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FLEXIBLE MANUFACTURING SYSTEM HANDBOOK

VOLUME III: BUYER'S / USER'S GUIDE

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U.S. ARMY TACOM

by Charles Stark Draper Lab., Inc.
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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 [illegible] 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 [illegible]

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PREFACE

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

- 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. Volume II contains detailed descriptions of the subsystems that make up a typical FMS as well as descriptions of several operational FMSs. This volume is designed to serve as a more detailed guide to planners at corporate and plant levels closer to the manufacturing environment. It shows how to specify and purchase an FMS and then deals with installation and operation. 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 PLANNING FOR A FLEXIBLE MANUFACTURING SYSTEM

1.1 CAN YOUR ORGANIZATION BENEFIT FROM AND SUPPORT AN FMS?

Is Flexible Manufacturing System technology right for your organization? To answer this question, it will be necessary to examine your future production needs as well as the experience and capabilities of your organization.

If you are now producing, or expect to produce, parts requiring similar manufacturing operations with aggregate volumes in the low- to mid-volume range, then an FMS may be applicable. These parts could be small quantity orders that are placed a number of times every year, medium quantity orders which are divided into batches to satisfy the customer's usage pattern or spare parts, i.e., neither mass-production nor one-of-a-kind. Parts which require processing on many different machines, frequent refixturing on the same machine, approximately the same machining cube, and modest tolerances are excellent FMS candidates.

Organizational experience with NC machines, and preferably CNC or DNC systems, is important. It will have allowed the work force to develop some of the electronic and computer skills needed to operate an FMS. Other needed skills include site planning, production planning, process planning, part programming, quality control, tool management and maintenance.

An adequate planning horizon is also required. The lead time for an FMS can approach 2 years from the date an acquisition decision is made. Quite often it will require another 6 months after installation to obtain full production. If the FMS is going to produce existing parts, the system can be brought up to full production gradually, since the production capability already exists and time is available to correct unexpected problems. When the FMS is introduced for new parts, adequate time must be allowed for installation and debugging. Rushing the FMS vendor during the design and installation phases often results in a longer shakedown period.

If your production requirements and organization satisfies these criteria, then an FMS will most likely be beneficial.

1.2 DEFINING MANUFACTURING GOALS

One of the most important steps in planning for an FMS is to define, as clearly as possible, how the system is to satisfy the present and future manufacturing needs. This will influence the specification to the FMS vendor and will prevent the system from being under- or over-designed. Typical FMS manufacturing goals include:

- Reduction in part manufacturing costs.

- Less skilled labor required.

- Reduction in part lead-time.
- Reduction in work-in-process inventory.
- Flexibility to produce spare parts or change product mix as market requirements demand.
- Staying at the forefront of technology.

1.3 STEPS FOR THE IMPLEMENTATION OF AN FMS

Figure 1 on page 3 through Figure 8 on page 8 summarize the steps required for FMS implementation and also provide a key to where information for each step can be found in this volume. Preceding the introduction of each implementation step in the text is a flowchart to highlight the step in relation to the implementation sequence. With each of these flowcharts, there is a list of the tasks to be accomplished and the data required for that implementation step.

Before proceeding further with this volume, the reader who is not completely familiar with FMS technology is strongly advised to read Volume II for a description of typical flexible manufacturing systems and their components.

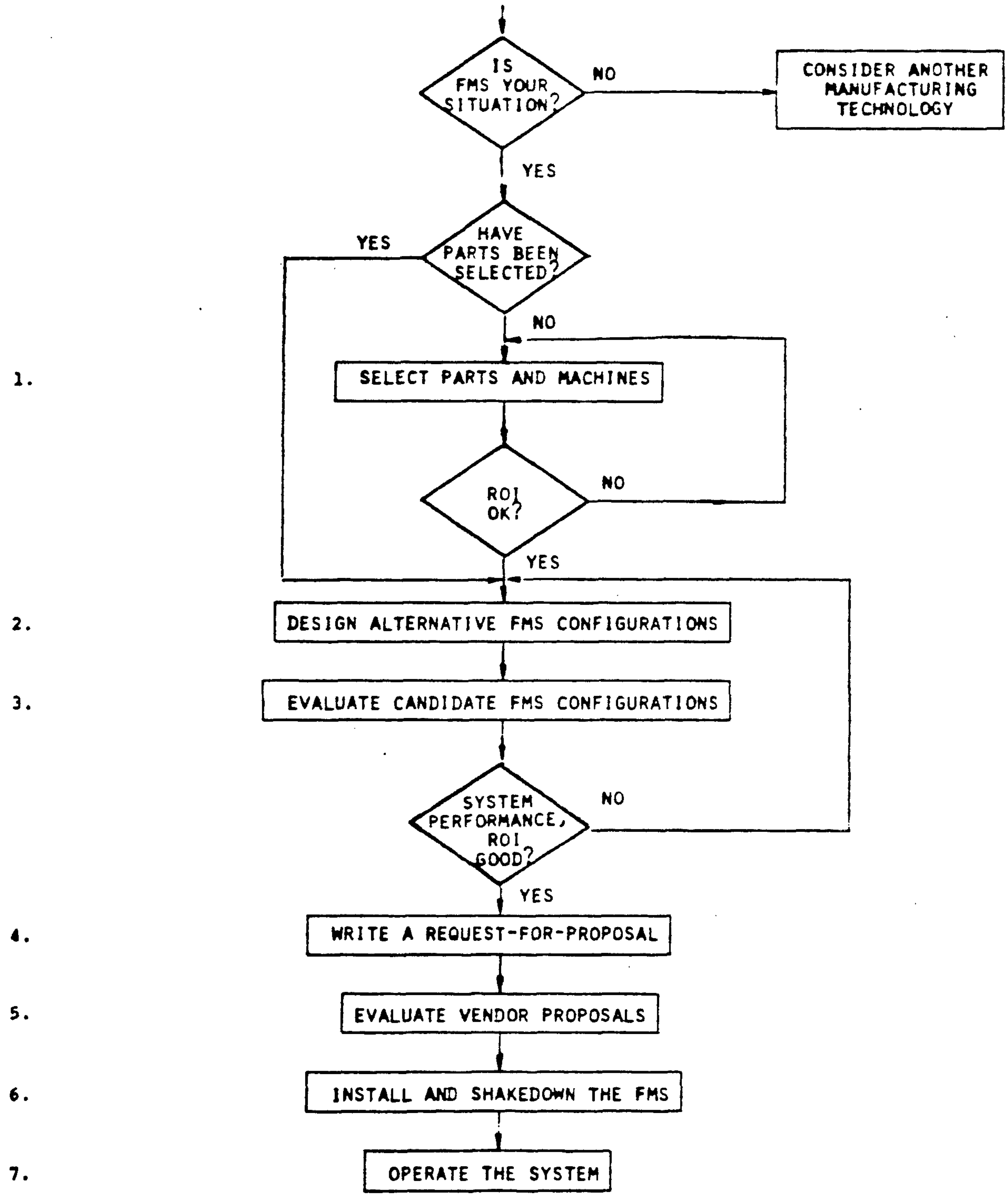

Figure 1. Decision Flowchart for the Acquisition of a Flexible Manufacturing System (FMS)

SELECT PARTS AND MACHINES

- Preselect parts and machines having FMS-compatible attributes from available candidates.
- Calculate current production cost of each part.
- Estimate FMS manufacturing cost for each part.
- Use either manual selection methods or a computer software package (e.g., Part and Machine Selection (PAMS) program, see Volume V) to select the most economically beneficial parts and machines.
- Perform investment analysis to determine if an FMS is an economic alternative.
- See "Parts and Machine Selection" on page 9 for details.

Figure 2. Steps in FMS Implementation: Step 1

DESIGN ALTERNATIVE FMS CONFIGURATIONS

1. Estimate the Work Content of the Selected Parts

- Develop FMS fixturing concepts for the selected parts, minimizing the number of fixturings.
- Process plan each part in detail, constrained by the limited tool capacity of an FMS and the effects of using different machines (roughing and finishing machines, for instance) on overall accuracy and cycle time.
- Determine the appropriate machinability data for each material, for each class of operation (rough milling, semifinish boring, etc.).
- Estimate production requirements for each part.
- Calculate part cycle times and tool usage (see Volume V for the CTIME software package to aid in the calculations).
- See "Configuration Design" on page 26 for details.

2. Design Several Equipment Configurations

- Choose specific vendors' equipment in each machine class; temper with company biases (toward horizontal rather than vertical machining centers, for example).
- Estimate the minimum number of machines (spindles) for each machine class.
- Modify this number of machines to account for shop and system efficiency, limited tool storage capacities, and desires for machine redundancy.
- Add a material handling system (MHS) and other desired nonmachining processes, such as an inspection machine, to complete the configuration.
- Layout the equipment and material handling system.
- Develop alternative design configurations from the original design.
- See "Configuration Design" on page 26 for details, and Volume IV for a configuration design example.

Figure 3. Steps in FMS Implementation: Step 2

EVALUATE CANDIDATE FMS CONFIGURATIONS

- Simulate the operation of each configuration based on predetermined scheduling, batching, and balancing rules to provide performance measures for each configuration.
- Improve the configuration designs until each provides satisfactory performance measures or is rejected.
- Perform a detailed investment analysis of each configuration.
- Examine and evaluate intangibles, such as flexibility, accuracy, etc.
- Choose the configuration which best satisfies the investment and intangible analyses.
- See "Evaluating Candidate FMS Designs" on page 39 for details, and Volume V for simulation and investment analysis software packages.

Figure 4. Steps in FMS Implementation: Step 3

WRITE A REQUEST-FOR-PROPOSAL (RFP)

- Write an RFP that conveys your findings and desires for an FMS.
- Avoid overspecification; allow the FMS vendors to be creative and competitive in designing an FMS for your situation.
- See "HOW TO WRITE THE REQUEST FOR PROPOSAL" on page 57 for details, and Volume IV for a sample RFP.

Figure 5. Steps in FMS Implementation: Step 4

EVALUATE VENDOR PROPOSALS

- Verify and evaluate vendor proposals using simulation and economic analysis.
- Evaluate the degree of success of each proposal in satisfying your nonquantifiable requirements.
- Choose the proposal which best satisfies your company's need.
- Work with the vendor to develop detailed specifications and prices.
- Place an order.
- See "HOW TO EVALUATE VENDOR PROPOSALS" on page 71 for details, and Volume IV for a sample vendor proposal.

Figure 6. Steps in FMS Implementation: Step 5

PREPARE FOR, INSTALL, AND SHAKEDOWN THE FMS

- Select and educate personnel to operate and maintain the FMS.
- Assess the quality control and production control departments' roles in the successful implementation and operation of the FMS and develop or augment policies to assure success.
- Develop a preventative maintenance plan and spare parts lists for the FMS.
- Prepare the FMS site.
- Assist vendor with installation and shakedown.
- Perform FMS acceptance tests.
- See "INSTALLATION AND SHAKEDOWN" on page 77 for details.

Figure 7. Steps in FMS Implementation: Step 6

OPERATE THE SYSTEM

- Schedule parts.
- Batch production if necessary.
- Allocate parts and tools to machines.
- Balance machine loads.
- Use a decision support system to optimize daily operations in the face of machine failure and changing part requirements.
- See "HOW TO OPERATE AN FMS" on page 87 for details.

Figure 8. Steps in FMS Implementation: Step 7

2.0 HOW TO DESIGN AND EVALUATE AN FMS

2.1 THE BUYER'S INITIATIVE

Machine-tool buyers traditionally have been able to assume a very straightforward -- and sometimes passive -- role in procuring equipment. Typically, the buyer decided what machine was best suited to the parts to be produced and bought it. Alternatively, he would send part blueprints to one or two selected vendors. The vendor would then match the production requirements of those parts to the capabilities of one of his machines and prepare a quote. The buyer would review this quote and either purchase the machine or look for other vendors.

Such an approach, when applied to procuring complex systems, has met with problems. Many buyers have not understood the large number of system parameters under their control, nor have they understood the strategic and operational ramifications of one specification as opposed to another.

To interface effectively with FMS vendors, the buyer should perform a preliminary design and evaluation of an FMS as though <u>he</u> were going to build and install it. This enables the buyer's staff to understand all the issues involved and results in an RFP that correctly conveys the requirements to the vendor. It also enables the staff to cooperate knowledgeably with the vendor during system shakedown and to subsequently operate the system at maximum utilization. There are three steps in this process:

1. Select a set of intended parts and machines, using either manual selection methods or the automated parts/machine-selection software package (see Volume V).

2. Design a number of equipment configurations.

3. Evaluate the design and its variations on technical and economic grounds.

"Parts and Machine Selection" through "Evaluating Candidate FMS Designs" on page 39 describe these steps in detail. Additional insight can be gained from case studies of specific FMS applications at General Electric and Rock Island Arsenal that are summarized in the text and presented in detail in Volume IV.

2.2 PARTS AND MACHINE SELECTION

This section discusses the most basic issue in the entire FMS design and evaluation process -- which parts can be matched to available FMS machines to maximize the cost savings compared with alternative production methods. While many qualitative factors also go into this decision, the driving concern for selecting a suitable combination of parts and machines is usually economic. Part and machine selection constitutes Step 1 of the

FMS implementation sequence and provides an estimate of system size, approximate return on investment (ROI), and payback period (Figures 9 and 10 summarize these steps).

2.2.1 Selection Methodology

Part machine selection based on economics can be performed either manually or via computer. Manual methods work well for situations where there are less than appproximately 40 candidate parts and a small number of FMS-type machines to be considered. When both parts and machines are to be selected from a larger number of candidates, however, manual methods become cumbersome and time-consuming. A computer-based part machine selection tool has been developed for use in this situation. It is described briefly later and in detail in Volume V.

Both the manual and the computerized methods choose parts based on the same concept, that of relative production cost savings. The present cost of producing each candidate part, either in-house or purchasing it from a vendor, is calculated first. The costs to produce each of those parts on an FMS are estimated next. Then the parts with the largest savings are chosen to fill the capacity of the machines chosen.

The procedures for both the manual and the computerized part-selection method are listed after Figure 10 and described in the following sections. As the procedures are quite similar, both approaches will be discussed in parallel. To illustrate the computerized part machine selection procedure, its application at the U.S. Army Arsenal at Rock Island, Illinois is summarized later. (A more detailed description of the Rock Island Arsenal study is presented in Volume IV.)

