parts.

1.2.4 Cleaning Stations

The cleaning stations may or may not be separate entities on the FMS line; they could be integral with the load/unload stations. Here, cleaning is considered chip removal (washing of the part, fixture, and pallet) and not deburring. Normally, deburring is performed off-line since it would interfere with the load/unload functions.

1.3 MATERIAL HANDLING SYSTEM

1.3.1 Part Transport

There are two principal forms of part transport: parts must be moved from outside the system into it, and they must be conveyed within it. It usually is not convenient to combine these functions because movement into the system involves raw parts while movement within the system involves part, fixture, and pallet assemblies. (FMSs for parts-of-rotation may not use fixtures or pallets.)

Because mounting parts on fixtures is, at present, usually a manual operation, movement of parts into the system logically is performed manually. Various types of cranes can be employed to maneuver parts too heavy to lift manually, and the technology exists to use robots as well. These would be located near the load/unload stations; and bins, magazines, or pallets of raw parts should be stacked nearby to facilitate the loading function. Large storage facilities for long-term part storage can be remote from the FMS; transport of parts to the line by forklift truck requires only that adequate traffic ways to the load/unload area be incorporated in the FMS design.

Within the system, there are many possible pallet-movement designs. The three principal categories are carts, roller conveyors, and robots. Guidance and control of carts can take many distinct forms. Carts can move along tracks, energized and controlled externally by the central computer. Sensors (optical, proximity, or limit switches) located at appropriate points along the track identify the precise location of the cart and can be used to position it to the required tolerance (typically 0.06 inch) to transfer pallets to a machine or unload station. Wheel encoders can be used as less precise feedback for the drive system and its programmed speeds. All carts should have dead-man bumpers at each end to help prevent accidents. White-Sundstrand uses an example of this type of MHS design.

Battery-powered carts can be moved along a flat floor, guided by an antenna that detects a wire embedded below the surface. Position sensors still must be used to control pallet transfer. The Cincinnati Milacron Variable Mission System uses this type of MHS, specifically the Eaton-Kenway Robocarrier.

A third cart design uses a tow chain in a trough under the floor. The chain moves continuously and cart movement is controlled by extending a drive pin from the cart down into the chain. At specific points along the guideway, computer-operated cam-type stop mechanisms raise the drive pins to halt cart movement. One advantage of this system is that it can provide some automatic buffering with stationary carts along the track. This system is used by Kearney and Trecker. A variation on this method from SI Handling uses a floor-mounted spinning cylinder that imparts motion to the roller drive of individual carts; a computer initiates drive disengagement, and the carts can be stopped at selectable locations.

A roller conveyor system can be designed to move pallets from the load stations to pallet exchangers located on the machines. Individual sections can have separate drives to control placement of pallets near machines. Limit or proximity switches can provide feedback to locate pallets along the conveyor. Side tracks and switching gear can support buffer zones within the system. In contrast to wire- or tow-guided carts, a conveyor system limits access to the major elements of the FMS because it must be raised above the floor level, so that it is aligned with the pallet exchangers on the machine tools.

An FMS may be modified to provide rapid access to additional tools by means of a cart or conveyor-carried auxiliary tool rack. A loading robot would transport the tools as required from the auxiliary rack to the machine (see Section 1.5.2).

Robots are a special consideration for an MHS and are generally applicable where spacing between machines is short and workpieces plus fixtures (if any) are relatively lightweight. They are most useful when machines are clustered in a circular work cell so that one robot can serve several machines. They are often used with unfixtured parts-of-rotation.

Robots are generally the crucial link in realizing an FMS for parts-of-rotation. Currently, there are a number of systems classified as rotational FMSs in the U.S. These systems might be better described as turning cells operated by programmable robots, connected by a nonpalletized conveyor system. The system is not usually controlled by a master computer, but the equipment generally consists of CNC lathes or other CNC turning machines, some of which currently have the capability to change cutting tools, chucks, or both. Most of the systems do not operate in a random part-processing mode, as do their prismatic counterparts. Instead, all of the equipment is set up to machine one distinct part, though each cell is responsible for a different step in the manufacturing process. Once the production quantity for the part is obtained, the system is shut down; tools and chucks are changed, if necessary (often rotary parts can be grouped to take advantage of the need for similar chucks and tools); the machines are given new NC programs for the next part; the correct robot programs are activated; part production begins again.

A typical operating sequence might be as follows. After deciding which part to process next, the NC programs for that part for each machine and the programs for the robots in each cell are loaded. The chucks and tools at each machine are changed, if necessary, and the grippers for the robots are changed. Raw workpieces are then placed on the conveyor from storage to the first cell -- usually on V-blocks to maintain orientation and keep them from rolling into or damaging each other -- and they start flowing to the first cell. The parts queue there while the robot loads and unloads the individual machines in the cell. The queueing area provides a buffer for minor imbalances between this cell and the one before it. Balance is achieved among the cells by activating or deactivating machines in that cell and by using the buffers. Upon completion at a cell, the robot places the part on the conveyor to the next cell, and so on. If the part can bypass a cell, there is usually a second conveyor accessible to the robot.

Industrial robots for loading machines in an FMS can either be stand-alone units that are programmed to act in conjunction with the motions (door opening, chuck grasp, spindle rotate, etc.) of the machine tool or bolted onto, or otherwise made integral with, the machine tool. The advantages of a stand-alone robot include its potential for servicing more than one machine and its capability to be removed easily and placed into service on a totally different machine. The advantages of robots that are part of the machine tool itself include reduced floor-space requirements and the lowered likelihood of serious software "bugs".

Choice of robot configuration -- whether it is built with Cartesian, cylindrical, polar or revolute axes -- depends on the type of machine it will serve. In general, cylindrical- or polar-coordinate robots are more appropriate to machine loading, whereas Cartesian-coordinate machines are simpler to equip with tactile-feedback sensors for assembly work and revolute (or anthropomorphic) coordinate machines have the greater dexterity needed for such processes as welding and spraying but at higher cost.

1.3.2 Buffer Storage

In addition to on-shuttle and off-shuttle queues at stations, several different kinds of buffer zones can be designed into an FMS. Buffer storage is necessary to gain flexibility in sequencing production through the system and to allow for contingencies on the line, such as machine or tool failure. The more obvious form of buffer is a separate loop of track or conveyor where pallets can be shuttled to allow others to proceed past them on the direct route. There can be many versions of the side loop, including even parallel tracks with multiple crossover points.

Buffer zones need not be distinct areas set aside for temporary storage if one type of pallet/fixture combination is not required to pass another. Simply circulating carts or pallets in the MHS while making only appropriate transfers would serve to buffer unwanted pallets. Extra loading stations also can act as buffers of limited capacity. Efficient choice of an MHS design lies in the careful analysis of system failure modes and resulting congestion. This analysis constitutes one of the most important elements in the design of a specific FMS with a prescribed piece-part set and is best performed by simulation (see Volume V).

1.4 CONTROL SYSTEM SOFTWARE

The FMS control system manages the total combination of devices in the system that contributes to the automatic operation of the production process. This includes the machine tool controllers, the material handling system, the system monitoring devices, the system communications, and finally the system computer. Computer software supplies all the control management and monitoring functions that enable the system to achieve high utilization.

The control system is easily visualized by considering all the elements of the system in a structured arrangement according to function. The following section will consider that structure and how each function of the structure relates to the overall system performance.

1.4.1 Control System Architecture

Control of complex systems is usually built on the basis of a hierarchical structure. This structure deals with the organization of tasks necessary for FMS operation and how these different tasks are related. The tasks are arranged in the hierarchy on the basis of their function or their role in system operation. The differences between various FMS vendors' systems are the way the tasks are allocated to the system resources and the way they are partitioned or combined in sets of control programs.

Perhaps the easiest way to describe the FMS hierarchical control structure is to compare it to a typical non-FMS shop. A four-level shop control structure is illustrated in Figure 2 on page 12.

The first level sets the parameters and production goals within which the shop will function. It serves the entire shop, providing data-base management, Material Requirements Planning (MRP), and the master schedule for all production, as well as the business priorities and guidelines for short-term and long-term operation. The second level consists of general manufacturing and support tasks. It also serves the entire shop, providing part process plans, NC programs, tool and fixture design, time standards and machinability data for any part when asked for it.

The third level involves general plant coordination -- the production control function. At this level, parts are scheduled for production according to the master schedule and available shop capacity; then job orders are released for those parts after obtaining the operation packages, routings, NC tapes, tools, and fixtures from manufacturing engineering. Production control keeps track of the progress of each job order as it flows through the shop and assigns production priorities to those parts based on their relative lateness.

The fourth level is concerned with departmental and individual machine operation -- shop-floor production requirements. At this level, the department foreman makes production decisions, such as machine loading, based on part priority, equipment availability, and work force present in an attempt to satisfy company objectives such as minimum part lateness, minimum work-in-process inventory, and so on. The machine operator also functions at this level, operating his machine to produce the parts as well as monitoring the machine and tools for proper operation, changing or repairing items as necessary. He provides the foreman with information on the current status of work, allowing the foreman to pass the information to production control as well as to plan subsequent machine loading and alert the tool crib as to the need for tools, fixtures, etc.