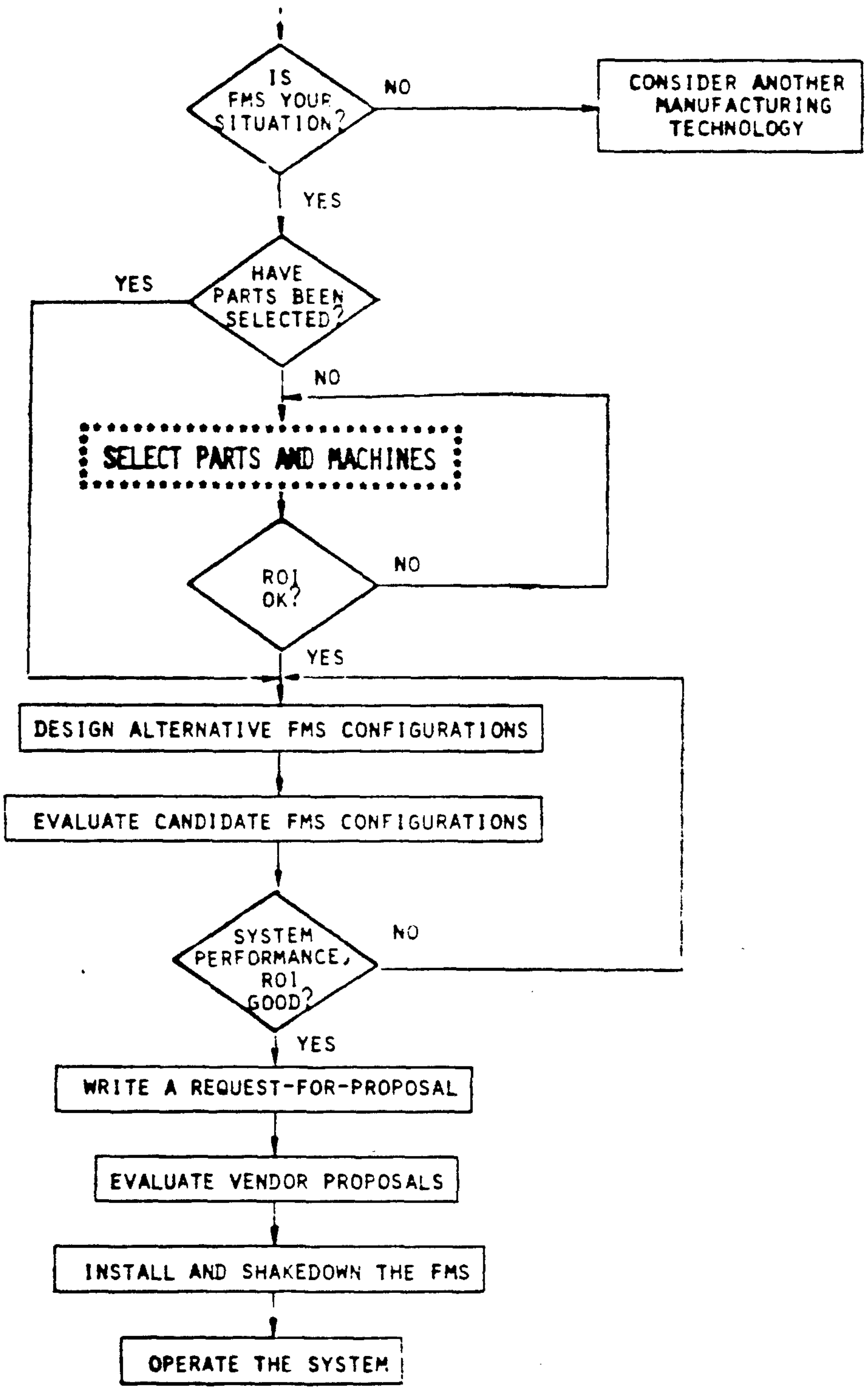

Figure 9. Acquisition of an FMS: Step 1

SELECT PARTS AND MACHINES

- Preselect parts and machines having FMS-compatible attributes from available candidates.

- Calculate current production cost of each part.

- Estimate FMS manufacturing cost for each part.

- Use either manual selection methods or a computer software package (e.g., PAMS, see Volume V) to select the most economically beneficial parts and machines.

- Perform investment analysis to determine if an FMS is an economic alternative.

- Data required:

  1. For each candidate part:

     - Machining cube size.
     - Material.
     - Cost to buy part from vendor (if a "buy" part).
     - Annual production volume.
     - Current machine types used in manufacturing sequence.
     - Setup time on each machine type.
     - Run time on each machine type.
     - Manufacturing cost for each unit of setup and run time (direct labor and overhead).
     - Unique identification of each tool.

  2. Cost of specific machines in each machine class, approximate cost of an MHS, computer, tools, fixtures, etc.

  3. Machining cube of each machine in each machine type.

  4. Estimated FMS manufacturing cost per part per unit of run time.

  5. Number of available production hours annually.

  6. Desired system(s) size(s) -- governed by projected amount of capital available for FMS purchase.

  7. Total investment for each specified system size.

Figure 10. Steps in FMS Implementation: Step 1

The two alternative procedures consist of the following steps:

	Manual	Computerized
1.	Determine initial guidelines.	Determine initial guidelines.
2.	Preselect from the candidate parts and machines those which have FMS-compatible attributes and establish part families.	Preselect from the candidate parts and machines those which have FMS-compatible attributes
3.	Collect data on candidate parts including process routing, process time, and current manufacturing cost data.	Collect data on candidate parts including process routing, process time, and current manufacturing cost data.
4.	Estimate the FMS manufacturing cost of each part.	Estimate the FMS manufacturing cost of each part, using computer-based manufacturing part-cost program described in Volume V and determine the annualized fixture cost.
5.	Choose specific vendors' machines in each potential FMS machine class and obtain prices.	Choose specific vendors' machines in each potential FMS machine class and obtain prices.
6.	Select parts based on relative savings between current and FMS production methods to load a chosen set of machines.	Select machines and parts using the computer-based selecselection tool described in Volume V to obtain the most cost-effective solution which meets your requirements.
7.	Determine the potential system payback period and ROI.	Determine the potential system payback period and ROI, using the computer-based investment analysis model described in Volume V.
8.	Choose a different set of machines and repeat the inment analysis if necessary.	
9.	Repeat steps (6), (7), and (8) several times to obtain the most cost-effective solution which meets your requirements.	

The iterative nature of the manual part machine selection method is an attempt to find the best solution among the candidate parts and machines, but usually the number of combinations is sufficiently large that all of them cannot be examined. Thus, the resulting manual solution is not necessarily the "best".

In contrast, the computerized part machine selection approach finds an optimum combination of parts and machines. The computer-based selection algorithm will estimate the relative savings of all the candidate parts. It also considers for each part the size of machine required, the amount of machining time used on that machine, and the amount of machining time remaining on that machine. Both parts and machines are selected simultaneously, and the approach assures that the best possible combination was chosen.

2.2.2 Initial Guidelines

This section discusses types of FMSs (prismatic, rotational) and size considerations, as well as other decisions that must be made before either selection method can be used.

A basic issue is the maximum size of the system (number of machines) to be considered. This may be determined by floor space availability, budgetary constraints, or simply by the size of the system that the available personnel handled.

A second issue is the total annual operating time of the FMS. As with stand-alone NC machines, an FMS is capital intensive and, therefore, the longer it operates per year, the better the ROI. This logic suggests a three-shift, 7-day-per-week operation. In addition, the level of production accuracy usually increases as the period between shutdowns is lengthened. Many factory environments will not support three-shift operation, however. People, in general, do not like to work the third shift, and there is no time for preventative maintenance. Often, 5-day-per-week, two-shift operation is more appropriate.

Also at issue is what class of parts to produce on the FMS: prismatic, rotational, or a combination. FMS technology for prismatic parts (flat or box-like, basically rectangular, solid parts) is well established due to 10 years of application. FMS technology for rotational parts (shafts and disks), especially between-centers shaft work, is still in its infancy. The turning of disk-shaped parts presents less of a problem, as these parts can be fixtured for vertical turret lathes which exist in basically prismatic FMSs. An FMS for each of these part classes will have its own design pecularities and problems. The choice should be based on the available work content in each class as well as how comfortable the organization is with the available FMS technology for each class. After choosing the class, it is necessary to choose between currently produced parts, completely new parts, spare parts, or some combination of these.

The range of part sizes to include in the FMS depends on a number of factors. The most obvious is the average size of the parts. Large parts dictate large machines. Small machines are usually better for small parts except when several small parts can be mounted on a single fixture.

Small (6-inch machining cube or less) parts usually have a small amount of work content, and may only need to be at any given machine for a few minutes. The shorter the cycle time in an FMS, the more parts that must be in the system at any one time. This may overload the MHS and degrade overall system efficiency. Large parts (36-inch machining cube or larger) usually require special material handling consideration, since neither their size or weight (when combined with a fixture and pallet) are easily handled by currently popular MHSs. Also, as part machining cube size increases, so does the cost of the machines to be used. Thus, there is a tendency to limit machining cube sizes to less than 36 inches and greater than 6 inches. This allows the parts to be transported using conventional material handling systems and can permit multiple loading of small parts on one large fixture, to lengthen the total time at each machine and reduce the possibility of MHS bottlenecks.

2.2.3 Preselection of Parts and Machines

Out of the total set of parts of potential interest, it should be possible to preselect a subset suitable for manufacture on an FMS. Similarly, out of the total of FMS machines available, it should be possible to identify a subset suitable for the set of candidate parts. Thus, the field is narrowed and the problem of final selection simplified.

If the candidate parts have been coded using a group technology classification system, then the fastest and simplest approach to preselection is to sort parts using the computer, based on FMS-compatible part attributes. Typical attributes include:

- Desired machining cube.
- Material (e.g., aluminum or steel).
- Form (prismatic solid, box, disk, flat).
- Types of operations (milling, drilling, boring, etc.).
- Tolerances.
- Production quantity.
- Machining time.
- Current number of fixturings.

These few criteria can usually greatly reduce the candidate part set with little effort. One company has recently completed the installation of a group technology classification and coding package and has processed approximately 3,300 different parts. Sorting those parts for FMS-compatible attributes revealed 677 parts that were promising candidates.

Without a group technology system, sorting manually by reviewing part prints and process plans can consume a great deal of time and personnel. A benefit of the automated part machine selection algorithm is that, although preselection is useful to eliminate unsuitable candidates and reduce the part set to be examined (saving computational time), the selection algorithm can review all of the candidate parts in a very short time and does not require group technology. However, the results must be reviewed in detail to make sure none of the unsuitable parts were chosen because of misleading information. For example, one manufacturer machined one end of a 10-foot long part on a small milling machine. Although the part was too large for a normal FMS, without sorting the parts based on size, all that was known about the part was that it was machined on a small milling machine and, therefore, acceptable for FMS production. If some selected parts are unsuitable, they are removed from the candidate part set and the selection program rerun. This iterative process is contniued until no unsuitable parts are chosen.

The number of FMS fixturings per part can also be used to preselect candidate parts. Although it can vary with system application, a rough rule of thumb is that if the part must be fixtured more than three or four times, it should be rejected. Again, this is done automatically by the computer program.

Another issue concerns tool wear. A part which requires extensive work on a hard material will wear out tools rapidly and impose excessive requirements for tool replacements. Such intervention interrupts the FMS and interferes with productivity. Clearly, a part requiring a large number of short operations would be preferable to one requiring a few very long operations.

Another method of preselecting parts, often used in conjunction with the manual part machine selection approach, is to group the parts into families. Grouping parts in this manner emphasizes the similarities of those parts, and one or two of the families can be chosen for manufacture on the FMS. Three common methods of grouping parts into families are:

- Assembly: All the parts necessary to produce some end item or subassembly.
- Size and Common Manufacturing Operations: A number of parts that require approximately the same machining cube and parts which require the same types of machining operations -- milling, drilling, tapping, etc.
- Type: All parts of the same type, e.g., transmission housings.

Often, some of the part families contain enough work content for a normal size FMS, and the decision will be to decide which one would be best. The drawback to this approach is that the most economic combination may include parts from a number of families. However, if each family consists of many parts, it may be possible to choose the family which has the most potential for FMS savings, and continue the preselection and selection processes on that family only.

The preselection of machines depends more on preferences than hard constraints. The class(es) of parts chosen will limit the classes of machines, as will the range of machining cubes chosen. Average accuracy requirements must also be considered, as well as part materials. Finally, familiarity with certain types of machines, say horizontal machining centers rather than vertical ones, can also be used to limit the number of candidate machines.

The net result of the preliminary planning pass for the FMS is a feasible set of parts and a set of machines from which everything unsuitable has been removed. These pared down sets provide the material for more detailed analysis and prepares for the next step -- approximate economic justification.

2.2.4 Data Collection

For both manual and automated part machine selection, the next step is to construct a data base (with the following components) for the parts/machines that are now under consideration:

1. Process-routing and operation data. At the planning stage, the following data will be required for each candidate part:

   - Routing Sequence -- The machine classes (e.g., lathes, machining centers -- standard-precision, high-precision, -- etc.) the part must visit to be machined, and the proper manufacturing sequence.

   - Estimate of total process time on each machine class.

   - Fixturing concepts and fixturing times.

2. Current Manufacturing Costs. Manufacturing costs can be estimated from the current cost of buying the part or from the components of in-house cost -- direct labor, overhead, etc. -- for each candidate part. Alternatively, the hourly machine rate cost used to quote jobs can be used. Neither of these cost concepts should include any reference to capital recovery costs or depreciation; they should strictly reflect daily operation cost. The manufacturing cost per part is then simply the machining time per part (MT) plus the setup time prorated over the part batch size (SU/BS) multiplied by the machine rate (MR) or shop labor rate (DL) modified by the applied overhead (OH), all multiplied by the part's annual production volume (P). That is:

$$\text{ANNUAL MANUFACTURING PART COST} = \left[MT + \frac{SU}{BS} \right] \times MR \times P$$

$$= \left[MT + \frac{SU}{BS} \right] \times DL \times OH \times P$$

2.2.5 FMS Manufacturing Cost

To be able to estimate the savings due to the use of an FMS, the approximate annual FMS manufacturing cost must be known to apply to the time the part will be in the FMS. Nominally, this time is the machining time plus the load and unload time required for each fixturing of the part, multiplied by the part's yearly production requirement. This cost can only be approximate due to the assumptions made as to manpower requirements, machining time, and load/unload time (fixturing time). Based on system size, it is possible to roughly estimate the manpower requirements. Required are a system manager, 0.25 electrical technician, and 0.25 mechanical technician for every four machines in the system. Depending upon the number of tools that might be required in the system (60 tools per machine is a good rule of thumb), 0.5 to 1.0 tool setter will be needed for every five machines. Finally, if part cycle times are short or there are many fixturings for each part, at least two loaders will be required.