In Figure 3 on page 14, the software functional control system is shown on the right side for a typical FMS. The hardware structure corresponding to

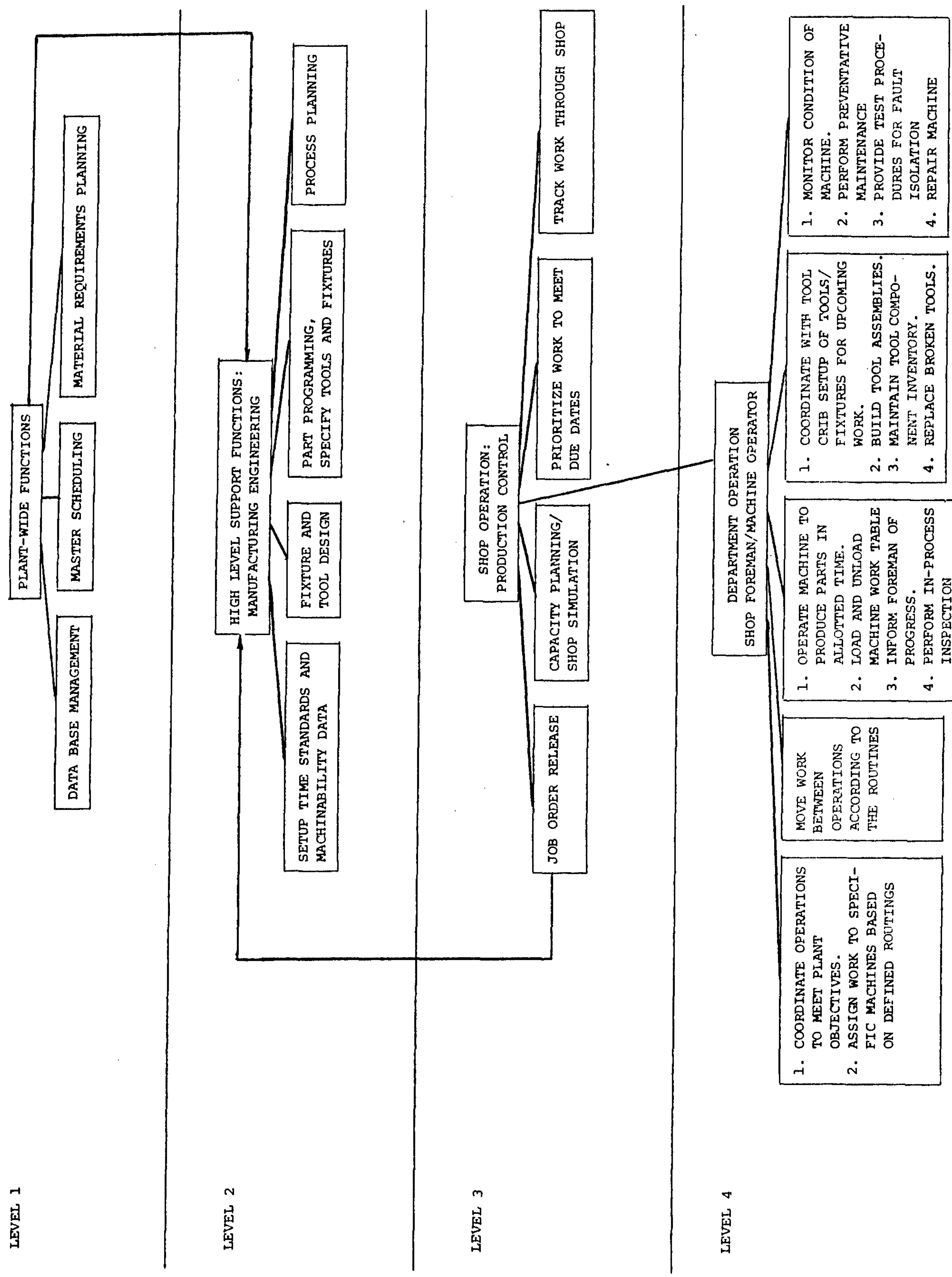


Figure 2. Manual Production Environment

this software structure is shown on the left side. A characteristic of this structure is that each level of the hierarchy must be able to function independently of levels above it. In other words, failure at the top does not cause cessation of activities below; higher levels are intended to support and expedite lower level functions.

The FMS hardware in this illustration is only a minimal representation of a "typical" FMS, namely a central control computer directing the operations of a material handling system, a set of computerized numerical controllers and a tool room communication link. The computer peripherals consist of disk storage, optional paper tape, a line printer, and a control console. However, this minimal representation of the hardware is sufficient to explain the software structure and functions. Also the software functions shown may in themselves contain several subfunctions.

1.4.2 Software Description

The FMS is usually part of a larger manufacturing environment, so the description here divides the architecture into a plant-wide level and an FMS level (see Figure 3 on page 14). The FMS level is further divided into three sublevels, described as follows. These functions are performed at the plant-wide level:

- Plant-wide MRP.
- Plant-wide production plans.
- Plant-wide data-base management and information system.

These plant-wide functions will typically set overall targets and production goals for a long time horizon. This information will usually reside in a mainframe computer and will serve as inputs to the three levels of operations described.

1.4.2.1 FMS Level-1 Operations

These encompass the following operational areas:

- Strategic decision-making for the FMS.
- Evaluating FMS performance.
- Ancillary support for FMS operation.

The execution of activities at this level will typically be supported by software on a mainframe computer. In some organizations, a viable alternative is to have a separate medium-sized computer for these activities, which can be considered a Decision Support System (DSS) computer.

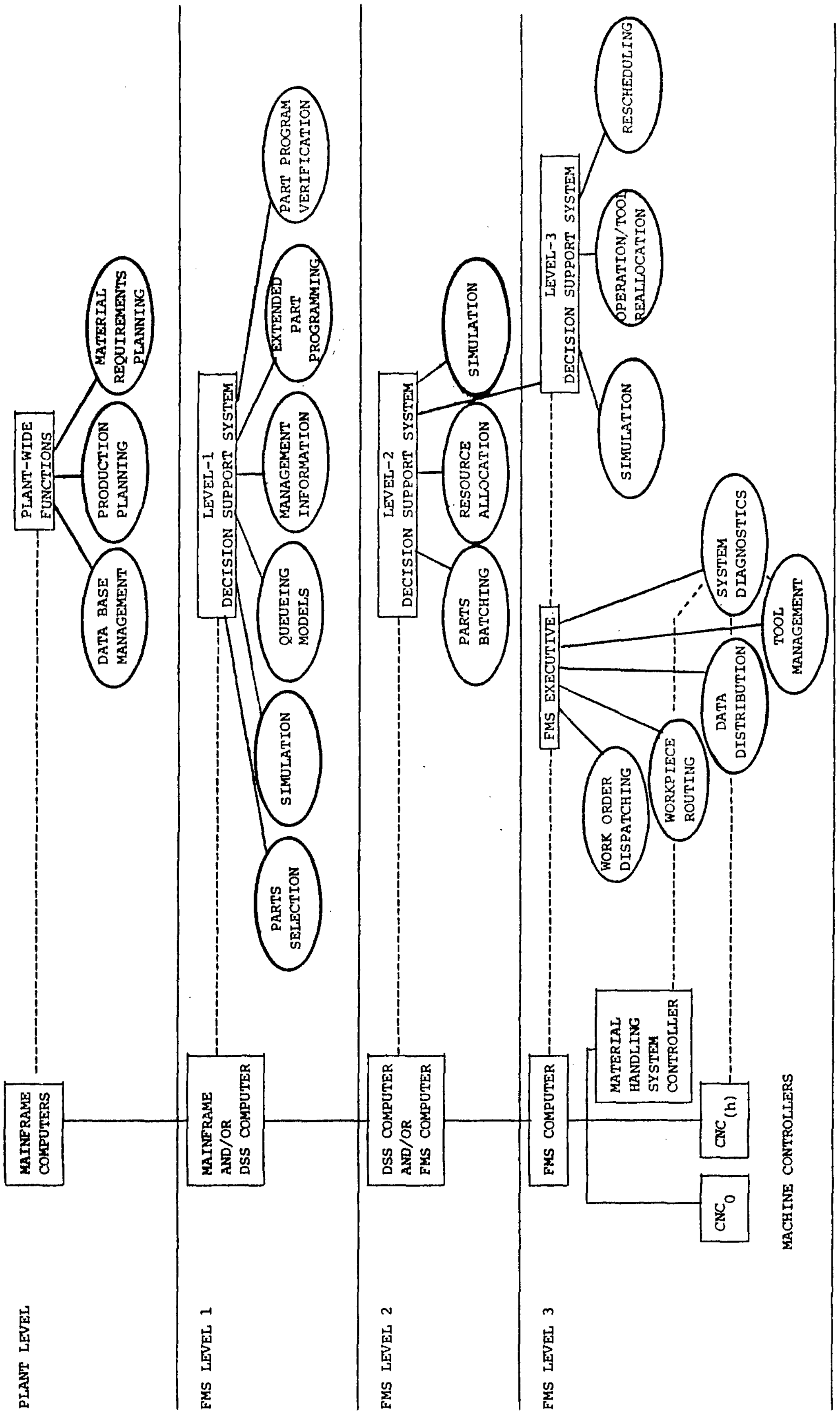


Figure 3. FMS Control System Architecture

1.4.2.2 FMS Level-2 Operations

This level encompasses decisions typically made by the FMS line supervisor, over a time horizon of several days or weeks. The main tasks to be performed at this level are:

- Dividing overall production targets into batches of parts.
- Within each batch, assigning system resources in a manner which maximizes resource utilization, i.e., balancing workloads.
- Responding to changes in upper-level production plans or material availability.

The main issues involved in each of these tasks are described in Section 6, "How to Operate an FMS" of Volume III. Also mentioned there are software tools the FMS supervisor should use to aid in decision-making. These software decision aids would typically reside on the FMS computer, or if this is not feasible, then on a DSS computer (as defined in the previous section).

1.4.2.3 FMS Level-3 Operations

This level is concerned with the real-time operation of the FMS. The functional areas involved are:

- Work-order scheduling and dispatching (which part to introduce next into the FMS, and when).
- Movement of workpieces and material handling system (which machine to send this workpiece to next, which cart to send to pick up this workpiece, etc.).
- Data distribution.
- Tool management.
- System monitoring and diagnostics.
- Reacting to disruptions (failures of one or more system components, sudden changes in production requirements).

During normal system operation, most of these decisions are made by software in the FMS computer and/or the MHS computer. However, when an exception occurs, such as failure of a machine, the FMS supervisor will usually take charge of the decision-making. The FMS supervisor's task can be considerably simplified by employing various software decision aids which typically should reside on the FMS computer to enable rapid implementation of the changed decisions, but in some systems the architecture could involve use of a separate DSS computer as described previously.

Details of some of the FMS level functions, as well as the relevant software decision aids, are discussed in Volume III. The functions of workpiece routing, data distribution, and system monitoring/diagnostics, are not discussed in Volume III and so are described in more detail below.