When estimating manpower requirements, the labor rate and overhead to apply to the system should be determined. In the simplest case, conventional direct labor cost plus overhead or the machine rate can be used. However, this usually does not provide sufficient overhead allocation because the overhead rate was based on the assumption of one man per machine, which is not the case with the FMS. It is often necessary to work with the accounting department to develop the direct labor rate and applied overhead rate for the particular situation.

Assumptions about machining time are easier to make. In the simplest case, assume that the cycle times in the FMS equal those in the conventional method. This is reasonable if the parts are currently produced on NC machining centers using palletized fixtures and pallet shuttles. If standard NC machining centers and job shop type temporary fixtures are used, up to 25% of the cycle time can be expected to be saved by changing to an FMS. In the case of conventional manual machines (especially if the equipment is old), a 50% savings in cycle time may be reasonable.

Fixturing time is the easiest of the assumptions to make. Although in reality the number of fixturings varies with each part, assume that, on average, each part requires two fixturings and each fixturing requires 8 minutes - 5 minutes to load and 3 to unload.

For the computerized selection method, an estimate of the amortized cost of fixtures is needed. This must be done for each part, as fixture complexity can vary widely from part to part. The amortized cost is a yearly value which represents the annual cost to the company for buying that fixture, based on some estimated rate-of-return (i) at which the company could have invested the money in some other project. Fixture prices (1982) range from approximately $4,000 for very simple fixtures to $15,000 to $20,000 for very complex window frame fixtures and pedestal fixtures. The number of fixtures and their costs are estimated and then amortized over the production life of the part at a chosen corporate rate (i). As an equation:

$$\text{AMORTIZED (ANNUALIZED) COST (AC)} = \frac{\text{TOTAL FIXTURE COST} \times i \times (1+i)^N}{(1+i)^N - 1}$$

where N is the part's production life.

This completes the basic elements of FMS manufacturing cost. The annual manufacturing cost per part on an FMS is then:

$$\text{ANNUAL FMS PART COST (AFPC)} = (MT + FT) \times P \times W \times (DL \times OH) + AC$$

where:

MT = Machining time

FT = Fixture time

P = Annual production rate

W = Number of workers

DL = Direct labor rate (in the same units as production time)

OH = Overhead rate

AC = Amortized fixture costs

2.2.6 FMS Machine Cost Data

It is now necessary to choose actual machines for each chosen machine class and determine their cost. This involves going to various vendors for quotes on the machines. It is best to choose a number of vendors in each class, as well as a number of sizes in each class.

To use the automated part and machine selection algorithm described as follows, it is necessary to know not only the cost of the machine but the amortized cost of that machine plus the remainder of the system -- MHS, computer control, tools, etc. This is accomplished by estimating the cost of the remainder of the system (based on system size) using the component costs from FMS vendors, amortizing that cost over the expected life of the system (usually 10 years), amortizing the cost of the machine over the same period, and adding the two annual costs together. The amortization equation is the same as for fixture amortization, but the concept of salvage value now comes into play. At the end of the useful life of the equipment, it may be of value to someone else and it can be sold. The equation now becomes:

$$\text{AMORTIZED COST} = \frac{(IC - SV) \times i \times (1 + i)^N}{(1 + i)^N - 1} + (SV \times i)$$

where:

IC = Investment cost

SV = Salvage value at year N

N = Production life

i = Investment interest rate

For each chosen machine, the value used in the program equals the amortized cost of the machine plus the amortized cost of the rest of the system (a constant for the size of system chosen).

2.2.7 Part and Machine Selection

At this point, the current cost to manufacture or buy each part is known, as well as the estimated FMS manufacturing cost for each part. Also, specific prices for machines in each FMS machine class (or an average price for a representative machine in each class) have been obtained. The next step is to actually select parts and machines for the FMS. Although the selection theory is the same, its implementation differs for the manual and automatic selection methods. The procedure for manual selection will be discussed first, followed by the automatic selection method.

To begin the manual selection process, a set of machines must be chosen from the available machine classes. This selection can be arbitrary, or it can be based on the current production equipment used to produce some of the parts. The number of machines from each machine class is somewhat arbitrary; however, the total number of machines should equal the maximum set by management at the beginning of this process.

Choose parts to load these machines in the following manner. For each part, subtract the FMS manufacturing cost from the conventional part cost to obtain a value for the cost savings for each part. Then begin loading the machines with the parts having the largest values. Base the available machine time on annual production hours available (two or three shifts, five days a week, fifty weeks per year) multiplied by an availability or efficiency factor (usually between 0.65 and 0.8, or 65% to 80%) to account for downtime, preventative maintenance, etc. The part cost savings and production time is already in annual values, so questions of sufficient aggregate production volumes are answered positively if the machines can be fully loaded. If two parts have equal savings, the one using the least machining time is usually better, so compare the machining times as well as the savings when choosing parts. Continue to choose parts until all machines are loaded or there are no more parts. Add up the savings for all of the parts chosen.

To use the computerized part machine selection algorithm, simply arrange the conventional production costs for each part, the FMS costs for each part, and machine prices into computer files for the computer-based Part and Machine Selection (PAMS) program to use. (PAMS, is discussed in detail in Volume V.) The program also requires the maximum system size (number of machines) desired and the annual number of production hours available, again adjusted by an availability factor. PAMS will then choose the best combination of parts and machines possible from the candidates and compute the total savings resulting from that combination.

2.2.8 Investment Analysis

To determine if an FMS is a viable production alternative, the relative ROI capital must be determined. This is accomplished by performing an investment analysis, described in detail in "Economic Analysis" on page 47. Briefly, the total system investment -- chosen machine cost plus average MHS and computer control costs -- is compared to the savings that system generates, considering taxes, depreciation, etc. The minimum acceptable ROI, as well as values for taxes and depreciation, must be obtained from the company's financial staff. Many companies have a minimum acceptable ROI value of approximately 25%, which translates into a 3-1/2-year payback period after taxes. However, this number is subject to change if the company's strategic objectives (such as maintaining competitive advantage) suggest it.

This ROI figure provides a figure-of-merit for the success of the manual part and machine selection approach. For the automated selection approach, this figure represents the best ROI that can be expected from the candidate parts and machines, and it can be used to decide whether to continue the project to a more detailed design level or to look at another production method. No matter which approach is used, however, the investment analysis results represent approximate values only.

2.2.9 The Iterative Manual Selection Process

The manual part machine selection technique only analyzes one combination of parts and machines at a time. Thus, the procedures discussed in "Part and Machine Selection" on page 20 and "Investment Analysis" need to be repeated a number of times, altering the parts and machines, until the "best" ROI is found.

2.2.10 Example Case Study

The following sections illustrate the automated part machine selection approach with a brief description of its application at the U.S. Army Arsenal at Rock Island, Illinois. A detailed discussion of this preliminary study can be found in Volume IV.

2.2.10.1 Description

Rock Island Arsenal is a batch-type metal parts manufacturing facility. The Arsenal uses 2,000 machine tools, including 50 NC machines, and employs a labor force of 650 workers for metal fabrication processes. The primary purpose of Rock Island Arsenal is to provide industry with sufficient lead time, if war is declared, to tool up their facilities for production of various armament parts. The required lead time is about 200 days. In wartime, Rock Island would manufacture 21 mobilization end items. In peacetime, there are only nine end items.

2.2.10.2 Work Content Distribution Study

The end items produced at Rock Island in peacetime include gun mounts, recoil mechanisms, machine guns, towed artillery and spare parts with monthly rates in the 1 to 106 range, though most of the items fall in the 10 to 20 per month range. There are a large number of parts, a total of 3,338 active part numbers, to be manufactured.

An analysis of the part work content distribution was made to distinguish work suitable for prismatic FMSs and work suitable for conventional rotary machines. The purpose of this study was to give an assessment of the relative significance of various types of machining systems (i.e., rotary or prismatic FMSs). The results showed that prismatic, FMS-compatible work content ranges from 38.53% to 61.76% of the overall machining work content for the nine end-items. The study, therefore, indicated a significant potential for FMS application.

Before a Group Technology classification and coding system was installed at Rock Island Arsenal, routing files alone were used to select parts for possible manufacture on an FMS. The routing of each of these parts and the manufacturing processes involved are contained in computer files. The files include a machine code (which indicates the type and size of machine used) for each operation to produce each part. The FMS-compatible processes included milling, boring, drilling, tapping, and some turning of disk-shaped parts. If the process routing files indicated that a part was processed on these types of machines, it was an initial FMS candidate.

If the part was processed by any of these machine groups and then by some other group, it was assumed to exit the FMS. If the reverse was true, it was assumed to enter the FMS. The total number of entries and exits from the FMS were counted from the process routing files. If they were numerous (three or more), the part was assumed not to be compatible with the FMS. Also, the total time spent on the FMS-compatible machines was accumulated to identify a maximum possible FMS work content.

2.2.10.3 Machine Classes

After viewing the Arsenal machines in operation and discussing them with the Arsenal personnel, the list of the FMS-compatible machine groups was finalized. Overall, 109 machine groups were listed as FMS-compatible, mainly in the categories of the milling, drilling, boring, and other hole-making operations, with two main exceptions. First, all deep-hole drills were eliminated because all of these are gun drills wherein the work, not the drill, rotates. Second, most planers were eliminated because they are used for very long parts.

In addition, the classes of machines for the proposed FMS were defined. Four classes with 10 models were selected. They were machining centers of small, medium, and large size; precision boring modules of small, medium, and large size; multiple-spindle modules of medium and large size; and vertical turret lathes of medium and large size.

2.2.10.4 Part Data Modification

A conservative approach was taken for the modifying the part processing data, compared with the "rules-of-thumb" proposed previously. Speciifically, the machining times were not decreased for the movement from stand-alone machines to FMS machines. Also, instead of assuming two setups (fixturings) for each part (at a total of 8 minutes each), an attempt was made to estimate the actual number and duration of the FMS setups for each part as follows. (The details of these modifications are described in Volume IV.)

2.2.10.5 Results of Part/Machine Selection

The data on parts and machines were processed using the software package PAMS (see Volume V) a number of times with different constraints on the number of FMS machines. Example outputs are shown in Figure 11 on page 25.

This case study illustrates that minimal part and machine data are required in order to use PAMS to determine whether FMS technology might be economical. From the economic output -- payback period, for example -- it can be decided to continue examination of the parts or to conclude the feasibility study. As illustrated, PAMS indicated that FMS technology has the potential for successful application to Rock Island Arsenal manufacturing. Based on this information, the decision was made to continue with a more detailed study.

No. of Machines in FMS	Machine Class: Machining Center small	Machine Class: Machining Center medium	Machine Class: Machining Center large	Machine Class: Vertical Turret Lathe	No. of Parts Selected	Cost Savings ($k/yr)	Total Cost of System ($k)	Pay Back Period (years)
20	5	7	7	1	229	3960	12,400	3.14
10	2	2	5	1	93	2532	7400	2.92
8	1	1	5	1	80	2136	6600	3.08
5	0	0	4	1	57	1536	5000	3.26
3	0	0	2	1	21	1128	3400	3.01

- Number of candidate parts = 1248
- Tool slots/machine = 60
- One shift operation

Figure 11. Sample Solutions for Rock Island FMS

2.3 CONFIGURATION DESIGN

This section describes FMS implementation Step 2 (Figure 12 on page 27 and Figure 13 on page 28 summarize these steps). FMS configuration design issues are discussed "Configuration Design Issues" on page 26. This is followed by a recommended configuration design method "Configuration Design Procedure" on page 35 and and a configuration design example ("Configuration Design Example: General Electric FMS" on page 36).

2.3.1 Configuration Design Issues

When the parts and machine types have been selected, it is possible to proceed to the system design process. There are several issues involved:

- Flexibility.
- MHS configurations.
- Machinability and process planning.
- Required accuracy.
- Required system availability.
- Tool-changer capacity.
- Other processes (inspection, heat treatment, finishing, etc.).

2.3.1.1 Flexibility

Flexibility in an FMS has many aspects. The most important of these is the random-processing capability which allows more than one part number in the system at one time. Usually, ratios of part types to one another can be arranged to meet current production needs, allowing rapid adaptability to changing market requirements. An FMS is also relatively insensitive to engineering design and tooling changes.

Some FMSs exhibit flexibility of a second type: fault tolerance. They continue to operate almost normally in the presence of machine failures, with other machines "covering" for the one out of service.

A third type of FMS flexibility is the ability to operate virtually untended. Maintenance and part fixturing can be performed during the first shift, while much of the actual production occurs during the second and third shifts.

Desired flexibility affects FMS design. Untended second- and third-shift operation implies some automatic, in-line inspection. Very high system

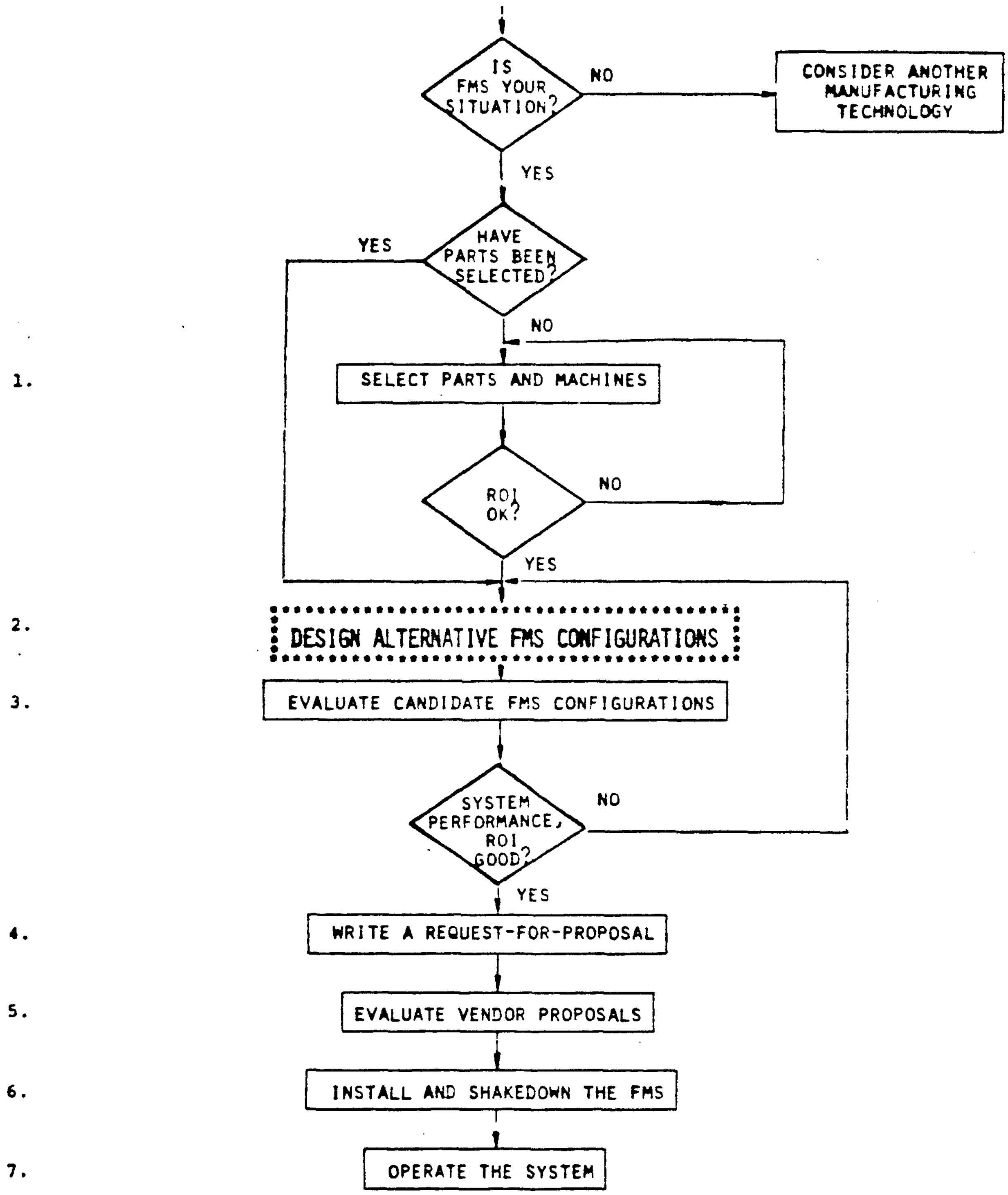

Figure 12. Acquisition of an FMS: Step 2

DESIGN ALTERNATIVE FMS CONFIGURATIONS

1. Estimate the Work Content of the Selected Parts

- Develop FMS fixturing concepts for the selected parts, minimizing the number of fixturings.

- Process plan each part in detail, constrained by the limited tool capacity of an FMS and the effects of using different machines (roughing and finishing machines, for instance) on overall accuracy and cycle time.

- Determine the appropriate machinability data for each material for each class of operation (rough milling, semifinish boring, etc.).

- Estimate production requirements for each part.

- Calculate part cycle times and tool usage (see Volume V for the Cycle Time (CTIME) software package to aid in the calculations).

2. Design Several Equipment Configurations

- Choose specific vendors' equipment in each machine class; temper with company biases (toward horizontal rather than vertical machining centers, for example).

- Estimate the minimum number of machines (spindles) for each machine class.

- Modify this number of machines to account for shop and system efficiency, limited tool storage capacities, and desires for machine redundancy.

- Add an MHS and other desired nonmachining processes, such as an inspection machine, to complete the configuration.

- Layout the equipment and MHS.

- Develop alternative design configurations from the original design.

- See Volume IV for a configuration design example.

Figure 13. Steps in FMS Implementation: Step 2 (Part 1 of 3)

- Develop the data required to estimate work content:

  a. Per part:

     - Production requirements (units per ship set, etc.).
     - Material.
     - Operation classes (rough milling, finish turning, drilling, tapping, etc.).
     - Manufacturing operations (process plans).
     - Tool diameter and number of teeth.
     - Length of cut.

  b. For each combination of material and operation class:

     - Machining speed, surface feet per minute.
     - Feed, inches per tooth or inches per revolution.
     - Machinability rating or power factor.

  c. For each potential FMS machine:

     - Maximum spindle speed, revolutions per minute.
     - Maximum tool feed, inches per minute.
     - Horsepower.
     - Chip-to-chip tool-change time, seconds.
     - Average rapid traverse time between repeated operations, seconds.

Figure 13. Steps in FMS Implementation: Step 2 (Part 2 of 3)

- Rotary table speed, degrees per second.
- Pallet shuttle time, one way (on or off machine), seconds.
- Data required for configuration design:
  a. Specific equipment from different vendors in each machine class.
  b. Options on that equipment, such as maximum tool-changer storage capacity, pallet shuttles, spindle probes, broken tool sensors, adaptive controls and diagnostics.
  c. Accuracy of each machine.
  d. Specific MHSs. (Most often, each machine vendor will have one or two MHSs available, matched to his equipment.) Specific inspection equipment, wash stations, tool-room equipment.
  e. Shop efficiency factor

Figure 13. Steps in FMS Implementation: Step 2 (Part 3 of 3)

availability implies not only reliable machines, MHS, and computer but possibly redundancies, such as back-up computers, duplicate machine types, and alternative routings in the MHS.

Flexibility affects other design features. If an FMS is expected to handle a very wide range of part types, the machines will have fairly general characteristics such as five-axis capability, reasonable precision, more than minimum horsepower, etc. A requirement to accommodate several part numbers simultaneously (without batching) implies large tool-storage capacities.

A related aspect of flexibility is the expandability of the system to accommodate future increases in demand or allow a "phased" installation - to maintain machine utilization over time and/or to prevent overtaxing the available capital. The degree of expandability desired will affect the choice of MHS and the arrangement (layout) of equipment in the configuration.

Flexibility is desirable, but it may increase cost. By the same token, too many special-purpose machines will hamper a system's ability to handle new part types. Yet, specialized machines, such as multiple-spindle head-changing units, may be needed to increase system throughput, thereby reducing the cost per part. Since future requirements can never be predicted with certainty, it is necessary to rely upon judgement, not just a cost/benefit analysis, to resolve the issue of flexibility.

2.3.1.2 Machinability and Process Planning for an FMS

Basic data about how the workpiece can be processed is crucial. When treated lightly, it has caused serious problems in several installations. One company overestimated feeds and speeds, resulting in poor surface finish, rapid turnover of tools, and finally, a 25% reduction in system throughput. Another company used the wrong material condition when obtaining machinability estimates from tables in the <u>Machining Data Handbook</u> (published by Metcut Research Associates, Cincinnati). Compounded by some other data mistakes, this error underestimated the cycle times of the parts by one half to one third, and correcting the situation resulted in a reduction in system throughput of 75%.

A logical approach to defining machinability data is to first obtain the optimum feeds and speeds for the part materials for each tool category from a machining data handbook. Then, the machine operators should be asked what feeds and speeds they routinely use when machining those same materials. The FMS feeds and speeds that should be used will fall between these two values, adjusted for part rigidity, the ability of dedicated fixtures to hold the parts better than standard component-built fixtures, and the use of new machine tools, perhaps with adaptive control to maintain optimum cutting parameters.

During the FMS configuration design, a change in feeds or speeds for a tool necessitates recalculating machining time for all the parts using that tool; if there are many parts, this revision process can become extremely time consuming (if done manually), especially if many alternatives are evaluated. The recalculations can be simplified by using a computer program to calculate cycle times, such as the CTIME program described in Volume V. Where the metal's characteristics are well known, it is better to assess the accuracy of machinability data before beginning configuration design, temper it with normal shop practice, and attempt to hold that data constant throughout the configuration design exercise.

Process planning for an FMS is different than process planning for stand-alone machines. There are two areas of critical importance: the fixturing approach used for each part and the selection of cutting tools. In an FMS, it is important to minimize both manual and automatic handling of the part. Careful attention to fixture designs can help. The use of window-frame and pedestal-type fixtures allows the greatest amount of access to a part when using either four- or five-axis machining centers. (Try to use four-axis, X, Y, Z, and rotary-table machining centers whenever possible. The cost of five-axis machining centers can seldom be justified by the parts' work content that might require a tilting table or spindle.)

The goal is to have one fixture type per part type, in order to have only one load/unload sequence. While this is seldom obtainable, a considerable amount of time should be spent analyzing each part to determine its best fixturing attitude(s) with respect to the required operations and the machines. Then the fixture(s) should be designed to maintain that attitude(s). Also, by matching machine axes, it is possible to minimize the number of fixtures and fixturing. For example, if vertical turret lathes (VTLs) are being employed for the rotational work content, investigate the use of vertical machining centers for the prismatic work content.

Tool-storage capacity needs can be minimized by standardizing the tool selection during process planning. This is most noticeable in the choice of milling cutters. For example, a standard 2- or 3-inch diameter shell mill could be used for all milling operations, except where corner radius or pocket size may not allow it. Also, compound boring bars should be investigated, where more than one diameter and/or chamfers may be cut at the same time. These are "specials" and priced accordingly, but they save time in tool changes and the cost of the additional single-tip bars. Plus, they may provide better accuracy. Though more difficult, it may be possible to standardize drill and tap sizes and hole patterns throughout the part set, again reducing the number of tools to set, store, control and maintain.

Changes in process plans can require additional tools, refixturing or rotating of the part, or may even require a special machine in the system. As with machinability data, make sure process plans remain as constant as possible throughout the design phase.

2.3.1.3 Precision

With the recent trend toward tight tolerances (e.g., 0.001 to 0.0001 inch), otherwise typical parts can require accuracy unavailable from general-purpose machines normally well suited for inclusion in an FMS. The FMS buyer/designer is faced with a number of alternatives.

The first alternative is to request an increase in tolerance, although it is unlikely that all of the offending tolerances will be relaxed.

If high-precision machining is required, consideration should be given to the advantages and disadvantages of producing those features off-line. When evaluating the off-line option, consider the additional time required due to transportation, the control problems resulting from a part leaving the system and possibly returning, whether the part will have to be removed from its fixture/pallet, and the cost of purchasing a high-precision machine, which may be underutilized.

If it is decided that the work should be done on-line, a high-precision machine must be included in the system. Compatibility problems can be minimized if the system vendor also supplies the special machine. Alternatively, the supplier may be willing to customize general-purpose equipment to obtain the desired accuracy, if the cost can be justified. However, problems might arise from this approach; the untried design may have to be debugged as it is brought on-line, delaying production. Finally, if the vendor will not build a high-precision machine, the prime vendor may obtain one elsewhere and integrate it into the system.

If the on-line machine is to perform only high-precision machining, it may well be underutilized and add to the cost of the parts. If, however, normal machining work is assigned to the high-precision machine, care must be taken to prevent its overloading, possibly affecting the machine's basic accuracy.

Finally, consider the need for environmental control to maintain a stable atmosphere with which to obtain the desired accuracy. This may include temperature control of the FMS area, part/fixture/pallet temperature soaking, and coolant temperature conditioning. It may also mean temperature control of the inspection equipment.

2.3.1.4 Up Time

Machine availability (usually expressed as a percent) is the time during which a machine is not failed, i.e., the time it would be processing a part if a part were available. This availability is also called the "uptime" percentage.

The time to repair a machine is composed of several factors:

1. Time required to discover the failure.

2. Time required to call a maintenance person.

3. Time required to diagnose the failure.

4. Time required to obtain replacement parts.

5. Time required to actually make the repair and test for proper operation.

Consequently, there can be considerable variation in the repair times. The average or mean-time-to-repair (MTTR) a machine in an established FMS is likely to be in the range of 0.5 to 2.0 hours. The MTTR and the mean-time-between-failures (MTBF) for a machine defines the machine's average availability figure.

System availability is the percentage of time that none of the system components are failed, i.e., all machines, controllers, computers, the MHS, etc., are "up". Clearly, the average availabilities of the components of an FMS must be high if the average system availability is to be high. For example, if each of the 10 components of an FMS has an average availability figure of 98% (and if the component failures are assumed to be always independent of one another), then the average availability of the system will be approximately 82% (i.e., 0.98 x 0.98... ten times). Usually, however, one or two of the components have availability figures lower than the rest, and these figures are then the primary determinants of the system availability.

Of course, the failure of one machine does not always mean that all production ceases until it is repaired. In a well designed flexible system, production can often continue (at a reduced rate) while portions are under repair. Parts that normally visit the failed machine might be rerouted to other, similar ones if the appropriate tooling and part programs can be made available. Or, the affected operations might temporarily be performed off-line, e.g., manual inspection in the case of a failed automatic inspection station. In the case of failure of the central computer controller, the machines could be operated semiautomatically from their own controllers.

Therefore, it is important to not only specify highly reliable system components, but to also anticipate failures. A common design method is to incorporate redundancy in the system. This may mean that the system contains two or more machines of each type. Or it may imply machines backing up dissimilar machines, e.g., a machining center might substitute for a multiple-spindle machine. Redundancy in the MHS implies multiple part carriers (e.g., carts) and multiple paths between stations (in case certain links should fail). Obviously, there are tradeoffs between system redundancy, system complexity, component reliability, capital cost, and the cost of lost production.

2.3.1.5 Tool Storage Capability

Machines with large tool-changer storage capacity are generally chosen because they reduce the need for production batching and they can facilitate the processing of parts rerouted from failed machines.

2.3.1.6 Other Processes

How many processes, in addition to machining, should be done on-line and how much should be done off-line? These other processes include very high accuracy machining, washing, inspection, stress relieving, heat treating, deburring, finishing, marking and assembly. Except for washing and inspection, in general these processes should be kept off-line. A rule of thumb is that if the part must be removed from the pallet/fixture before starting an operation, that operation should be done off-line.

However, considering the control problems created by sending parts off-line (especially if the parts must be removed from their fixtures) and then returning them, in certain cases the cost of providing on-line equipment for some of these processes is justifiable, though the processes need not be automated. For example, a manual inspection station could be on-line.

2.3.1.7 Material Handling Systems

The simplest MHS consists of a person and a cart, manually moving palleted parts from machine to machine under computer direction. (According to some definitions, such a system would not qualify as a true FMS due to the nonautomated MHS.) To reduce machine waiting times, a shuttle loader can be added to each machine tool. This manual system will work for small FMSs, where the distance between machines is short and where parts are relatively small and light. However, for larger systems and/or heavier parts, automatic MHSs are more applicable. These systems consist primarily of carts, conveyors, or robots that carry pallets automatically to and from each shuttle loader. If the loader is full, the pallet will circulate in the MHS, wait in front of the machine, or go to an off-line buffer storage area. At present, a person is usually required to fixture and defixture parts at load/unload stations (the Japanese have successfully used a robot in some applications), but the rest of the system is under direct computer control.