- Workpiece Routing

  The workpiece routing software module controls the movement of workpieces through the system. This module has several subfunctions. The first is to control the material handling system for the movement of workpieces between machines. It will also control the shuttle mechanisms to transfer workpiece pallets from the transporters to the machine tools. Finally, it will have a traffic scheduling algorithm that will determine the exact movement of each transporter, i.e., what will move, when it will move, and where it will go. This module examines the system status and keeps track of where everything is so that it can determine the most expeditious movement of workpieces. The module must manage all the resources of the material handling system including pallets and parts for optimum performance.

- Data Distribution

  An enormous amount of data is transferred within the FMS, and the data distribution software module controls this data transfer. This module is responsible for:

  1. Transferring NC control programs to the machine controllers.

  2. Maintaining libraries of part programs.

  3. Maintaining files of system performance data.

  4. Controlling and handling all system communications.

  The data distribution module also maintains the security status of the data, checking for proper identification of requests for data before issuance. For example, it will prevent a part program destined for one machine from being sent to another. This module may also have the feature of issuing optional on-line reports to line personnel.

- System Diagnostics

  The FMS system is equipped to monitor the operations by feedback sensors within the material handling system and the machine tool controllers. Whenever a failure is detected, the system manager is notified and operations may cease. A library of diagnostic programs will be used to ascertain the nature of the failure. Because of the number and complexity of the elements in the system, this library of diagnostics can become quite large. The effectiveness of the failure detection and diagnostics will depend in large measure on the number of sensor points in the system and the sophistication of the diagnostic techniques. Various vendors have different diagnostic packages involving software, hardware, or both. Some vendors offer a remote diagnostics capability wherein a computer at the vendor's site communicates with the customer's FMS computer via a telephone line.

Some forms of tool failure are detectable by the control system or by measurement of the loads. In a tapping operation, the controller could observe that the spindle drive power did not change during what should have been the tapping operation, indicating that a tap had likely broken. (There is equipment that can directly determine that a tap has broken, but solutions to sensing situations that do not involve the procurement of additional sensors are preferred where possible.)

A broken flute would result in an excessive current draw when a defective drill was used. Given the choice between adding complexity to the system software while using existing equipment or adding equipment such as a conformal tool probe, the choice, as before, is usually software complexity.

- System Monitoring

Monitoring for system diagnostics is done by the host computer or by a separate computer system. The first option allows direct access to data within the host computer, and use of existing interfaces to other system elements, i.e., programmable logic controllers (PLCs), to gather any additional data. The capacity of the host computer may have to be expanded to perform the additional workload, but the cost would generally be lower than that of a separate computer.

Another option allows the monitoring system to function more independently of the FMS if desired, often using a self-contained computer subsystem. The monitor system could thus detect failure of the FMS computer, though operations data may be lost during the failure.

The data base for monitoring could be separate from the FMS data base, or, if monitoring software is resident on the FMS computer, it could be an extension of the FMS data base.

In general, monitoring for diagnostics and system health requires a view of the system over an extended time frame, both past and future, due to accumulation of historical data and projection into the future. FMS data requirements tend to be more current, with only a limited view of future scheduled events. Thus, the addition of monitoring data to the FMS data base will result in an expansion along the time horizon.

In addition, the data in an FMS may be "distributed", with much of the information on individual machines not gathered into any central location. Monitoring, on the other hand, requires that data on each system element be combined to arrive at an overall system status. Thus, data would need to be centralized or periodically collected in order to support the monitoring and Management Information System (MIS) functions. This uses the data communication path to the higher level computers above the FMS central computer.

The use of monitoring can affect existing interfaces between organizations. It would be possible to have the tool room tied into the system to enable direct monitoring of tool wear and usage as well as determining new tooling requirements. Production control could access up-to-the-minute system status in planning new production schedules and projecting customer ship dates. It should be pointed out that these interfaces will not be eliminated, but instead, the organizational efficiency will be increased by reducing the amount of information that must flow verbally or on paper and ensuring that all decisions are based on the same, current data base.

1.5 OTHER SIGNIFICANT ELEMENTS

1.5.1 Fixtures and Pallets

Pallets used in an FMS are usually those offered by the machine tool builder; the shuttle, conveyance, and load/unload stations must be designed to be compatible with the pallets. Almost invariably, precision-grade couplings will be used to orient the pallet on the machine. This mechanism provides the precise indexing capabilities necessary to perform multisided machining on a part or to accommodate more than one part on a fixture. An important design consideration of the pallet conveyances is protecting this coupler from chips and other foreign material. Even the stickiness of evaporation residue must be considered in choosing a coolant. The machining center itself normally has a protective device built in to shield the coupler when a pallet is removed from the machine. Despite these safeguards, a common manufacturing problem is coupler contamination which leads to machining errors. Quick recognition of the problem through inspection is necessary to minimize scrap rate.

Fixtures can take many forms in an FMS. They may range from simple, one-part clamps, similar in design to those used on a stand-alone machine, to complex picture-frame and pedestal fixtures that allow machining access from several sides, to even larger fixtures accommodating two or more parts which aid in reducing the nonproductive time used by tool changing and part transportation.

The choice of fixtures depends on many factors in an FMS. A basic manufacturing process plan first must be developed to estimate the number of different fixtures required. Cycle times must be estimated. Then scheduling through a simulation program will give some idea of how a piece-part fits into the overall part mix. At this point, decisions on the number of parts per pallet and the access required for each machining setup can be made more constructively. There will be several iterations through the simulation before a final process plan can be developed to best take advantage of the FMS. Additionally, consideration must be given to the effects of multiple fixtures on part accuracy. An expensive picture-frame fixture that allows all the machining on a part to be accomplished in one fixturing may be significantly better than machining the part mounted sequentially on a number of less expensive fixtures. In this latter case, tolerances may also build up and cause rejection of the part.

1.5.2 Tooling

One of the problems associated with an FMS producing a large family of parts is the limitation on the tooling complement imposed by the number of tool pockets offered by the machine-tool vendor. Often, special tooling needed to prepare and finish a single complex hole can occupy several pockets. None of this tooling may be able to be used in other areas or on other piece-parts. Tapped holes require at least two tools. It is not difficult to be severely constrained in machine-tool assignment flexibility by tooling limitations. Therefore, it is prudent to keep this in mind when developing process plans. One should take advantage of as much tool commonality as possible, limiting the number of different face mills and end mills. It may even be worthwhile to conduct a design review to reduce the number of different bolt sizes in the end products to minimize the variety of drills and taps on the line.

Tooling for multiple-spindle heads generally cannot be shared, except in the case of identical hole patterns in a family of parts. Generally, each head is associated with one piece-part. In designing an FMS, choosing a multiple-spindle head machine comes as the result of tradeoff studies between the productivity gains (short cycle time) of the multiple-spindle head with its part-specific configuration and the slower production of the adaptable single-spindle machine. There is no redundancy if the line has but one multiple-spindle machine; if it develops a failure, however, throughput is drastically reduced for parts produced on it. Transferring the parts to single-spindle machines in the system is usually more complicated than waiting for the machine to be repaired.

Tooling can be classfied according to where it resides, inside or out of the FMS. Tools in a machine's tool chain are in the system. There are several methods of maintaining readily accessed off-line tool storage to help alleviate the limited tool complement of each machine. One vendor has devised a "wine-bottle storage rack" that is put on a cart in place of a piece-part fixture. Tools in it are exchanged for some in the tool chain when piece-part production calls for them, such as at a batch change. The exchange is somewhat time-consuming, so it is most advantageous to reserve this option for the batch change situation rather than to intrinsically expand the tool complement of a machine tool for continuous production of a piece-part. Another vendor uses circular tool magazines that demount from the machining center and can be retooled near the machine.

Another technique to accommodate batch change employs an overhead automated tool storage and retrieval system. The Messerschmitt-Bolkow-Blohm (MBB) system delivers a tool set to a machine in time to prepare for a new piece-part batch that also is transferred to the machine automatically. This dramatically extends the part mix, with minimal manual interface at the machine.

Other techniques for effectively expanding a machine's tool handling capability to circumvent this limitation in the face of a broad part-mix requirement are under development. One would use a robot to transfer tools from a dense matrix located near the machine directly to the tool chain. This might be done during the machining cycle to avoid interrupting production.

1.5.3 Coolant and Chip Handling Systems

Since the FMS represents a fairly dense cluster of machines, it is usually efficient to design a central coolant distribution and chip separation system. (An exception to this might be systems in which different materials are being machined. In that case, different coolants might be used, making it inadvisable to mix them, as well as the different chip types -- considering the potential chip reclaimation returns.) If the floor is designed to incorporate such a central system, machines can be cleaned periodically by flushing with coolant. A natural extension is to design load/unload stations to include the same cleaning and flushing method and be part of the central system. A simple way to achieve this is to build these stations on an open-metal grid above the main coolant trough. Chips fall directly through the grid and flow to the separator.

An important consideration in choosing a particular coolant for the FMS is the nature of the residue after water has evaporated from it. An oily or sticky base of low volatility will create many problems of dirt or chips sticking to tool shanks, spindle tapers, and curvic couplings, despite commonly employed cleaning-air blasts.

1.5.4 People

When an FMS is operating reliably, the number of people required to maintain its operation can be reduced to a few. Typically, there would be one foreman, enough loaders to adequately feed the line, and one machinist to care for up to half a dozen machining centers.

The machinist would maintain tools and be aware of tool breakage on machines for which he is responsible. Also he would replace worn tools by either reading outputs of a tool monitoring program, if the FMS has one, or using personal experience and judgement. Additionally, he would maintain the machine operation during his shift and initiate any special service requests necessitated by machine failure.

The loaders are responsible for keeping part mounting surfaces clean, properly mounting workpieces to fixtures with prescribed clamping forces, and communicating with warehouse workers to ensure continuous flow of raw castings and finished parts to and from their work stations.

The line foreman oversees the entire operation of the line. He is responsible for maintaining continuity of the line's production in the face of the various failures that may occur. He may even interface with the computer to implement part routing changes that may not be automatically arranged by the computer's recognition of a failure mode.

It must be emphasized that the work force described to this point is for a fully operational FMS. The start-up crew for a new line would be greater, with more machinists, production engineers, and maintenance personnel diagnosing the problems in the shakedown phase of an FMS installation.

There is also an indirect labor group associated with any FMS. This is comprised of programmers, process planners, manufacturing engineers, electrical/mechanical maintenance personnel, computer maintenance personnel, etc., who provide support when new parts are to be introduced to the line or who maintain the computer. These people are not assigned full time to the FMS in contrast to those described earlier. Quality assurance personnel will be required if there is no on-line inspection machine in the system, and they may still be required even if there is a machine.

1.5.5 Inspection Systems

The inspection process can be performed on- or off-line and each has its advantages. An on-line inspection machine can be programmed to identify machining errors and implement tool offset changes directly through the central computer. Of course, all machining errors cannot be rectified in this manner. Perhaps the greatest benefit of an on-line inspection system is the quick identification of manufacturing problems. An off-line system has inherent lags due to remote location, part fixturing or locating delays, and perhaps lack of automated inspection.

The on-line machine is not an answer to all of these problems, however. In general, inspection is considerably slower than the production rate and it is difficult to perform 100% inspection on an on-line system.

There are other philosophical questions regarding the utility of the on-line system. Since it is in the machine environment, can it perform adequately if this is not well controlled? Since the part is inspected in its clamped, as-manufactured state, is this a reasonable condition for inspection? This method is best for identifying changes in cutting tool performance, but may not tell if parts are made to print.

1.5.6 FMS Off-Line Components

Automated deburring is not currently performed on-line in an FMS, although certain manufacturing techniques (e.g., holes countersunk before drilling) can reduce the burden of manual deburring.

Another common off-line operation would be part cleaning to remove all chips and coolant residue. This station might include some painting or other forms of surface preservation prior to shipment.

2.0 THREE EXAMPLE FLEXIBLE MANUFACTURING SYSTEMS

Figure 4 on page 24 is a representative listing of FMSs presently installed in the United States. Three of these are described in more detail in this section. These particular systems were chosen as examples of modern FMSs currently offered by U.S. machine tool vendors, based on the age of the system and the wide range of manufacturing operations they perform.

2.1 KEARNEY AND TRECKER FMS AT AVCO-LYCOMING, STRATFORD, CONNECTICUT

2.1.1 Overview

AVCO-Lycoming, Stratford, Connecticut, is currently machining ten stainless steel, turbine-engine components for the M-1 tank on an FMS designed by Kearney and Trecker Company (K&T) and installed in 1979. The system consists of seven horizontal Direct Numerical Control (DNC) machining centers, three VTLs, and load/unload stations interconnected by a cart tow-line MHS (see Figure 5 on page 25).

2.1.2 System Elements

The system contains seven horizontal spindle, five-axis DNC machining centers (K&T "Modu-Line" machines) and three Bullard VTLs. All of the machines are equipped with automatic tool changers and pallet exchangers. The material handling system consists of in-floor tow chains arranged in several loops (if the assigned station is occupied when the cart arrives, it continues on, but remains in the MHS loop nearest the station). These loops form buffers for the system, so the machines are not idle due to lack of parts. The control system and software were designed by K&T; they perform DNC, MHS control, part scheduling, and management reporting.

2.2 DETROIT DIESEL ALLISON, INDIANAPOLIS, INDIANA

2.2.1 Overview

Detroit Diesel Allison, Indianapolis, Indiana, will be machining 40 large transmission covers and housings on an FMS designed by White-Sundstrand Corporation and installed during the first half of 1983. The system consists of four horizontal-spindle DNC machining centers; four tilt-head

Installation	Vendor	Date Installed	MHS	Central Computer Type	Machine Complement	No. of Parts	Parts per Year	Part Description
Sundstrand Aviation	White-Sundstrand	1967	Roller Conveyor		•8 OM-2 •2 multi-spindle drills			Aluminum pump parts
Rockwell	K&T	1977	Towline	Interdata	•7 K&T Modu-Lines machining centers •Portage inspection station	45	25,000	Automotive axle carriers
Ingersoll-Rand	White-Sundstrand	1970	Roller Conveyor	IBM 360/30	•2 5-axis Omnimil •2 4-axis Omnimil •2 4-axis drilling	140	20,000	Hoist and motor cases
Allis-Chalmers	K&T	1970-1973	Towline	Interdata	•5 Modu-Lines •4 duplex head indexers •1 milling	8	23,000	Agricultural equipment
AVCO-Williamsport	K&T	1975-1978	Towline	Interdata	•11 Modu-Lines •2 MM-880 machining center •2 single-head indexers •1 duplex-head indexer	9	24,000	Aircraft engines
Caterpillar	White-Sundstrand	1973	Shuttle Car	DEC	•2 VTLs •4 5-axis OM-3 •3 4-axis drilling •1 DEA inspection	6	6,660	Crank case housings, covers
Detroit Diesel Allison	White-Sundstrand	1963	Shuttle Car	DEC with DNC Computer	•4 Series 80 machining centers •4 Series 80 tilt head machining centers	40		Large transmission housings
AVCO-Lycoming	K&T	1979	Towline	Interdata	•3 VTLs •7 Modu-Lines • Pallet storage system	10	15,000	Engine manufacturing, turbine
John Deere	K&T	1981	Towline	DEC	•9 Modu-Lines •3 Simplex head indexers	8	5,000	Farm equipment
Caterpillar	Giddings & Lewis	1980	Tracked Towline	DEC	•6 Standard machining centers • A special boring machine			Construction equipment
International Harvester	Giddings & Lewis	1981	Towline	DEC	•4 Machining centers			
AVCO	Giddings & Lewis	1982	Towline	DEC	•10 Machining centers			

Figure 4. U.S. FMS Installations

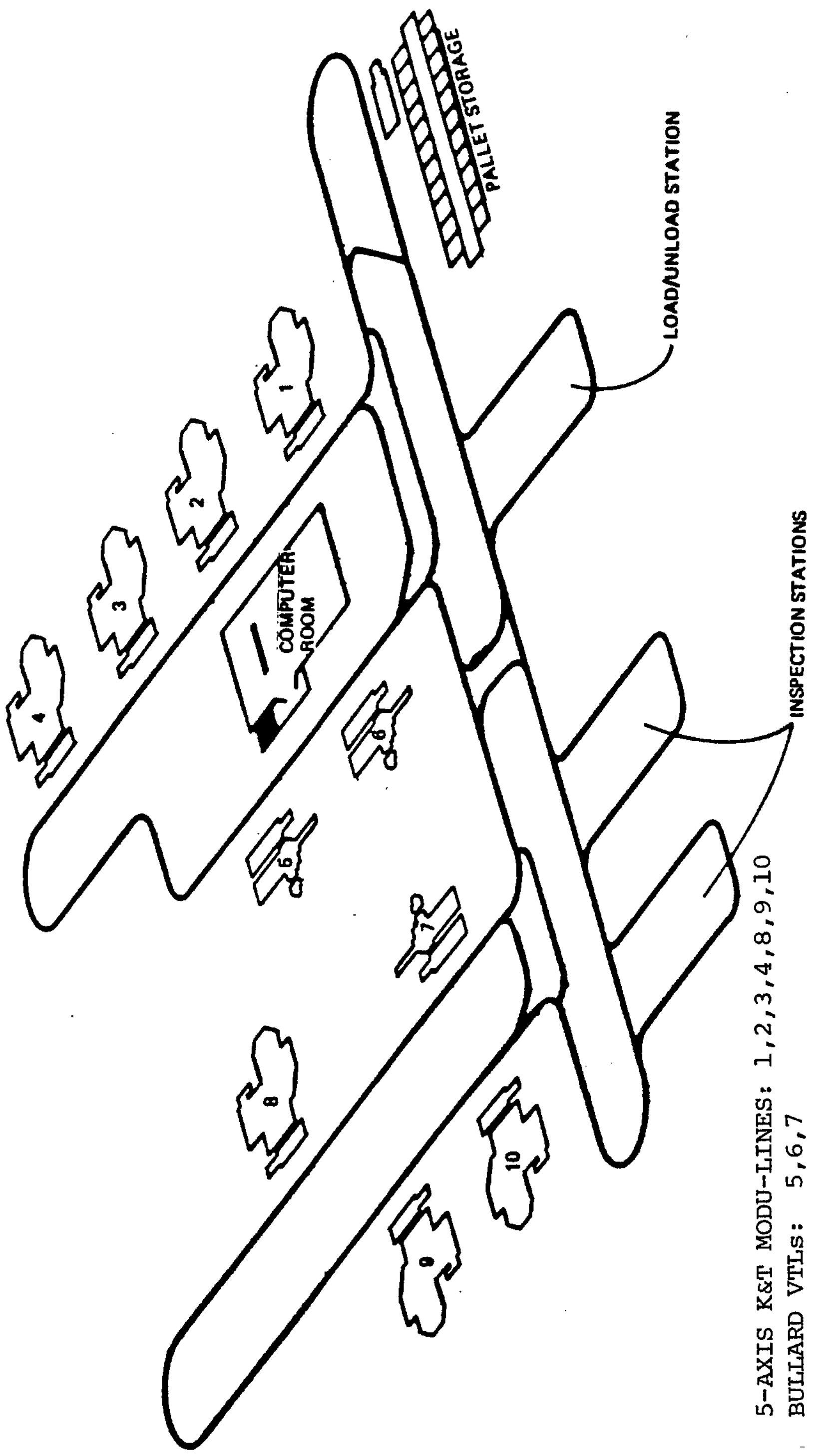


Figure 5. Kearney and Trecker FMS

DNC machining centers; one DNC inspection machine; and a single, two-way straight-line track guiding two pallet exchanging carts. Seven of the machines are located on one side of the track; on the opposite side of the track, between the remaining two machines, are fifteen load/unload stations (see Figure 6 on page 27). These load/unload stations are located on a raised, steel-grid platform that allows a loader to flush chips away using coolant carrying hoses. The floor is structured to conduct coolant to a recirculating pump and to allow a complete hosing wash of the machines, carts, and floor at the end of the day.