The choice of MHS type is somewhat restricted in practice. Most FMS vendors have designed their systems around one, or at most two, types of MHSs.

2.3.2 Configuration Design Procedure

The design of an FMS configuration is a four-step process. The steps are:

1. Based on the work content of the parts or the recommendations of the part/machine-selection algorithm (if used) and company biases (toward horizonal-spindle rather than vertical-spindle machining centers, for example), choose specific vendors' equipment in each required machine class (horizontal or vertical lathes or machining centers, standard

or high-precision machines, etc.) with sufficient horsepower and accuracy to produce the parts selected.

2. Using the work content of the selected parts, production requirements, available work hours, and data about the chosen equipment, estimate the minimum number of spindles -- or the number of machines in each class -- necessary to obtain the production goal.

3. Modify (increase) the number of machines in each class, including inspection machines, by taking into account machine and system efficiency, limited tool capacities, desires for redundancy, and machine-loading decisions with respect to any high-precision machines. (This adjustment could be done intuitively or with the help of the Mean VAlue Analysis of Queues (MVAQ) software package based on the queueing theory described in Volume V.)

4. Add an MHS, wash stations, and other nonmachining processes to complete the configuration design.

From this point on, the design process is more aptly named the "design and evaluation process", because of its iterative nature, i.e., design, evaluate, redesign, etc.

2.3.3 Configuration Design Example: General Electric FMS

General Electric Ordnance Systems Division (GEOS, Pittsfield, Massachusetts) currently purchases 11 machined parts from outside sources. The following paragraphs summarize the preliminary results of an on-going study performed to determine the advantages and disadvantages of producing these parts in-house on an FMS. (This design example is presented in more detail in Volume IV.)

The parts are aluminum and have numerous thin cross sections. They are prismatic, can be machined in a 24-inch cube, and have an initial production rate of 600 each per year. These attributes led the Advanced Manufacturing Engineering staff at GEOS to consider purchasing an FMS to produce the parts.

The first step in designing an FMS was to develop the work content (process plans) for each part. Planners at GEOS immediately found that developing the process plans for all 11 parts and recalculating them for changes in machinability or machines would be tedious. A machine cycle time calculation program (CTIME) was created (see Volume V), incorporating standard feed, speed, and time equations, yet allowing changes in machinability data, machine parameters, and machining elements. It facilitated rapid examination of the effects of such changes, especially during machinability experiments and when comparing different machines with different automatic tool-changing times.

To minimize setup time and the number of setups, the planners assumed the parts would be machined in "window-frame" fixtures mounted on pallets, allowing access to at least four sides of the parts. The planners then entered the machining elements for each part into the computer, along with tool information, machinability data, and average machine tool data. The CTIME program estimated the cutting time, dead time (tool change, travel, part rotation, etc.), and total time for production, as well as the machine spindle speeds and feeds.

They found that, assuming the equipment would be used two shifts during each workday, there were two spindles' worth of work content at the present production rate for the 11 parts. Additionally, approximately 30% of the work content required high-precision machining (tolerances of less than ± 0.0005 inch). This information was used to develop the configuration alternative matrix illustrated in Figure 14 on page 38. The types of MHS are shown on the vertical axis and the types of machines are shown on the horizontal axis. Thus, each box represents an FMS configuration consisting of specific machines and a specific MHS.

In the matrix, configuration I,0 is a common job shop and is the present manufacturing method. The other alternatives represent compromises in FMS design issues, such as precision, redundancy, and manpower reduction. Column A consists of configurations with one NC general-purpose machining center and a number of manually operating precision boring mills. Note that the required number of boring mills is less in column A than in column 0 because time is saved by setting up the parts on pallets rather than on the machine beds.

Some of the obvious characteristics of this alternative are as follows. System maintenance requirements are principally for standard mechanical failures of the machines; little electronics or NC skill is required. At least four precision boring mills are needed to satisfy production requirements, resulting in high capital expenditure to perform 30% of the work content. Significant time will be used transporting parts from the general-purpose NC machine to the high-precision machines. Finally, while there is redundancy in the manual boring mills, none exists for the NC machine. If that machine fails, production will cease or the highprecision machines will be required to do general work, greatly reducing production and possibly damaging the machines.

Column B consists of configurations with one NC general-purpose machining center and one NC high-precision machining center. These configurations share many of the problems of those in column A. Manpower is reduced (fully automatic operation is feasible), but there is no redundancy, and high accuracy is more difficult to maintain without manual intervention. Redundancy can be created by adding a second machine of each class, but that would be extremely expensive since two machines can handle all the work. Compatibility of equipment becomes a concern, since not many manufacturers produce both standard and high-precision machining centers. Controls, pallets, and tooling can be different, and often one manufacturer will hestitate to interface another's equipment with his own. Maintenance requirements also increase.

Column C consists of configurations with two high-precision machining centers, and the configurations assume that the machines are sturdy enough to be unaffected by roughing work. If this assumption holds true, many of the design problems mentioned previously are solved. There is full redundancy, no compatibility problems, little manpower required, and no trans-

		Bolted Fixtures	Palleted Fixtures		
	Machine / Material Handling	O GP Mach Center (1) Precision Boring Mills (6)	A GP Mach Center (1) Precision Boring Mills (4)	B GP Mach Center (1) Precision Mach Center (1)	C Precision Mach Center (2)
MANUAL	I Manual	Job shop			
AUTOMATED	II Carousel Loader	(N.A.)			
AUTOMATED	III Line (conveyor or cart)	(N.A.)			
AUTOMATED	IV Loop (conveyor or cart)	(N.A.)			

Figure 14. GEOS FMS Configuration Alternatives

portation time from machine to machine. Accuracy is still more difficult to obtain than with manual intervention, however, and maintenance still requires highly skilled electronics and mechanical workers.

To each of these configurations, various methods of material handling would be added. Inspection equipment, wash stations, and so on, complete the designs. The evaluation of configuration designs is discussed in the next section.

2.4 EVALUATING CANDIDATE FMS DESIGNS

"Configuration Design" on page 26 discussed the design of a variety of FMS configurations. This section describes how these configurations can be compared with respect to cost, throughput, reliability, accuracy, and ROI. This is Step 3 of the FMS implementation process (Figure 15 on page 40 and Figure 16 on page 41).

Evaluation of a number of alternative FMS configurations should be performed using a systematic, step-by-step approach. A systematic evaluation technique is presented in this section; the steps may be summarized as follows:

1. Construct an evaluation matrix showing all factors considered important to the evaluation of each configuration.

2. Develop operational strategies -- batching, balancing, scheduling, and dispatching rules to provide realistic input data to the simulation and economic analysis.

3. Simulate the operation of the configuration, noting performance measures for the economic analysis and for comparison to alternative configurations.

4. Improve the design or create a new design, repeating the steps in "Configuration Design Procedure" on page 35.

5. Repeat steps (1), (2), and (3) until a variety of design configurations have been examined.

6. Examine the configurations with respect to investment analysis; estimate their ROI and payback period.

7. Complete the evaluation matrix, and choose the configuration having the best rating.

2.4.1 Evaluation Matrix

A very useful means of organizing the configuration evaluation is to construct a matrix such as that illustrated in Figure 17 on page 44. Across

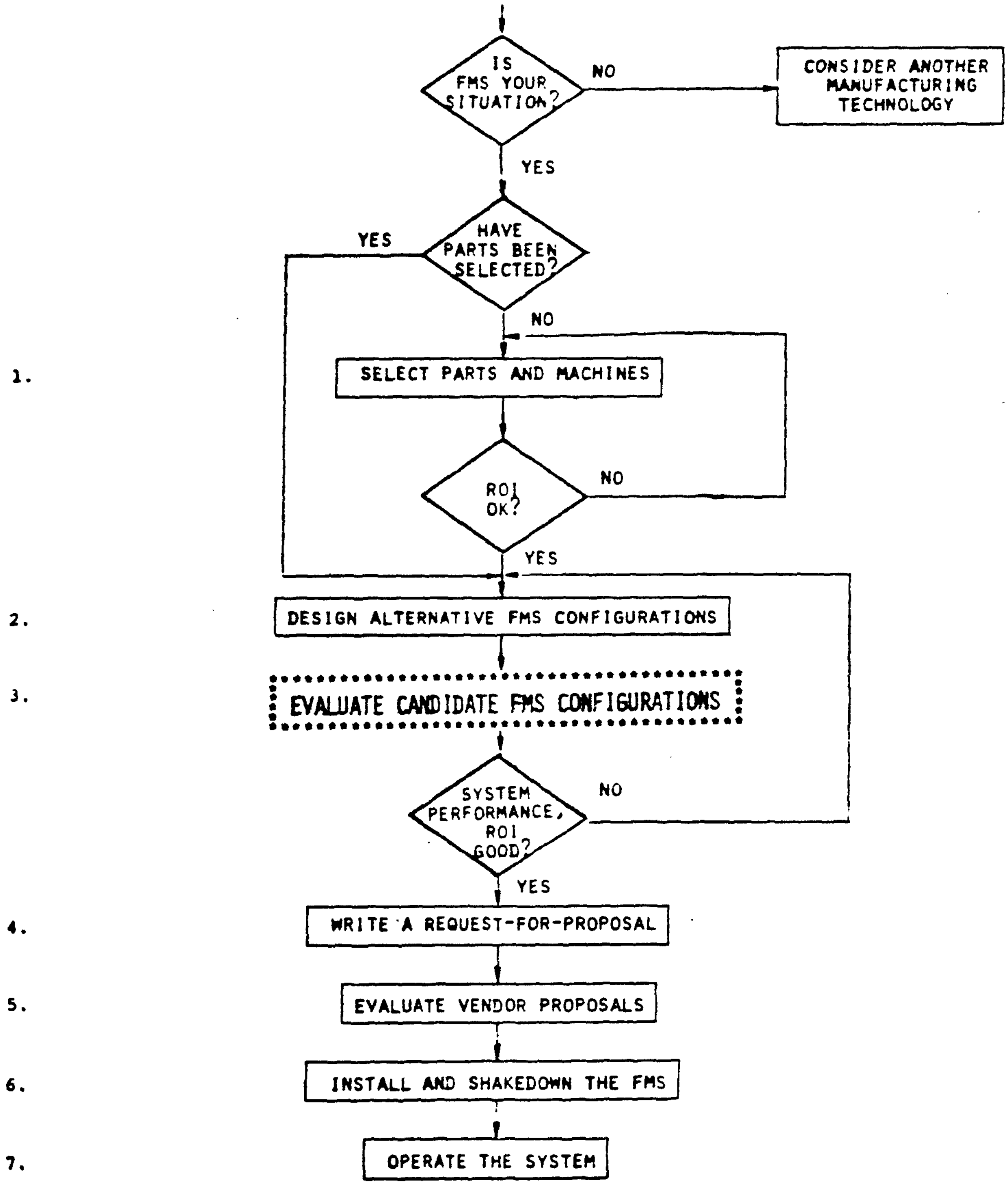

Figure 15. Acquisition of an FMS: Step 3

EVALUATE CANDIDATE FMS CONFIGURATIONS

- Simulate the operation of each configuration based on predetermined scheduling, batching, and balancing rules to provide performance measures for each configuration.
- Improve the configuration designs until each provides satisfactory performance measures or is rejected.
- Perform a detailed investment analysis of each configuration.
- Examine and evaluate intangibles, such as flexibility, accuracy, etc.
- Choose the configuration which best satisfies the investment and intangible analyses.
- See Volume V for simulation and investment analysis software packages.
- Data required for configuration evaluation:

  1. Per part:

     - Routing between machines (primary and alternatives).
     - Run time at each machine.
     - Number of unique fixture types.
     - Quantity of each fixture type.
     - Number of tools at each machine.
     - Inspection time.
     - Fixturing and defixturing times.

  2. For simulation:

     - Part data.
     - Layout of configuration -- number of stations for each machine type, load/unload, inspection, wash, and storage.
     - Part routings (primary and alternative) based on batching, balancing, scheduling strategies.
     - Travel time between stations.
     - Production requirements.
     - Available production time.
     - System efficiency factor.
     - Material handling operations logic.
     - Failure rates per machine and MHS (optional).
     - Maximum number of pallets/fixtures in the system at one time.

Figure 16. Steps in FMS Implementation: Step 3 (Part 1 of 2)

3. For economic analysis:

- Part cycle times (from simulation).
- FMS manufacturing costs per unit time (direct labor, overhead).
- Number of batches needed to meet production requirements.
- Number of workers used to change system over at end of batch.
- Production time lost due to batch changeovers.
- Number of full-time workers in the FMS.
- Total investment including:
  - Machine tool costs.
  - Inspection machine costs.
  - Load/unload station costs.
  - Material handling system costs.
  - Computer costs.
  - Fixture costs.
  - Pallet costs.
  - Cutting tool costs.
  - Part programming costs.
  - Engineering costs.
  - Installation costs.
  - Spare part costs.

- Depreciation schedule.
- Investment tax credit.
- Tax rate.
- Minimum acceptable ROI.

4. For intangibles:

- Weighting scheme: A subjective scale applied to the evaluation criteria indicating their relative importance.
- Rating scheme: A scale (from one to five, for example) showing the degree of compliance of any configuration to any criterion.

Figure 16. Steps in FMS Implementation: Step 3 (Part 2 of 2)

the top of the matrix, list the configuration designs. Down the left-hand side, list the important evaluation criteria. For each criterion, determine a value that indicates that criterion's relative importance to the other criteria, say a number from one to five. This then becomes the criterion's weighting value. Considerable judgement must be used in selecting and weighting the evaluation criteria. It is important to achieve an organization-wide concensus as to the criteria and their relative importance. This involvement will also help gain organization-wide FMS acceptance.

At the same time, a rating scheme should be developed to indicate the degree of compliance any configuration has to any criterion. This can also be a number from one to five, for instance.

Eight important criteria are:

- Cost.
- System throughput.
- Predicted system availability.
- System flexibility, particularly the ability to adapt to changing part types.
- Effectiveness in handling problems of precision, if any.
- Tool-storage limitations and the resulting requirements for batching.
- Redundancy.
- Surge capacity.

Each configuration will have two numbers associated with each criterion; the rating value and the "score". The score equals the weighting value of the criterion multiplied by the rating value of the configuration for that criterion. High scores are associated with high compliance with important criteria.

After the matrix is complete (all configurations have been evaluated), the scores for each configuration are summed. The configuration with the highest total score should be the most acceptable configuration. An example of the use of the evaluation matrix for General Electric is provided below in "Evaluation Matrix: General Electric FMS Configuration Evaluation" on page 54.