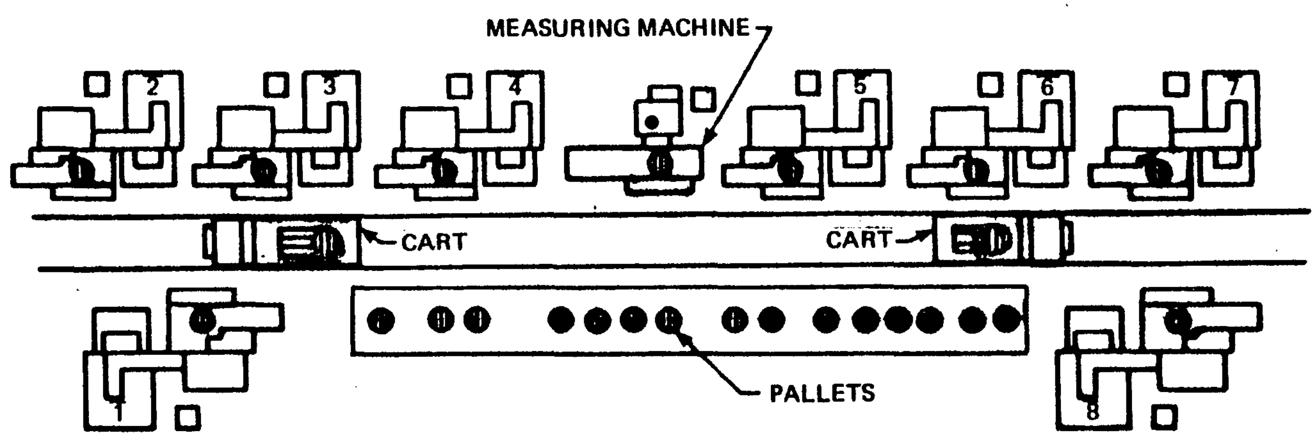
Behind the load/unload stations are stock bins from which the loaders draw stored, rough castings and into which the finished castings are placed. The central (host) computer is remote from the line in an air-conditioned room above the system foreman's office, approximately 50 feet from the line. This computer communicates to the stand-alone computer (SAC), which permits the foreman to control operations. Both computers can communicate to each of the soft-wired integrated numerical control (SWINC) computers next to each machine (including the inspection machine).

2.2.2 System Elements

The system contains eight machining centers and one inspection machine; the four tilt-head machines are special adaptations of Sundstrand's Series 80 Omnimill, and the rest are stock options of that machine. The four horizontal-spindle machining centers have 40-horsepower motors and the four tilt-head machining centers have 25-horsepower motors. All of the machining centers are equipped with pallet exchangers and 90-pocket automatic tool changers. Pallets are oriented with precision couplings, and when a pallet is raised by the exchanger arms, a rotating cover moves over the coupling on the machine table to protect it from dirt. The automatic tool changers require the head to move to the top of its vertical travel for an exchange, a distance of about 5 feet above the pallet. The tilt-head machines must have their spindles horizontal for a tool change.

The inspection machine is a Series 80 Omnimill without a spindle, motor, drive, and automatic tool changer; a Renishaw probe is mounted in a receptacle in place of the spindle and is used to locate part features and verify their manufacturing accuracy. The remaining stations consist of 15 load/unload stations. At these stations, loaders use chain-hoists to load and unload parts to and from fixtures and perform the only special cleaning of the pallets and fixtures, a simple wash using coolant hoses at the station. Any heat treatment, painting, major deburring, etc., is done off-line.

The MHS consists of two two-way pallet exchange carts and 19 fixture/pallet combinations. The pallets are 42 inches in diameter and have ground surfaces. The fixtures are located on the pallets by two 1.5-inch diameter by 1-inch long pins. The carts ride a two-rail track, one rail of which has a raised shoulder to limit lateral cart movement. The carts have absolute wheel encoders and use optically sensed overhead flags (approximately 0.75-inch square) to initiate pulse counting. After passing a flag, some 3 or 4 feet before a destination, the cart deceler-



WHITE SUNDSTRAND TILT-HEAD MACHINES: 1, 2, 7, 8
WHITE SUNDSTRAND HORIZONTAL SPINDLE MACHINES: 3, 4, 5, 6

Figure 6. White-Sundstrand FMS

ates to a speed about one-half normal rate until about 3 inches from the destination, where a creep mode begins until the cart reaches the destination, indicated by a second flag. Positioning accuracy probably is on the order of 1/16 inch. A cart can transport only one part/fixture/pallet combination at a time, although it can momentarily hold two during pallet exchange sequences. The carts have an extended bar dead-man stop at each end connected by ribbons running along the cart sides. These ribbons can be grasped to stop a cart in an emergency and the dead-man stops prevent damage if for some reason the carts should collide. Buffer storage is accomplished using empty load/unload stations or the carts themselves.

The DNC consists of a Digital Equipment Corporation (DEC) host computer and terminals, a Sundstrand SAC for shop floor control, and a SWINC unit for each machine. The NC part programs are downloaded directly from the host to the individual SWINC units; the SAC unit coordinates downloading with cart movement and pallet loading, as well as allowing the foreman to override the host when problems occur. Software was provided by Sundstrand. Aside from performing control functions, such as downloading NC programs, cart movement, part scheduling and release and tool control, the software generates a number of management and operational reports. For management, performance measures are accumulated for each part number and station in the system, summaries of which are printed out daily. Some examples of operational reports are as follows:

- Station status.
- Part number or program task executing in station.
- Tools required by operation, where assigned, etc.
- Operation set assignment by station number.
- Current part routing.
- Part and inspection programs currently in use by the system.
- Inspection data.
- Operator instructions.

The software is also capable of tool residence monitoring to keep track of tool usage, tool life, and signal when they should be replaced.

2.3 GIDDINGS AND LEWIS FMS AT CATERPILLAR TRACTOR COMPANY, AURORA, ILLINOIS

2.3.1 Overview

Caterpillar Tractor Company, Aurora, Illinois, is presently machining eight large steel weldments (4 x 4 x 12 foot part envelope) on an FMS designed by Giddings and Lewis and installed during the first 6 months of 1980. The system consists of six general precision DNC horizontal machining centers, a high-precision DNC horizontal machining center, and ten carts that ride two side-by-side, one-way tracks (one forward, one reverse) with several crossovers between tracks. All of the machines are located on one side of the tracks; there is a load station at one end and an unload station at the other (see Figure 7 on page 30). This flexible manufacturing system is one station of a much larger fabrication process; pieces are not stored in quantity before or after machining but have scheduled arrival and departure times, so there is no need for storage bins. The host computer is located in an elevated, temperature-controlled booth beside the system, and is connected directly to the DNC control units for each machine.

2.3.2 System Elements

There are seven machining centers in the system; two duplicate 7-inch diameter spindle DNC horizontal machining centers, four duplicate 6-inch diameter spindle DNC horizontal machining centers (currently dedicated to drilling and tapping), and a DNC high-precision horizontal machining center for boring. Each machine is equipped with a 40-pocket, automatic tool changer which examines tools automatically for breakage after each usage. The machines do not have pallet shuttles; due to the size and weight of the parts, the carts function as pallets and fixtures and, once at the machine, do not move until the machining operation is complete. During operation, every machine in each class is identically tooled (and tool sharing between pieces is common), providing considerable redundancy. The remaining work stations are the load and unload stations, at which the operators load/unload parts to and from the carts using an overhead crane.

The MHS consists of 10 carts/pallets/fixtures that ride unidirectionally on one of two two-railed tracks (one track for forward, one for reverse) and are moved by a drag-chain under each track. To change the cart's direction, special mechanisms actuate the crossover links to shift the carts from one track to another. The machines are connected to the MHS by a single two-way track spur and drag-chain; once a cart is on that spur, no others can use it (i.e., they cannot be used as buffers for the machines they serve). There are two classes of carts: one class is designed to accommodate any piece so that its "top" is up, and the other is designed to accommodate any piece so its "bottom" is up. Buffer storage is provided through on-track queues; however, it is possible for these queues to block the MHS.

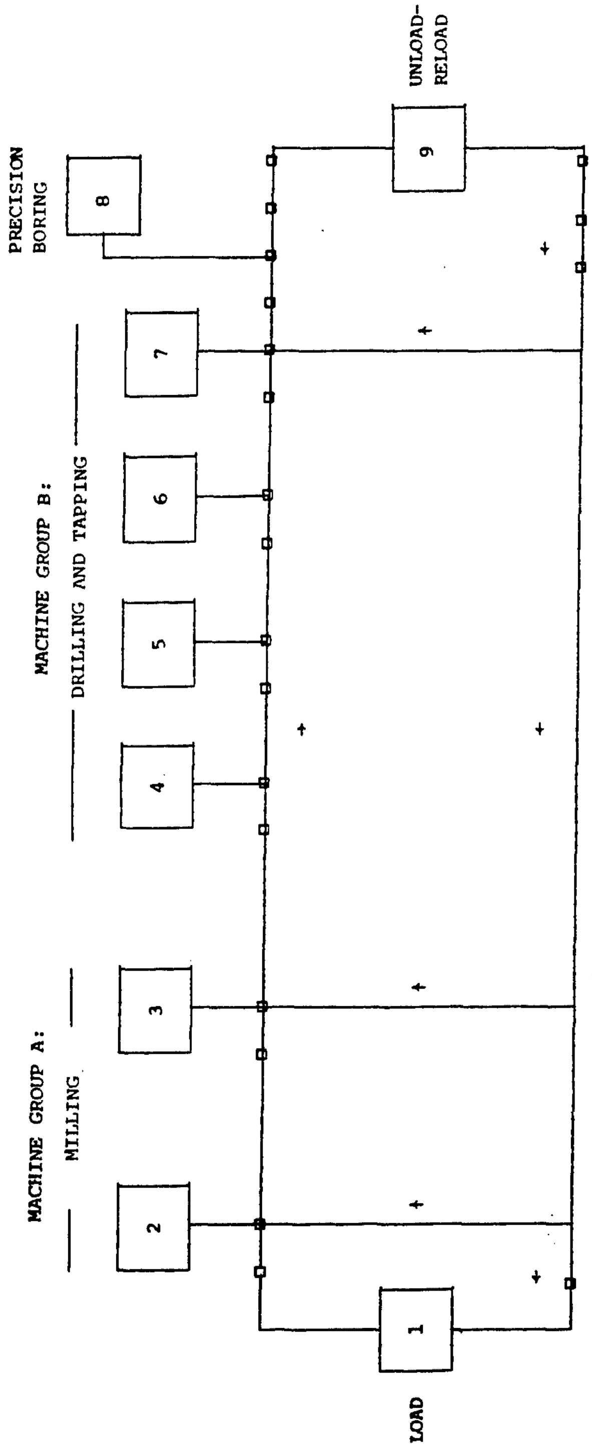


Figure 7. Giddings and Lewis FMS

The control system consists of a DEC host computer (PDP-11/60) connected to a Giddings and Lewis 800M NC unit for each machine. The host can be connected by dataphone to a computer at Giddings and Lewis for diagnostic aid if the system fails. The host computer downloads the NC part programs to the NC units block by block as the information is required. If a machine fails during an operation, the part can be transferred to any open machine of the same class as the failed machine and machining will resume as though uninterrupted. Each component of the system can be operated "manually"; if the host computer fails, machining can be controlled from the NC units and the carts can be moved by hand. Software was designed by Giddings and Lewis. The host computer is responsible for all control and reporting functions; the loader enters the part and cart codes and the system schedules that cart to arrive at the next available machine in the proper class and continues to control the cart until the unloader removes the completed piece. There is a real-time CRT display of track and station status and management reports can be generated daily, weekly, or monthly. A total of five people are needed full time to run the system: one loader, one unloader, one skilled machinist for the precision boring station, one tool setter, and one management person.

3.0 PROJECTED TRENDS IN FMS TECHNOLOGY

There are a number of directions in which FMS technology will proceed in the future, driven both by the need to overcome certain present obstacles and by the availability of concepts that come to practical fruition. The changes will affect the machines, the tools, the transport mechanisms, the control hardware and software, and the workpieces themselves.

Many of the trends in the following list are now in progress, but some are still on the horizon:

- Machine adjustable, tool-changer compatible tools:
  - Cutting tools (boring bars, etc.).
  - Forming tools.
  - Gauges.
- Automatic tool loading/unloading into tool-changer magazines from tool crib.
- Automatic tool crib operation and connection to FMSs.
- Automatic tool exchanges between machines.
- Compact, large capacity, high-speed, random-access, tool-changer magazines.
- Tool wear and breakage sensors and algorithms (using system parameter correlation methods).
- On-line inspection.
- On-machine inspection:
  - Tool-changer loading devices (e.g., robots).
  - Independent of tool storage, changer, and spindle.
- Adaptive error determination and compensation systems:
  - Drive axes, error profile compensation.
  - Alignment compensation.
  - Force and weight compensation.
  - Temperature compensation.
  - Wear compensation.

- Tighter coupling of CAD and CAM, e.g., CAD systems help designers create FMS-compatible designs.

- More comprehensive and data-accessible manufacturing monitoring systems.

- Comprehensive production planning and management systems to handle:

  - Inventory.

  - Ordering.

  - Batching definition.

  - Scheduling.

  - Routing.

  - Rescheduling/rerouting for contingencies.

- Fail-soft, graceful degradation of machines and systems.

- Automatic generation of system initialization and startup procedures, and a "checklist" for any stoppage or failure condition.

- Automatic part fixturing and defixturing, automatic part storage and retrieval.

- Automatic pallet and fixture storage and retrieval, with automatic insertion into and extraction from the system.

- Automatic identification and tracking of individual tools, pallets, fixtures, parts, carts, movable elements, etc., including automatic location during system startup.

- Automated integration of more classes of manufacturing operations, including:

  - Milling.

  - Turning.

  - Forming.

  - Inspection.

  - Finishing.

  - Heat treating.

  - Shearing.

  - Assembly.

  - Testing.

- Improvements in automated chip flushing and clearing, part cleaning, chip collection and reclaiming, and coolant reconditioning.

- Improvements in automatic temperature control of parts, pallets, fixtures, machines, and coolants.

- Improvements in inherent machine-tool and inspection machine accuracy, as the increase in "near-net-shape" technology reduces the need for heavy machining and places the emphasis on high-precision machining.

- Better equipment maintainability through increased use of:

  - Automatic fault detection and isolation.

  - Built-in diagnostic and repair aids (test cooperative aids).

  - Modular construction.

  - Redundant equipment configurations (on a single machine tool allowing on-line repair).

- Increasingly larger FMSs (federations of FMSs) with better integration into the factory planning and operation systems (MRP, etc.).

There exists an extensive range of machines that are candidates of varying degrees for inclusion in an FMS. The following pages show a November 1981 listing of the characteristics of machining centers.

There are two lists. In the first list, machine characteristics are presented for VTLs and vertical boring mills (VBMs) with table diameters up to 39 inches and some vertical-spindle chucking machines (VCMs). The second list is for vertical and horizontal machining centers.

The listing (data base) includes machines available in the U.S. which accommodate workpieces up to about 6-feet long and which have spindle motors with up to 25 horsepower. Each machine is identified for type (horizontal or vertical spindles). Available movements of the table, head, and quill are denoted. Tool-changer capacity is listed. Spindle speed range and workpiece feed ranges are presented, including rapid traverse values if outside the normal feed range. Positioning accuracy and repeatability are given. Contouring modes available in the NC software are given in terms of the number of different axis combinations permitted in an interpolation, which can be linear (L) or circular (C). For example, 3L signifies X, Y, and Z may be varied simultaneously to produce a straight-line cut. Where only L and C are denoted, the full interpolative capability is not given in the manufacturer's literature. Options of pallet changers and fourth- and fifth-axis NC control are denoted.

VERTICAL TURRET LATHE MANUFACTURER	MODEL	TYPE	TABLE DIA	MAX SWG	MAX WK HT	MAX TBL LOAD	CROSS RAIL TVL	RAM HEAD TVL	SIDE HEAD TVL	TUR HEAD TVL	TUR STA& TOOL	FEEDS IPM	SLIDE POS ACC+-	SLIDE POS REP+-	TUR INDX ACC+-	DRIVE HP	TBL SPDS	CON-TOUR	COMMENTS
1 NORWELL	VBM-09	VBM	36	52	36	13200	20			30	4 12	0-40 200RT				50	2.2-450	2L 2C	
2 BULLARD	DYN-AU-TAPE	VTL	36	48			12	51V 31H	OPT? OPT?	37V 30H	4-6 10								
3 BULLARD	AKU-TAPE NC	VCM	28	30				N N	N N	15V 12H	5 5	0-200				100	8-530		
4 BABCOCK & WILCOX	DETROIT 1100	VTL	28	30				N N	N N	24V 17H	5	0-50 200RT				50	3-1500	L C	
5 EX-CELL-O	451 NC	VTL		25				N N	N N	20V 12H	6 6	TO 250	.0005	.0002	.0002 @15R	30	33-297		
6 GRAY W&S	VFR	VTL	36	52		30000		N N	N N	30V 58H	5 5	.05-60 200RT			5 SEC	50	5.3-485		
7 MONARCH MORANDO	VLN TOOLCHANGE	VBM	36	39			23-39	31-39V 43H	31-47V 20H	N N	N 12	.01 300				40-75	4.7-412		
8 MONARCH MORANDO	VLN TURRET	VTL	36	39			23-39	N N	31-47V 20H	30V 31H	5 5	.01-300				40-75	4.7-412		
9 MOTCH	125 VNC	VCM		25	12			N N	N N	18V 20H	6 6	0-200				50	33-1055	L C	
10 MOTCH	135 VNC	VCM		35	15			N N	N N	24V 28H	6 6	0-150				60	20-660	L C	
11 O-M LTD.	VT4-9	VTL	36	47	31	11000		N N	16V 19H	30V 41H	5 5	.0004-189IPR				50	2.4-400	L C	
12 IKEGAI	VT1100 TOOLCHANGE	VBM	39	45		8800		27V 43H	N N	N N	N 8	-240				50	6-180	L C	OPT FDBACK GAGING +- .0006 IN.

VERTICAL TURRET LATHE MANUFACTURER	MODEL	TYPE	TABLE DIA	MAX SWG	MAX WK HT	MAX TBL LOAD	CROSS RAIL TVL	RAM HEAD TVL	SIDE HEAD TVL	TUR HEAD TVL	TUR STA& TOOL	FEEDS IPM	SLIDE POS ACC+-	SLIDE POS REP+-	TUR INDX ACC+-	DRIVE HP	TBL SPDS	CON-TOUR	COMMENTS
13 WICKMAN	36FRNC	VTL	36								5-6 5-6	.01- 200	.0005			75	7.5- 200	L C	
14 WICKMAN	36ERNC TOOLCHANGE	VBM	36								N 16	.01- 200	.0005			75	7.5- 200	L C	
15																			
16																			
17																			

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVELOPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEATABILITY +- IN.	CONTOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
1 ACROLOC	VIII	V		32X 16Y	8Z 16Z 16Z	12	N		0- 4000				1L 2C	N	4 OPT	
2 AUTONUM- ERICS	S-1 ATC	V	1000#	31.3 17.5Y	4.9Z	24	Y	4	100- 3700	.5- 240	.0005/FT .001	.0001 .00001 KNEE	3L 2C	N		
3 AUTONUM- ERICS	S-2 ATC	V	500#	27.3X 13.5Y	4.9Z 14.4Z	24	Y	3	100- 3700	.5- 240	.0005/FT .001	.0001 .00001 KNEE	3L 2C	N		
4 BOSTON DIGITAL	312	V		18X 12Y	12Z	12		2	400- 7000			40 MUIN RES		N	4 OPT	
5 BRIDGEPORT	BTC II	V	1000#	30X 15Y	8Z 13W	24		7.5	10- 3600	.1- 80	.001	.0005 .00025 RES	3L 2C	N	N	
6 BROWN & SHARPE	1000VC	V	3000#	25X 40Y	21.6Z	24	Y	7.5	20- 4000	.01- 400	.001	.0005	3L	N	N	
7 BROWN & SHARPE	1500VC	V	4400#	60X 30Y	25Z	24 (40) OPT	Y	10	20- 4000	.1- 400	.001	.0005	3L 2C	N	4 OPT	
8 BROWN & SHARPE	2000VC	V	4400#	80X 30Y	25Z	24 (40) OPT	Y	10	20- 4000	.1- 400	.0015	.0005	3L 2C	N	4 OPT	
9 BURGMASTER	VTC-325	V		40X 20Y	10Z	20		7.5	30- 2000	.1-					Y	

	MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
10	BURGMASTER	HTC-325	H		24X 36Y	14Z	20		7.5	30- 2000	.1-					Y	
11	BURGMASTER	VTC-330	V		45X 30Y	12Z	20		10	30- 2000	.1-					Y	
12	BURGMASTER	VTC- 330L	V		60X 36Y	12Z	20		10	30- 2000	.1-					Y	
13	BURGMASTER	VTC- 330XL	V		84X 36Y	12Z	20		10	30- 2000	.1-					Y	
14	BURGMASTER	HTC330	H		45X 36Y	25Z	20		10	30- 2000	.1-					Y	
15	BURGMASTER	HTC330L	H		60X 36Y	31Z	20		10	30- 2000	.1-					Y	
16	BURGMASTER	VTC-40	V		45-84X 30-36Y	16Z	30		15	30- 2000						Y	
17	CINCINNATI MILACRON	CINTEMAT 10VC	V	80X 26Y 20Z 3000#	40-80X 20-26Y	20Z	30	Y	10	25- 4000	.5- 200 400RT	.001	.0005		N	4 OPT	
18	CINCINNATI MILACRON	20VC	V	6000#	72X 30Y	30Z	30	Y	20	20- 4000	.5- 150 200RT	.001	.0005		N	N	

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
19 CINCINNATI MILACRON	CIM-X 720	H	1000#	24X 15Y (KNEE)	20Z	24	Y	10	21-3750	.5-200	.001	.0005	3L 3C	N	Y	TABLE TYPE
20 CINCINNATI MILACRON	10HC	H	5000-10000#	40-100 X 40Y	26Z	30	Y	10	25-4000	-400			3L 3C	OPT.		TABLE TYPE
21 CINCINNATI MILACRON	15HC	H	4000#	30-100 X 28Z	24Y 36 (OPT)	30 (60 OPT)	Y	15	20-3300	.2-150 400RT	.0005	.0003	3L 3C	N	4TH	TRAVELING COLUMN (IN Z)
22 CINCINNATI MILACRON	20HC	H	4000#	44-100 X 28Z	36Y	30 (60 OPT)	Y	20	20-3300	.2-150 400RT	.0005	.0003	3L 3C	2STA FIXED	4TH	TRAVELING COLUMN (IN Z)
23 CINCINNATI MILACRON	25HC	H		TO 96 X TO 48 Z	TO 60Y	30 (10 OPT)	Y	25	15-3000	.2-150	.0005	.0003	3L 3C	OPT.	4TH	TABLE TYPE
24 CINCINNATI MILACRON	25HC	H		48X 36Z	36Y	30 (10 OPT)	Y	25	15-3000	.2-150	.0005	.0003	3L 3C	2 OR MORE FIXED STA	4Y 5 OPT	TRAVELING COLUMN
25 DEVLIEG	FS 40	H	5000#	40X 16Z	40Y - 60 60	32 OR 48	Y	15	20-3000	.1-200 X-Y	.0003	.0001	Y	Y	4TH W/ AWC	FIXED SPINDLE
26 DEVLIEG	FS60	H	6500#	60X 16Z	40-60	32 OR 40	Y	15	20-3000	.1-200 X-Y	.0005	.0001	Y	Y	4TH W AWC	FIXED SPINDLE
27 DEVLIEG	JMC 340, 360	H	5000-6500#	40-60X 16W	40-60 Y 16Z	32 OR 48	Y	15	20-3000	.1-200 X-Y	.0003-.0005	.0001	Y	Y	4TH W/ AWC	MOVEABLE SPINDLE

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
28 DEVLIEG	SERIES K 19MODELS	H		48-120X 16-24W	36-60 Y 20-26	32 OR 48	Y	15-30	14-1450	.1-150 X-Y			Y	Y SEMI	4TH W/ AWC	MOVEABLE SPINDLE
29 EXCELLO	THE MACHINE	H	1000#	20X 14Z	14Y	20		5	0-3600	.01-100 300RT	.0005	.0002		OPT	4TH 72POS	
30 EXCELLO	105 WORKCENT	H		24X 16Z	18Y	24		5	0-3600	.01-300	.0005	.0002		OPT	4 OPT	
31 EXCELLO	105 LX WORKCENT	H		60X 18Z	30Y	24		5	0-3600	.01-300	.0005-.00075	.0002		OPT	4 OPT	
32 EXCELLO	108A WORKCENT	H	1500#	24X 18Z	18Y	30-60		15	20-3000	.01-100 300RT	.0005	.0002		OPT	4TH	
33 GIDDINGS & LEWIS	15VFC	V		96-192X 36Y	14Z 36Z 36Z	40	N	15	15-1500	.1-100	.0005/FT	.0005		N	4 OPT	TOOL CHANGERS IN THE WAY
34 GIDDINGS & LEWIS	10HS	H			72X 24Y 24Z	24 40		10	30-3000	.1-300	.001/FT	.0005				TRAVELING COLUMN
35 GIDDINGS & LEWIS	10 VFS	V			72X 24Y 32Z	48		10	85-3000	.1-300	.001/FT	.0005	2L 2C			MOVING COLUMN
36 HILLYER	CNC200	V	4000#	50X 30Y	18Z	24		10	60-3500	.25-300	.001	.0005 .0001RES				

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
37 HILLYER	CNC300	V	4000#	30X 48Y	18Z	30		15	40- 2500	.25- 300	.001	.0005 .0001RES				
38 HILLYER	CNC600	V	6000#	60X 48Y	18Z	30		15	40- 2500	.25- 300	.001	.0005 .0001RES				
39 HITACHI SEIKI	MINIMATI 500	H	1100#	23.5X	20Y 13.8Z 13.8Z	18		5	28- 3150	0- 80 480RT	.0008/FT	.0004	2L 2C	OPT		PALLET TRANSFER DESIGNED FOR CONVEYOR LINE
40 HITACHI SEIKI	SEIKIMAT 500	H	1100- 1400#	27.5X 23.5Z 33.5X	23.5Y 27.5Y 27.5Y	26	Y	12	28- 3150	.1- 100 400RT		.0001RES	2L 2C	OPT	4 OPT	PALLET TRANSFER DESIGNED FOR CONVEYOR LINE
41 HITACHI SEIKI	6MC	H	1000#	31.5X 27.5Z	27.5Y	36- 60 60	Y	10	20- 1600	.05- 84 400RT			2L 2C	N	4 LIM	
42 HITACHI SEIKI	9MC	H	2000#	43X 27.5Z	39.5Y	36- 60 60	Y	10	20- 1600	.05- 84 400RT			2L 2C	N	4 LIM	
43 HITACHI SEIKI	12MC	H	3000#	59X 31.5Z	51Y	36- 60	Y	15	20- 1600	.05- 84 400RT			2L 2C	N	4 LIM	
44 HOWA	MILLAC 2	H		23 5/8 X 15 3/4 Z	19 11 /16Y /16Y	20	Y	10	50- 2500	.04- 78 236RT		.0004 RES	2L 2C	OPT	N	
45 HURCO	MI	V		26X 13Y	14Z	12	N	3	150- 3600	.1- 100 250RT	.001	.0005	L 2C	N	N	MBII LARGER

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVELOPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEATABILITY +- IN.	CONTOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
46 HYDRAPOINT MOOG	SUPER 10	V		20X 10Y	5Z 11.5 KNEE	10	N	2	60- 4100	1- 44 300RT	.001	.0003	N	N	N	
47 HYDRAPOINT MOOG	83- 1000MC	V		20X 10Y	5Z 11.5 KNEE	24	Y	2	65- 4090	1- 44 300RT	.001	.0003	N	N	4 OPT	
48 HYDRAPOINT MOOG	83- 2000 MC	V		20X 10Y	5Z 11.5 KNEE	24	Y	2	65- 4090	.5- 300	.001	.0003	2L 2C	N	N	
49 HYDRAPOINT MOOG	83- 3000 MC	V		20X 10Y	6Z 14.5 KNEE	24	Y	5	50- 4500	.3- 350	.001	.0003	3L 2C	N	N	
50 KEARNEY & TRECKER	MILLWAUK MATIC180	H	1500# 16"PAL	20X 20Z	20Y	30	Y	10	50- 4000	.1- 400	.0005/FT .0008	.0003	3L 3C	Y	4	MULTI-DRILL AND TAP CAPABILITY
51 KEARNEY & TRECKER	200	H	1500# 18"PAL	24X	20Y 20Z	30- 52	Y	15	4- 3600	.1- 400	.001 (.0004 OPT)	.0005 .(.0002 OPT)	3L 3C	OPT	4 OPT	MULTI-DRILL AND TAP CAPABILITY
52 KEARNEY & TRECKER	600	H	1500# 24"PAL	30X	26Y 20Z	30- 52	Y	15	4- 3000 8-	.1- 400	.001 (.0004 OPT)	.0005 (.0002 OPT)	3L 3C	OPT	4 OPT	MULTI-DRILL AND TAP CAPABILITY
53 KEARNEY & TRECKER	800	H	3500# 31.5PA	43X	35.4Y 31.5Z	42- 68	Y	20	20- 3600	.1- 400	.001 .00050PT	.0005 (.0003 OPT)	3L 3C	N	4 OPT	
54 MAKINO	FNC85	V		34X 16Y	16Z	12- 20	12N 20Y	7.5	28- 2240 3500 OPT	.04- 94.5 393RT			L C	N	4 OPT	