The following sections attempt to illuminate the steps in the evaluation process by suggesting approaches to defining operational strategies for the configurations, simulating the configurations, analyzing the economics of each configuration, and finally choosing one of the alternatives.

	Poor		->		Excellent
Ranking:	1	2	3	4	5

	Not Important		->		Very Important
Weighting:	1	2	3	4	5

Criteria	Weighting	Configuration A	B	C
Shipset Production Time				
System Availability				
Redundancy				
Precision/Accuracy				
Flexibility				
Tool Capacity				
Cost/ROI				
Inspection				
Surge Capacity				

Figure 17. Evaluation Matrix: Configuration Design Evaluation

2.4.2 Operational Strategies

Two concepts are important to the optimal loading of an FMS:

- Batching and balancing.
- Scheduling and dispatching.

These strategies are formulated in general at this point in the evaluation process to provide realistic machine loading data for simulation of each configuration.

2.4.2.1 Production Batching and Machine Balancing

Production batching, the division of production into subgroups or lots, is necessary when tool storage capacity limitations do not allow all the desired parts to be machined in an FMS at one time. Occasionally, balancing the workload on the machines may be so difficult that batching is required.

Balancing the workload on each machine tool attempts to maximize machine-tool utilization as well as relieve or avoid potential bottlenecks in the system, with the intent of maximizing system throughput. Often, however, it will not be possible to balance everything. This is especially true in systems with different types of machines, e.g., general-purpose machines and specials.

Balancing can also be difficult where a large number of tools are needed for certain parts. The division of work content and tool-changer storage limitations are crucial. Additionally, if parts are required to visit a number of machines, the effects of transport time and MHS congestion may reduce system throughput.

Optimization software use greatly reduces the need for trial-and-error batching and balancing for simulation. Batching and balancing theory and software are described in detail in Volume V.

At the completion of the batching and balancing exercises, specific parts and tools will have been allocated to specific machines in an attempt to maximize system throughput. This "optimum allocation" process is in reality iterative; the allocation provides realistic information for the simulation. The simulation results indicate the "goodness" of the allocation and may suggest modifications which can be resimulated.

2.4.2.2 Scheduling and Dispatching

The strategies for batching and balancing must be implemented systematically through scheduling algorithms and dispatching rules. These allow parts to enter and leave the system in the proper sequence at the proper time. Although the rules are discussed in greater depth later (for the actual operation of an FMS), they must be determined at this point so that the simulations can be made realistic.

2.4.3 Simulation

After developing the strategies -- both for batching and for scheduling -- the second step in analyzing alternative FMS configurations is to obtain system performance measures. For general measures, e.g., system throughput, average time a workpiece is in the system, station utilization, etc., queueing models are usually a fast, inexpensive choice (see MVAQ queueing model software package, Volume V).

When compared with detailed simulations, queueing models are typically accurate to within 10%. For greater detail and random failure analysis, simulation models must be used. Both models are driven by the operational strategies plus part data, machinability data, and system data.

Typical output from a simulation includes:

- Performance measures, such as system throughput or average time to produce one set of parts, machine and MHS utilization, etc.
- System bottlenecks.
- System's reaction to machine or MHS failures.

2.4.3.1 Choosing a Queueing Model or Simulation Package

Typical queueing models and simulator characteristics as well as currently available FMS simulation software packages are discussed in Volume V. Some highlights are repeated here.

Options include purchasing so-called "generalized" packages, using packages currently in the public domain, or developing your own. FMS vendor packages, if available, will be tailored to their individual systems approach, and the buyer may need a different one for each company that proposes a system.

Simulation software may have been created around a certain class of FMSs, usually with a specific type of MHS (conveyor, tow-line carts, or carts on rails). When used to simulate another class of systems, the results must be suspect. General FMS simulation packages should be adaptable, ideally to evaluate a variety of MHSs.

System throughput, average production time per part set and the utilization of the machines, MHS and workers are usually all generated by the packages. However, queueing models and some simulators cannot model the effect of failures on these performance measures. Also, they may not automatically indicate the number of functional units (machines, carts, fixtures) necessary for optimum throughput.

On the other hand, too detailed a model can be both expensive and complicated to use. The most desirable simulation or queueing model would be one in which the level of detail could be tailored to a particular need.

2.4.3.2 Simulation Example: General Electric FMS Configuration Evaluation

This section summarizes the modeling and simulation of alternative configurations for the GEOS design example. Volume IV provides further details.

Three different simulation models were constructed in order to faithfully model the various MHSs. In all, 20 different configuration designs were simulated. The models were written in the discrete-event simulation language, Extended Control and Simulation Language (ESCL). In the design stage, part and machine data were first "preprocessed" using the CTIME program (Volume V) in conjunction with machinability data to calculate total operation times. A summary was used to batch the production and to balance each machine.

This information was then used with information on a particular MHS system to create an appropriate model for each of the alternative configurations. Simulations were performed for sets of 50, 60, and 90 parts for all 20 alternative configurations. A sample of the simulation output for one such configuration is illustrated in Figure 18 on page 48. Output information was collected for each of the configurations and organized to facilitate the economic analysis.

2.4.4 Economic Analysis

In "Parts and Machine Selection" on page 9, parts and machines were selected and an approximate economic analysis performed. In this section, the detailed analysis is performed which, if satisfactory, will be used to later justify the system to upper management. Techniques for system analysis using net present value and ROI are developed and described in detail in Volume V. In the following sections, the basic economic theory is described and then illustrated through the use of a case study. Of course, different organizations use different accounting methods so the information here must serve as a guide only.

OUTPUT FROM GEMOVER -- C2 #2 OF 3 BATCHES
2 MACHINES IN 1 GROUPS

*** INPUT DATA ***

SIDE	PART#	GRP 1
1	1	1642
2	1	1149
3	4	1668
4	4	1416
5	9	610
6	11	394

THIS OUTPUT ASSUMES THE FOLLOWING: THERE ARE 240 PRODUCTION HOURS AVAILABLE PER MONTH (300 ACTUAL HOURS WITH A MACHINING EFFICIENCY OF 80 PERCENT). THREE DIFFERENT LEVELS OF PRODUCTION ARE TO BE CONSIDERED; 50, 60 AND 90 SHIPSETS PER MONTH. EACH SHIPSET IS MACHINED IN 3.0 BATCHES DUE TO THE TOOL CHANGING CAPACITY OF THIS MACHINE CONFIGURATION.

38773 UNITS OF TIME FOR 10 SHIP-SET:ONE BATCH EACH
TIME PER SHIP-SET: 7753.9 (193.8 MIN)

TOTAL PRODUCTION TIME FOR 50. SHIPSETS: 9693.2 MIN
PORTION OF AVAILABLE HRS USED .673
PRODUCTION HRS LEFT: 78.4

TOTAL PRODUCTION TIME FOR 60. SHIPSETS: 11631. MIN
PORTION OF AVAILABLE HRS USED .807
PRODUCTION HRS LEFT: 46.1

TOTAL PRODUCTION TIME FOR 90. SHIPSETS: 17447. MIN
PORTION OF AVAILABLE HRS USED 1.211
PRODUCTION HRS LEFT: -50.7

PROCESS WAS STARTED 59 TIMES
MOVE WAS STARTED 120 TIMES
BUFFER WAS USED 0 TIMES
UTILIZATION OF WORKER .2228
UTILIZATION OF MOVER .7427

*** PRODUCTION OF PARTS ***

SIDE	SCHED	COMP
1	10	10
2	10	10
3	10	10
4	10	10
5	10	10
6	10	10
TOTAL	60	60

*** PALLET UTILIZATION ***

NO.	UTLZN
1	.981
2	.603
3	.927
4	.550
5	.593
6	.760

*** STATION PERFORMANCE ***

NO.	GROUP	UTLZN
1	1	.766
2	1	1.000

*** OPERATIONS COMPLETED ***

SIDE	GRP 1
1	10
2	10
3	9
4	10
5	10
6	10
TOTAL	59

Figure 18. Simulation Output

2.4.4.1 Economic Analysis Theory

There are three basic categories of FMS economic analysis: replacement, capacity expansion, and displacement.

In each of these categories, the annualized acquisition cost of an FMS is compared to other manufacturing alternatives, based on the difference in part manufacturing costs and capital invested.

Replacement analysis, often referred to as "cost reduction analysis", examines the replacement of current machines and technology with FMS machines and technology. This approach is used primarily when introduction of an FMS promises a significant reduction in manufacturing cost over the current method.

Capacity expansion (sometimes referred to as "cost avoidance analysis") examines the procurement of an FMS instead of additional stand-alone machines to either manufacture a new family of parts or produce a greater volume of current parts. This approach is also used instead of replacement analysis when the current machines made available by introducing the FMS can be used on other parts immediately.

Displacement analysis examines the displacement of current machines by an FMS to provide additional manufacturing capacity sometime in the future. This approach can be used when no additional capacity is needed presently but will be needed in the future, shifting the analysis emphasis from replacement to time-phased expansion or cost avoidance. Experience has shown that FMS justification using standard cost accounting procedures is most easily accomplished when additional capacity is required. The economic analysis software package discussed in Volume V can be used for all of these approaches.

Two economic modeling techniques, each with its own advantages and disadvantages, can be used to perform the economic analysis regardless of the category chosen. The "Net-Present-Value" (NPV) technique estimates the present values of all of the savings and expenditures for the FMS over its useful life, discounted back to the "present" by some value which represents the opportunity cost to a company for making that investment. In other words, if the company could presently invest at an interest rate of 18% annually, then the discount rate would be 18%. The "net-present-value" equals the present value minus the initial investment for the FMS. If the net present value of the FMS is greater than zero, then the FMS is paying more than the discount rate on the money invested and should be implemented. If the value is less than zero, the FMS is not economically justifiable.

The "Internal-Rate-of-Return" (IRR) technique estimates the discount rate at which all of the savings and expenditures for the FMS over its useful life just equal the initial investment. It is exactly the same as the NPV technique, except that it estimates the discount rate instead of starting with it as a given. The project's IRR is then compared to a minimum acceptable value; if it is larger than that minimum value, the project is acceptable.

Both modeling techniques include the effects of taxes, depreciation, labor-rate and material-cost escalation, and any other cash in-flows or out-flows. Two major differences exist, however. First, the NPV technique makes an explicit assumption about the discount rate while the IRR technique has an implicit assumption. The discount rate is the assumed investment rate or reinvestment rate (like interest) at which the company could invest the income from the FMS. The rate specified in the NPV technique is the investment rate that the company feels is likely for the service life of the FMS. On the other hand, the IRR technique assumes that whatever discount rate equates the investment to the present value of the savings at time zero is a realistic reinvestment rate. However, as this discount rate begins to become much larger than the threshold rate, it becomes less likely that in reality the rate will be a feasible reinvestment rate.

If the discount rate generated by the IRR technique is of questionable merit, then why is this technique the more widely used? The answer lies in the second difference. The discount rate estimated by the IRR technique can be used as an index to compare different projects; it can indicate the best project on a relative scale. It is difficult to determine from the NPV technique which project makes the best use of the capital invested in it.

The basic methodology for economic analysis is to look at the increment of capital invested and compare it to the savings or costs resulting from it. For all categories of analysis, the manufacturing costs (direct labor, material, and overhead) to produce the parts must be calculated for both the conventional method, usually stand-alone machines, and for the FMS. In cases where the parts were produced principally on manual machines, the first alternative should be to produce them on NC machines and then to compare both alternatives with the FMS.

When performing replacement analysis, the increment of capital invested will be the investment for the FMS (the salvage value of all equipment that the FMS can eliminate is considered a cash in-flow in Year One). This is then compared to the savings generated by using an FMS instead of the machines replaced over the life of the FMS or the project, whichever is less.

If it is an expansion analysis, the investment increment is the difference in the cost of purchasing the standard equipment necessary and purchasing an FMS. This is again compared to the savings or costs of producing the parts on an FMS instead of the conventional machines. Because of the higher utilization of machines in an FMS, it is not unusual to find that the investment in an FMS is less than that necessary to purchase the additional conventional equipment. In this situation, the FMS can be beneficial even if it costs more to produce the parts on it.

Finally, for displacement analysis, the FMS investment is compared to the investment over time of the machines that would have been required. This comparison, as before, is based on the savings or costs of producing the parts on an FMS instead of the conventional machines plus a cost for storing and not using the conventional machine while it waits to be used. This opportunity cost of stored equipment is modeled as an additional cost due to the purchase of an FMS and is subtracted from the annual savings of the FMS.

If more than two alternatives are being compared, the economic modeling software automatically performs an incremental analysis. The alternatives are reviewed in ascending magnitude of investment and each increment of additional capital is either justified or rejected.

2.4.4.2 Economic Analysis Example: General Electric FMS Configuration Evaluation

Continuing the General Electric design example, this section summarizes the economic analysis of the configuration alternatives. (Additional details are contained in Volume IV.) Recall that this falls into the "capacity expansion" category.

The investment analysis of the FMS alternatives was done in two stages using the Investment Analysis Program (IAP). The first stage used a computer procedure that estimated the manufacturing cost (direct labor, material, and overhead) to produce a ship-set of parts using each alternative configuration. The second stage used another procedure that calculated the individual incremental-return-on-investments (IROIs) and payback periods both before and after taxes.

The first procedure, "Manufacturing Part Cost", estimated the manufacturing cost per set of parts for each configuration based on the number of full-time workers needed, the cost of a set's worth of castings, and a machine rate (a single dollar figure for direct labor and overhead) calculated by GEOS. If no machine rate had been available, the program could have used the average hourly direct labor rate and applied overhead to it. Any other annual operating costs not included in the machine rate or overhead, such as special inspection gauges, were amortized over the year's production and added to the cost of each part set in order to estimate the manufacturing cost per ship-set. These input data are illustrated in Figure 19 on page 52.

The second set of procedures, collectively called "Investment Analysis", calculated the IROI and payback period for each project, before and after taxes, using the NPR technique. The total installed cost was compared to the present worth of the net annual savings attributable to that configuration. (The net annual savings equals the cost of purchasing a ship-set from a vendor minus the manufacturing cost for the set produced on that FMS configuration. Costs for both vendor and in-house manufacturing were allowed to escalate annually at a predetermined rate, and the payback period was adjusted for the anticipated annual rate of inflation during that period.) The inputs and outputs of the investment analysis procedures IRR ad NPV are shown in Figure 20 on page 53.