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
55 MAKINO	FNC105	V		41X 20Y	20Z	12- 24	12N 24Y	10	28- 2240 3500 OPT	.04- 94.5 393RT			L C	N	4 OPT	
56 MAKINO	FNC125	V		49X 27.5Y	23.5 Z	12- 24	12N 20Y	15	28- 2240 3500 OPT	.04- 94.5 393RT			L C	N	4 OPT	
57 MAKINO	MC60	H		24X 18Z	16Y	20- 30	Y	10	28- 3500	.01- 400			L C	N	4 OPT	
58 MAKINO	MC100	H		40X 38Z	31.5 Y	30	Y	15	10- 4000	.03- 400	.0004	.0002	L C	OPT	4 OPT	WITH SCALE FEEDBACK ACCURACY .0003 REPEAT 80MUIN
59 MAZAK	MICRO CENTER	V		30X 16Y	8Z 12W	24	Y	5	28- 4000	480RT	.0005	.0001 REP				
60 MAZAK	POWERCEN V-10	V	2200#	40X 20Y	20Z	20 OR 24	Y	10	22- 3150							
61 MAZAK	V-15	V	3300#	40X 20Y	30Z	20 OR 24	Y	15	14- 2000	400RT						
62 MAZAK	H-15	H	2200#	43X 33Y	29Z	30	Y	15	14- 2000	400RT			L C	OPT	4 OPT	ALSO TOOL DRUM CHANGER, MULTI-SPINDLE HEADS
63 MITSUBISHI	MPA50A	H	1760#	24.8X 19.7Z	24.8Y	30- 40	Y	10	40- 3100	.04- 142 394RT	.0004 .0002/FT		3L 2C	OPT	4 OPT	

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
64 MITSUBISHI	MP80A	H	3300#	49X 31.5Z	31.5Y	30- 40	Y	20	40- 3150	.04- 142 394RT			3L 2C	OPT	4 OPT	
65 MITSUI SEIKI	MAGNUM 4	V	1760#	33.4X 19.6Y	19.6Z	20		10	15- 3150	.05- 94.4 400RT			L C	N	N	
66 MITSUI SEIKI	MAGNUM 5	V	3300#	41.3X 20Y	24Z	20	Y	10	15- 3150	.05- 94.4 400RT	.0006 (.0002 OPT)	.00012 .00008 OPT	L C	N	N	
67 MONARCH	VMC75	V	3000#	40X 20Y	10Z 21Z	20 OR 40	Y	7.5	45- 3500	.1- 300	.001	.0005	2L 2C	N	N	
68 MONARCH	VMC150	V	4000#	50X 30Y		20 OR 40	Y	11	45- 3500	.1- 400	.001	.0005	L C	N	4 OPT	
69 MONARCH	HMC	H	24X 24Y 30Z 2500#	40X 30Y	18Z	30- 50	Y	15	40- 3500	.1- 150	.0005	.00015	L C	N	4 Y	
70 NEWALL	VERTEX 200	V		35.4X 19.6Y	15.7Z	24 OR 30	Y	10	25-	.04- 39 200RT	.001 .0005 OPT	.0001 .00005 OPT	3L 2C	N	N	
71 OKUMA	LM70-AT TURNING			27S ?X 6Y	41Z	10 + 8 TUR	Y	30+3	100- 1200	TO 47		.0001 RES	2L 2C	N	4 Y	TURNING AND MILLING (LIMITED)
72 OLIVETTI	HORIZON 20	H	2200#	23.6X 15.8Y	21.6Y	20		9	25- 3200	.004- 314	.0004	.0002	L C	N	4 OPT	

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
73 OLIVETTI	HORIZON 21	H	2200#	23.6Y 15.8Z	24.4 Y	40		9	25- 3200	.004- 314	.0004	.0002	L C	N	4 OPT	
74 OOYA	RE-1M	V	1760#	43X 20.5Y	20.7 Z	20	Y	10	40- 4000	.004- 161 393RT	.0008 IN 20"		L C	N		
75 OOYA	RE-2M	V	5500#	51X 29.5Y	27.6 Z Z	32	Y	15	18- 2240	.004- 161 393RT	.0008 IN 20"		L C	N		
76 OSAKA KIKO	MCH 400	H		24X 17 3/4 Z	17.75 Y	20 (30)	Y	10	60- 3000	.1- 240 400RT			2L 2C	OPT	4 OPT	
77 OSAKA KIKO	MCV 500	V	1600#	40X 20Y	22	20	Y	10	35- 3000	.1- 240 400RT			2L 2C	N	4 OPT	
78 PRATT & WHITNEY	TRIMAC VII	V	2500#	54X 26Y	20Z	25	Y OPT	7.5	60- 3600	.2- 100	.001	.0005	2L 2C	N		
79 PRATT & WHITNEY	TRIMAC XV	V	3500#	60X 29Y	24Z	25	Y OPT.	15	45- 3600	.1- 300	.001	.0005	3L 2C	N	N	
80 PRATT & WHITNEY	AZTEC 10	H	1760#	24X 20Y	22Z	24	Y	10	50- 2500	.1- 200	.001	.005	L C	N		
81 PRATT & WHITNEY	AZTEC 15	H	2200#	34X 26Z	28Y	24	Y	15	50- 3100	.1- 200	.001	.0005	L C	N		

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
82 RAMBAUDI	MINIRAM NC/1	V		23.6X 15.8Y	17.7 Z	24	N	10	40- 3000	0- 79 200RT				N	4 OPT	
83 RAMBAUDI	MINIRAM NC/2	V		23.6X 15.8Y	17.7 Z	24 (X2)	N	10	40- 3000	0-79 200RT				N	4 OPT	2 SPDL 2 TOOL CHANGERS
84 SHELDON	2040 VC	V	10000#	40X 20Y	20Z	30	Y	10	80- 2000	.5- 300 400RT	.0005	.00025	L C	N	N	
85 SHELDON	3040 VC	V	10000#	40X 30Y	20Z	30	Y	10	80- 2000	.5- 300 400RT	.0005	.00025	L C	N	N	
86 SIP	4000 CNC	H	8000#	47X 47Y 16W	24Z	40	Y	14	10- 3000	0- 240	.0002		2L 2C	N	4,5 OPT	
87 SIP	8000	V	6000 TO 12000#	35-79X 24-47Y	29- 57Z 57Z	40 (60 OPT)	Y	14	10- 3000	0- 240	.0002		3L 2C	N	4,5 OPT	
88 TOSHIBA	BMC -5B	H	1760#	24.8X 19.7Z	19.7 Y	24	Y	10	28- 3150	.1- 142 394RT	.0005/ 24"	.0002	3L 2C	OPT	4,5 OPT	
89 TOSHIBA	BMC -6B	H	2200#	31.5X 24.8Z	24.8Y	24	N	12	28- 3150	.1- 142 394RT	.0005/ 24	.0002	3L 2C	OPT	4 OPT	
90 TOSHIBA	BMC -8B	H	3300#	39.4X 31.5Z	31.5Y	30	Y	15	28- 3150	.1- 142 394RT	.0005/ 24	.0002	3L 2C	OPT	4 OPT	

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVEL-OPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEAT-ABILITY +- IN.	CON-TOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
91 TOSHIBA	BTN -10B	H	4400#	55.1X 43.3Z	39.4Y 16W 16W	60 (90 OPT)	Y			.01- 250			3L 2C	OPT	4.5 OPT	BORE DIAMETER MEASUREMENT FUNCTION X-Y CIRC. INT. ONLY
92 TOYADA	FHN50	H		28X 19.7Z	19.7Y	32	Y	10	20- 3150				?	N		
93 WHITE-SUNDSTRAND	OMNI-ONE	H	3200# 22"CUB	24X 18Z	22Y	24 (60 OPT)	Y	15	18- 3200	.1- 400	.0002/FT .0005	.0001	L C	OPT	4.5 OPT	
94 WHITE-SUNDSTRAND	OMNI-TWO	H	3500# 30"CUB	40X 26Z	32Y	60	Y	15	18- 3200	.1- 400	.00025/F .0005	.0001	L C	OPT	4,5 OPT	
95 YASDA	PRODUCTI CENTER	H	880#	19.7X 15.8Z	15.8Y	30	Y	9.6	23- 2250	.04- 161 394RT	.0008/FT	.0002	2L 2C	OPT		
96 YASDA	PREC.CEN YBM-70N	H	2200#	27.5X 23.6Y	23.6Z	30 (50 OPT)	Y	13	30- 3000				3L 2C	OPT	4 OPT	OIL HOLE DRILL, MULTI-SPINDLE HEAD OPTION.
97 YASDA	PREC.CEN YBM-90N	H	2200#	35.4X 27.6Z	23.6Y	40 (60 OPT)	Y	15	30- 2400		.0004/ 20"	.00012	3L 3C	OPT	4 OPT	
98 BEAVER	NC5-ATC	V	1000#	24X 14Y	6Z + 16.8 KNEE	30		5	50- 4000	240RT	.001/12	.0003		N		
99 BUTLER	MC500	H		25.5X 9.8Z	19.5Z	20		10	5- 3800	T0158 315RT				2 TABLE		2 TOOL TURRET HEAD

MACHINING CENTER MANUFACTURER	MODEL	TYPE	ENVELOPE	TABLE TRAVEL	QUILL AND HEAD	NO OF TOOLS	TOOL RANDOM ACCESS	HP	SPINDLE SPEEDS RPM	FEEDS IN/MIN	ACCURACY +- IN.	REPEATABILITY +- IN.	CONTOUR	AUTO WORK CHNG	4TH 5TH AXIS INTEGRAL	COMMENTS
100 HAMAI	MC50V	V		43.3X 27.6Y	20Z	20 (24 OPT)	Y	15	22- 3150	.1- 142 400RT			3L 2C	OPT	4 OPT	OPTIONAL ROBOT FOR LOAD, UNLOAD OF WORKPIECES
101 HITACHI	MACCMAT-IC 36V	V	1100#	23.5X 12.625 Y	18.88 Z	24	Y	5	100- 4000	.25- 120 400RT	.0006/12	.0002	3L 2C	N	N	
102 HITACHI	MACCMAT-IC 48V	V	1100#	31.5X 16.5Y	18.88 Z	24	Y	5	100- 4000	.25- 120 400RT	.0006/12	.0002	3L 2C	N	N	
103 SHIZUOKA	MILLMAST B-10V	V	2200#	40X 20Y	20Z	16	N	10	10- 3270	.2- 120 400RT	.0005/12	.0002	L C	N	4 OPT	
104 SPINDLE WIZARD	SERIES 2	V	1000#	31.5X 17.5Y	5.1Z + KNEE	24	Y	5	80- 3800	.01- 300 300RT	.001/12"	.0003	3L 2C	N	4,5 OPT	LIKE A BRIDGEPORT
105																