In the case study, results of the economic analysis indicated that the fully automated three-machine (including an inspection machine) system was the most beneficial according to the criterion of choosing the largest investment with an acceptable IROI. General Electric was also interested

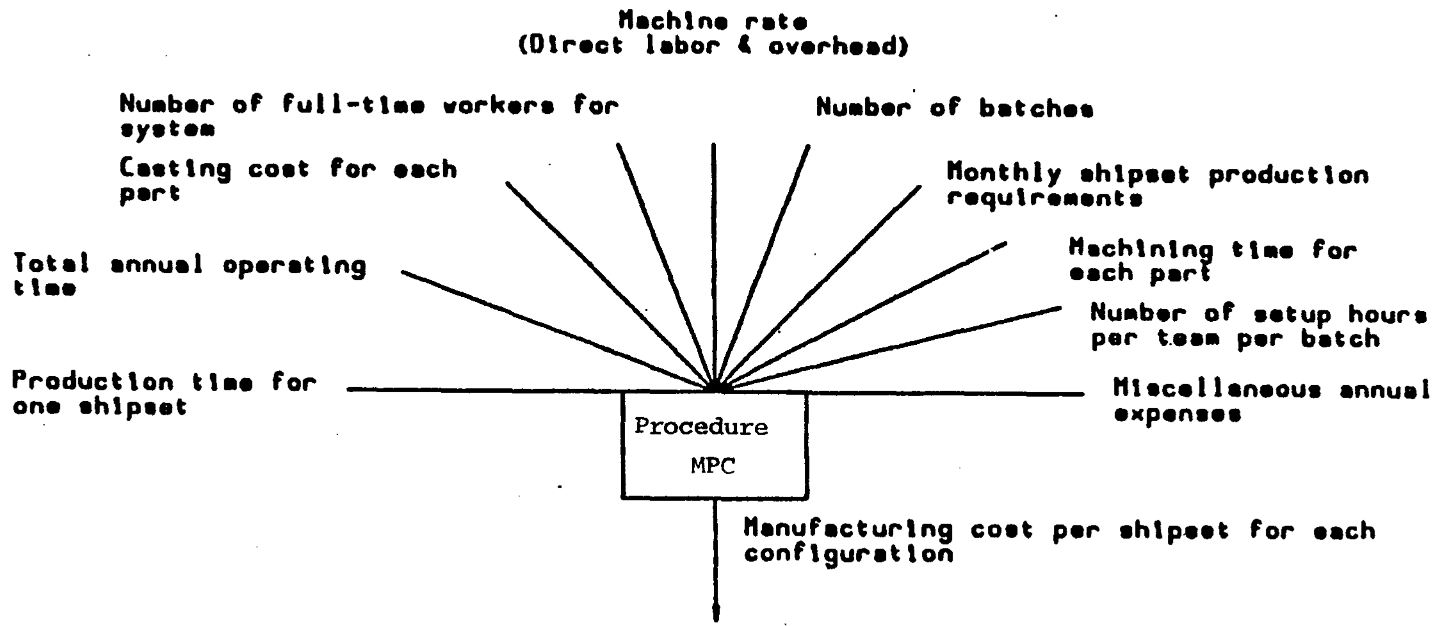

Figure 19. Input Data to the Manufacturing Part Cost Procedure, MPC

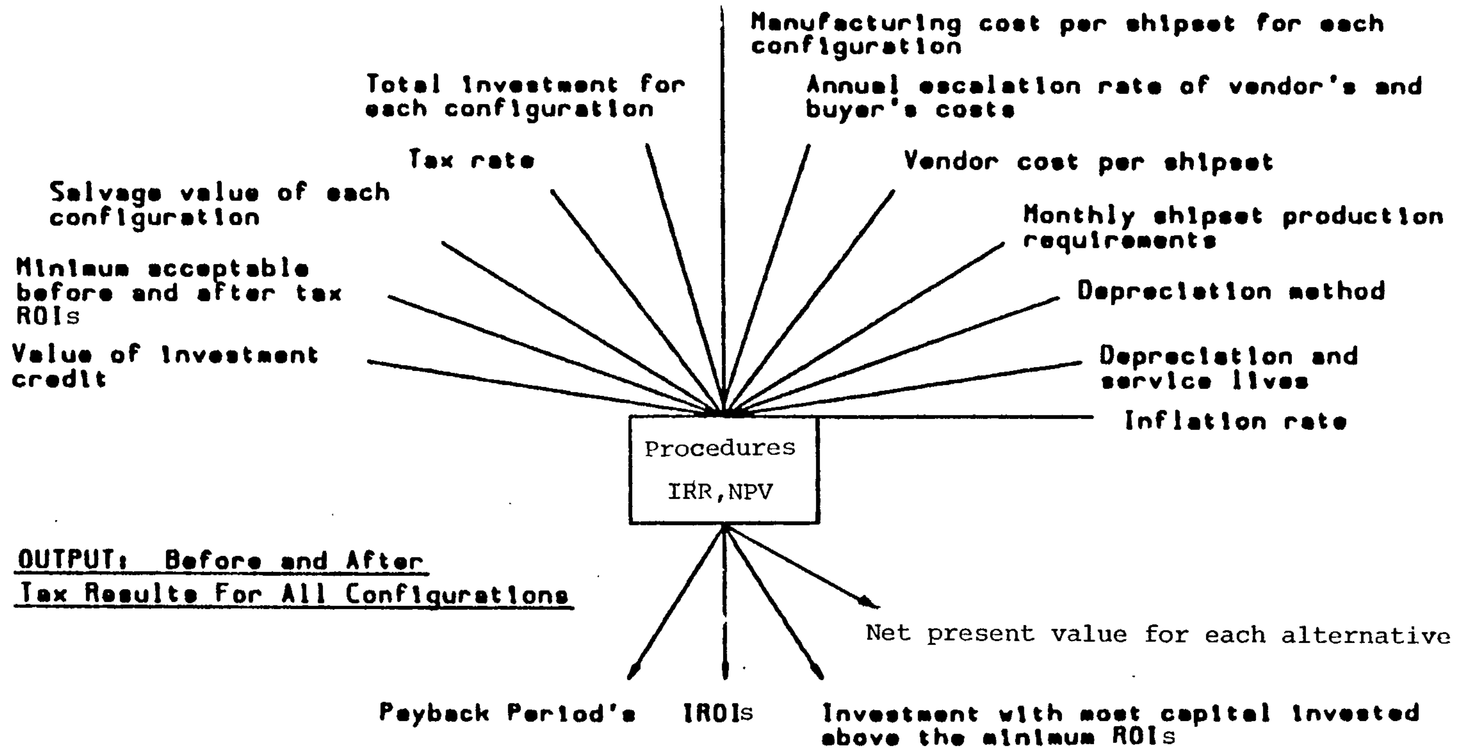

Figure 20. Input Data to the Investment Analysis Procedures, NPV and IRR

in determining whether each increment of capital invested in the chosen project above a "bare-bones" system of two DNC machining centers and manual material handling was justified. The analysis indicated that the fully automated system was justifiable.

2.4.5 Evaluation Matrix: General Electric FMS Configuration Evaluation

The evaluation matrix presented in Figure 21 on page 55 provides an example of how the concept was applied to the General Electric configuration case study. Listed across the top of the form is a sample of the twenty configurations evaluated. Down the left-hand column are the evaluation criteria, and the number next to each criterion is the weighting factor mutually agreed upon for the study. The diagonal in each box on the right-hand side separates the rating of the configuration with respect to a criterion from the "score" for that criterion. The rating is a relative value from one to five conveying the relative compliance of the configuration with that criterion (five indicating that the configuraion completely satisfies that criterion) and the "score" equals the rating multiplied by the weighting value for that criterion.

The matrix was useful in evaluating each configuration with respect to intangibles -- criteria that are difficult or impossible to evaluate strictly mathematically. Criteria such as flexiblity, accuracy, redundancy, and so on, are typical intangibles.

Configuration 17 had the highest total score. It was chosen as the configuration on which to base the RFP.

2.5 FINAL CHOICE OF AN FMS CONFIGURATION

Completion of the systematic configuration evaluation procedure described here will indicate which of the FMS design configurations, if any, should be chosen to produce a given group or family of parts.

The word "indicate" is crucial here, for the evaluation cannot choose the "best" configuration. The final decision must be tempered by judgement. Alternatives to an FMS must also be considered.

	Poor		->		Excellent
Ranking:	1	2	3	4	5

	Not Important		->		Very Important
Weighting:	1	2	3	4	5

Criteria	Weighting	Configuration 1	8	17
Ship-Set Production Time	5	2/10	4/20	5/25
System Availability	4	4/16	4/16	4/16
Redundancy	4	2/ 8	1/ 4	5/20
Precision/Accuracy	5	5/25	4/20	4/20
Flexibility	4	2/ 8	2/ 8	5/20
Tool Capacity	2	1/ 2	2/ 4	3/ 6
Cost/ROI	5	1/ 5	2/10	4/20
Inspection	4	3/12	3/12	3/12
Surge Capacity	3	2/ 6	4/12	4/12
Total Score:		92	106	151

Figure 21. General Electric Configuration Evaluation Matrix (Subset of Total)

3.0 HOW TO WRITE THE REQUEST FOR PROPOSAL

After an FMS configuration design that best satisfies the evaluation criteria has been chosen, it is necessary to convey the findings of the study to potential vendors who will provide the FMS. This is accomplished by creating an RFP, which is Step 4 of the implementation sequence. Figure 22 on page 58 and Figure 23 on page 59 summarize this step. An example RFP is shown in Volume IV.

The elements of a typical RFP depend upon the buyer's experience and willingness to become involved in the design process, as well as his desire to control the specification process and performance of the FMS after it is installed and operating. At a minimum, the vendor needs:

- Drawings of the parts to be produced.
- Yearly production requirements and available production time.
- System delivery date.

However, this minimal specification approach should be avoided. If the buyer has completed the design and evaluation steps outlined in Section 2, he will be able to write a more complete RFP and will be in a good position to work with the vendors and to evaluate their proposals.

3.1 STRATEGY FOR WRITING A REQUEST-FOR-PROPOSAL

In reviewing the myriad of topics that could be included in an RFP, it is important not to lose sight of its overall goal: to obtain quotes from a number of vendors, each of which may have a different approach. Also, although it is possible to reduce the number of request/proposal iterations by considering details in advance, it is unlikely that the final vendor will be chosen in response to the first RFP. FMSs are relatively new and quite complex; neither buyers nor vendors have had enough experience producing and operating them to be able to specify a system definitively in one iteration. There may be three or four iterations between the initial request and the signing of a contract. In between, the specifications become more detailed and well defined, and the number of prospective vendors decreases.

There is a strategy, therefore, in what to specify in the RFP and what is best left unsaid. In this way, the number of potential vendors is not limited nor their creativity stifled, but the buyer still controls the system design.

The major consideration, then, is the amount of information to include in the initial RFP. This can range from specifying only the production requirements and supplying the part prints to specifying the entire system (machines, MHSs, tools, layouts, etc.).

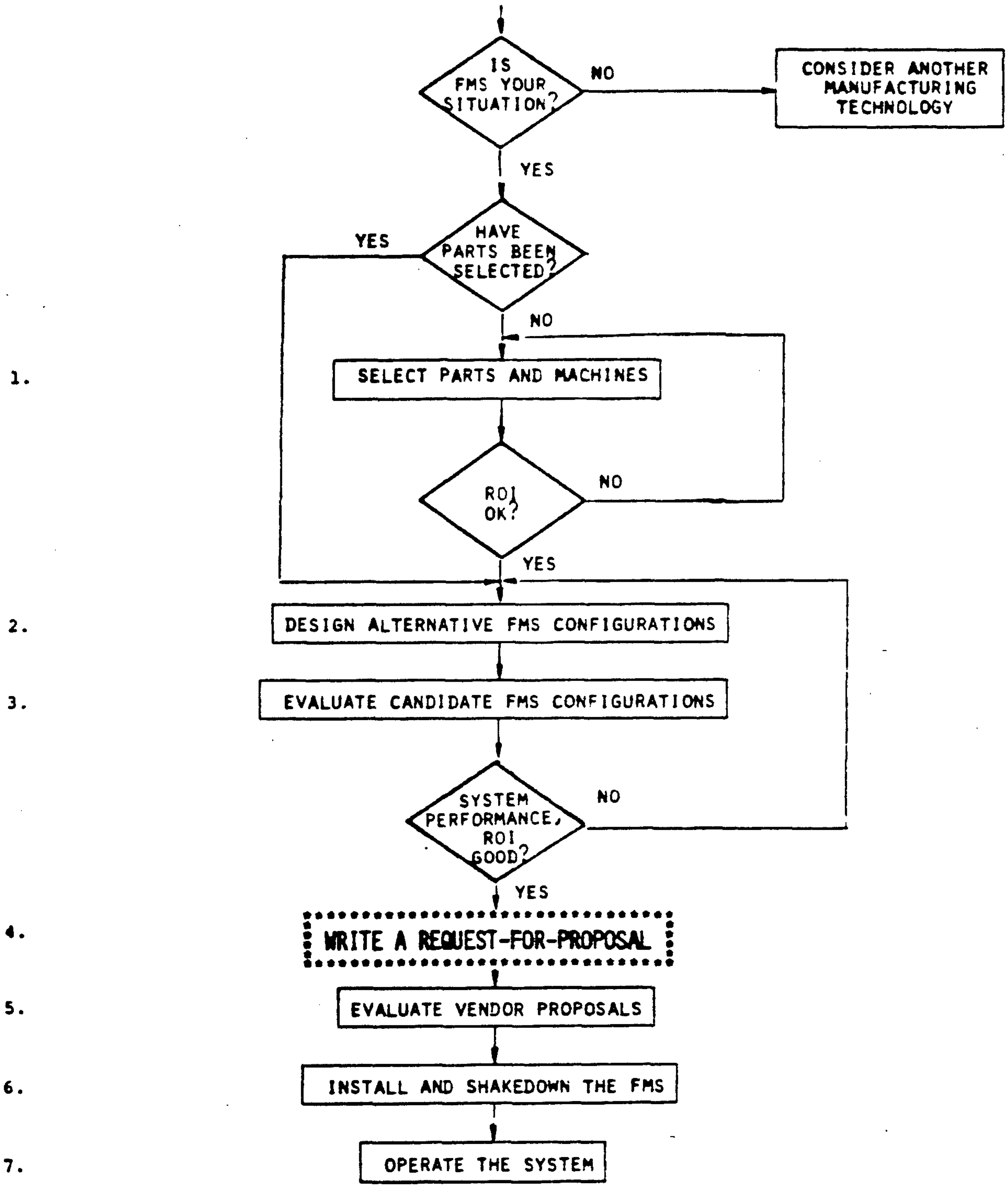

Figure 22. Acquisition of an FMS: Step 4

WRITE A REQUEST-FOR-PROPOSAL

- Write an RFP that conveys your findings and desires for an FMS.
- Avoid overspecification; allow the FMS vendors to be creative and competitive in designing an FMS for your situation.
- See Volume IV for a sample RFP.
- Data required for writing the RFP:

1. Necessary:
   - Part drawings.
   - Annual production requirements.
   - Available production time.
   - Accuracy requirements.
   - Performance tests expected.
   - Desired system availability.

2. Recommended:
   - Process plans and fixturing concepts.
   - Desired auxiliary equipment, such as inspection machines, part wash stations, etc.
   - Desired software capability.
   - Available floor space.
   - Utilities available.
   - Desired system redundancy.
   - Delivery date.

3. Optional:
   - Capacity of the system, in terms of maximum machining horsepower, tool storage, maximum part dimensions (machining cube) and weight, etc.
   - Equipment biases.
   - MHS components desired.
   - Plans for future expansion.

Figure 23. Steps in FMS Implementation: Step 4

It is desirable, when possible, to include process plans and the desired fixturing approach for the part set with the initial RFP. There are three reasons for this:

- It greatly reduces the amount of work a potential vendor must do and encourages more vendors to bid.
- It assures that parts will be machined in an acceptable fashion.
- It provides an equal basis for comparison of various proposals.

This is not to say that the vendor may not deviate from these plans; if a better fixturing concept or sequence can be developed, he should be allowed to examine it.

If the buyer is not sure about the need for certain equipment, such as an automated MHS or automatic inspection machine, they should be left as "options" for the vendors to justify if they choose to include them in their system design.

A final consideration is in how to present the RFP to the vendor. The most common approach is to mail each potential vendor (determined by the buyer's staff) the RFP packet and wait for a reply. Alternatively, the vendors can be invited to the buyer's facility individually to receive a copy of the RFP and initiate an exchange of ideas. This way, it is possible to form an early impression of the vendors' capabilities.

3.2 ELEMENTS OF THE REQUEST-FOR-PROPOSAL

3.2.1 Specifications

Specifications for a flexible manufacturing system can be categorized into three major groups: mission specifications, performance specifications, and subsystem specifications.

Mission specifications include:

- Drawings of the parts to be produced.
- Process plans and fixturing concepts.
- Yearly production requirements and available production time (alternatively, system throughput), plus surge capacity required.
- Delivery date.

Performance specifications include:

- System availability (as opposed to stand-alone machine availability).

- Desired redundancy.

- Accuracy requirements.

- Performance tests (qualifying and acceptance tests) for individual machines and for the entire system.

Subsystem specifications include:

- Physical "capacity" of the system, such as horsepower, tool-storage capacity, maximum part dimensions and weight, computer power, etc.

- Machinery desired, such as horizontal or vertical machining centers, dedicated drilling/tapping machines, head changers, etc.

- Auxiliary equipment, such as automatic inspection machines, deburring stations, heat treating equipment, washing stations.

- Desired software capabilities, e.g., details of a management information system, diagnostic packages, decision support packages, scheduling and dispatching packages, a system simulation, etc.

- MHS components (including pallets and fixtures) and topology (including available floor space and utilities).

- If necessary, standardized controllers. (This may rule out certain vendors or may reduce certain system capabilities.)

- Applicable industry standards, such as those for NC part programs and languages and the needed computer interfaces.

- FMS operations manuals.

- FMS software documentation.

Those specifications not stated will be filled in by the vendor. The level of specification detail will determine how tightly the designs are controlled.

3.2.1.1 Mission Specifications

The most critical of the specifications provided are the part drawings and the required system production requirements.

The part drawings should be as clear and detailed as possible, and they should represent the latest revisions. As an aid to the vendor, critical or unusual tolerance requirements should be highlighted in some way that attracts attention. Including more than one set of drawings allows the vendor's various systems groups to begin work on a proposal at the same time.

As an additional aid for the vendor, as well as providing a means for an equal comparision between vendor proposals and assuring that the parts can be made, the vendor should be provided with process plans and fixturing concepts for each part.

System production specifications include the production requirements of the system (stated as either a monthly or yearly figure) and the allowable working hours that will be available for system operation. In addition, if there will be an occasional need to exceed the average throughput specified, a "surge" capacity should be stated. Finally, specify the desired flexibility to changes in the parts or part mix that may occur during the system's life.

A key element in a vendor's proposal is the delivery schedule. If this is to be specified by the buyer, the dates should be as realistic as possible. System purchases are not the same as single machine-tool purchases. The amount of lead time required to design, fabricate, test, ship, and install a system is different for each vendor and for each system design. Currently (1982), the lead time to first system operation is in excess of 12 months from the time a purchase agreement is signed. The shakedown period required to bring the FMS up to full production is an additional 6 months or more.

3.2.1.2 Performance Specifications

The desired level of system availability -- the percentage of time all components of the system are functioning normally -- can be stated in the RFP, but this value is very difficult for either the vendor or the buyer to estimate accurately. The vendors will have information gathered over time on the availability of systems they have previously installed, and this figure averages from 65% to 85%. Stating a desired availability of 75% will indicate to the vendors the minimum amount of availability that will be acceptable in normal operation, and they should provide enough redundancy in the system to provide that availability.

Redundancy is the amount of "backup" in the system for each subsystem. For instance, if the system contains at least two of every type of machine and fixture, production can continue at some reduced rate while a failure is repaired. The more of any one machine there is, the less likely a failure of one is going to affect production. However, redundancy is expensive; a balance should be struck between redundancy and cost. It is possible to examine the cost of redundancy using economic analysis to estimate the cost of not producing an item or producing it late and comparing to the cost of having redundant equipment which may not be used fully.

If there are unusual accuracy requirements, they should be highlighted and the vendors should be expected to discuss their solutions to these problems in detail. This discussion might include: the best accuracy the vendor feels he can obtain in normal practice, the option of taking unusual precautions (with accompanying cost increases) in building the machines to obtain higher intrinsic accuracy, how he might use manual intervention to inspect and reset boring bars, the use of probes in the machine spindle, etc.

Performance tests usually include results of detailed simulations of the proposed system plus documented proof of the accuracy and capability of each machine. The buyer should request that the vendor, using computer simulation, verify that his proposed FMS configuration will achieve the necessary average throughput desired. The simulation should also indicate the utilization of each of the system elements and provide evidence as to the surge capacity. The effects of machine and MHS failures on throughput should be examined at different failure rates to assure that the desired redundancy has been built into the system. The buyer may also ask that various batching, balancing, scheduling, and dispatching strategies be simulated. This will indicate which are best and will document the effects of each. The results of these simulation runs should be provided for review either with the proposal or at the final specification stage.

Performance specifications for each subsystem element can also be included in the RFP. These tests are most often used to verify the integrity and inherent accuracy of the machines. They usually involve tracing a master calibration piece with a measuring probe and examining the error between the actual and programmed movement of the machine for various temperatures and lengths of time. (After system installation, it may be wise to permanently mount such a "master gauge" to a pallet for periodic inspection of machine alignment, and for the analysis of the effects machine "crashes".) Machining tests (qualifying tests) may also be specified, but the results of this type of testing procedure are much more susceptible to the introduction of errors from sources other than the machine, such as the pallet, fixture, part, cutting tools, etc. The vendor should be required to document the results of all tests for all machines, so that if a problem with a machine occurs at some later date, both the buyer and the vendor have a common reference point from which to start their investigation.

Information on the desired system and subsystem acceptance tests, to be performed both at the vendor's site before shipping and at the buyer's plant after installation, should be included in the RFP in detail, to prevent misunderstandings later. These tests usually require a number of actual production pieces to be run off. The number of pieces to be machined in each case and the limits of acceptable error are usually agreed upon after a vendor presents his proposal and it is accepted, but it is important to provide enough information for the vendor to estimate the cost and time involved.

3.2.1.3 Subsystem Specifications

Subsystem specifications include optional information on specific attributes of the equipment the vendor will provide. This can include the physical capacity of the system, such as machine horsepower, pallet sizes, machine travel, computer memory size, number of material handling units, and so on. Any software capacity constraints should also be mentioned.

This information should be given if the FMS might be used in the future for parts which differ in size, material, or weight from the proposed part set.

Specific types of machines desired should be mentioned if there is a preference. For example, horizontal machines may be preferred because the existing tooling is designed for horizontal machines, the process planners are familiar with horizontal machines, etc. It may be requested that the vendor investigate some dedicated equipment, such as head-changers, cluster heads, etc., where it is believed the equipment might be cost effective. However, it is best not to stifle the vendor's creativity: provide guidelines, not rules.

Preference, if any, for certain types of MHSs should be mentioned in this section. If the floors are uneven, shallow, or poorly surfaced, with small turning areas, or the machines will be arranged in an unusual fashion, the vendors will need this information to choose their MHSs. In addition, specify possible future expansion requirements for the line.

Auxiliary equipment -- such as automated inspection equipment, deburring, etc. -- are usually best treated as options, due to the fact that not all vendors can supply all of these items and because the justification for each item may be desired separately. Options are discussed later.

Additional specifications that should be provided to the vendor include those of available floor space, atmospheric control possible, and utilities available (heat, power, light, chilled water, compressed air, etc.). Interface specifications are necessary if the system is to communicate with equipment already installed. Also, specify any applicable standards, such as those for NC part programming languages and media. Lastly, inform the vendors of the desired proposal format -- how to divide the system into components and price those components -- so that the evaluation is not hindered.

3.2.2 System Control and Monitoring

Overall control is important because just as much as the machines, it determines how well the system will function. It is centralized in a computer that has direct data and system status links to the processing, material handling, tool management, and inspection functions.

The architecture of the control defines the relationship between the computer and the other system elements, and it can vary significantly between FMS manufacturers. Modularity, subsystem autonomy, reconfigurability after machine failure, and growth and operational expansion all depend, in different degrees, on how the software system is structured.

Operation of the FMS involves, in its simplest form, the following functions:

- Part program preparation.

- Part program loading.
- Machine scheduling and operation.
- System monitoring.
- System diagnostics.
- Operator displays and controls.
- Tool management.

The FMS is likely to operate in several modes and the control system must adapt to each. There is automatic or full operation, where all systems are working as desired. There is a setup or changeover condition a short-term, partial failure mode where the system may be operated in a semiautomatic fashion. Also, there is a full failure mode, where a severe failure precludes operating the components as a system. The control system determines how to obtain the best response in all these situations; it is important to pay attention to it early in the specification process. By specifying that the system degrade "gracefully", backup features that allow the FMS to function to some degree when individual subsystems fail should be included. For example, there should be enough memory at the controllers to enable the machines to function as stand-alone machines if the FMS computer fails.

Although standard software is provided, additional software may be desired. A management decision support system is often needed. Such a system might include batching/balancing software, real-time scheduling routines, a simulation for examining changes due to failures, and tooling status displays.

Another area of special software includes line monitoring and diagnostics. Timely detection and identification of failures greatly reduces the effort required to service the FMS, since failure diagnosis usually demands much more time than correcting the fault.

The vendor may also be requested to develop NC part programs in the language the buyer currently uses, as well as process plans or operation sheets. A very useful software feature is the ability to edit and update NC programs either at individual machines or from the FMS control computer. This saves time and allows optimization of "tapes" in real-time for the machines that will make the parts. NC tape verification, using a plotter or cathode ray tube (CRT) graphics package, should also be considered.

3.2.3 Documentation

Documentation for all equipment includes operation manuals, software manuals, maintenance manuals, and recommended spare parts lists. Multiple copies are recommended, particularly of the software itself. Also, specify the frequency of contract progress reporting as well as the principal items to be covered in the reports.

3.2.4 Vendor Responsibility

In the case of a system that includes machines from more than one vendor, there is the question of who will take responsibility for properly integrating the equipment. Normally, buyers do not have the expertise to perform this function. In general, if inspection machines, high accuracy machines, etc., from other vendors are to be integrated into the line, the overall responsibility must be placed on the shoulders of the prime vendor. If there is to be a service team at the plant during installation, include that also. Finally, describe the amount of subcontracting the vendor will be allowed and how that subcontracting is to be accomplished.

The preparation of the site, machine and MHS foundations, service and utility pits, coolant troughs, etc., are almost always the buyer's responsibility. Integrity of the foundations plays a very large role in the smooth operation and everyday accuracy of the FMS.

3.2.5 Post-Installation Support

Two important areas of post-installation support that should be mentioned specifically in the RFP are the system's warranty period and the services to be provided after installation. Both topics are negotiable. The warranty usually covers materials and workmanship of all system elements and software for a minimum period of 1 year. If an element fails within the warranty period, the warranty pertaining to it is often extended for a year from the date of repair. Post-installation service might include periodic inspection of equipment, supply of spare parts, and links to a diagnostic computer at the vendor's plant. Clauses for updating obsolete hardware or software should be made clear.

3.3 SYSTEM OPTIONS

3.3.1 Inspection

Available inspection methods include manual inspection with standard instruments; using automated coordinate measuring machines; and inspection with new techniques such as optical imaging, laser interferometry, and other sensors. How these tecniques are used, not necessarily which ones are used, can make the difference in an FMS.

Inspection philosophies include:

- Preprocess inspection on the machine tool, to verify head alignment, spindle concentricity, tool position, etc.

- In-process checks for dimensional control,detection of tool wear, plus adaptive control of cutting speed and feed rate. Included in this philosophy is the use of spindle probes for part alignment (determining axis compensation) and part and feature presence (hole or no hole, excess stock or lack of stock).

- Post-process inspection, to verify and document the correct dimensions and finish.

No matter what the techniques and philosophy, six questions with respect to specifying a system must be answered:

- Should inspection be on-line or off-line?

- How many inspectors or inspection stations are needed to maintain the desired production rate?

- Should there be statistical sampling or 100% inspection? What features should be inspected?

- What inspection data would be most useful to the control system; how much data will be archived?

- Should parts be deburred and cleaned before inspection? (If so, additional stations for deburring and cleaning will have to be added.)

- Should parts be unfixtured or fixtured for inspection?

The current trend is to on-line coordinate measuring machines which communicate with machining center controls and offset some machining errors. They can monitor quality in real-time and alert the system operator to problems before a significant number of parts are affected. Unfortunately, these machines are costly and fairly slow; more than one may be necessary to maintain throughput.

Measuring probes, stored in the machine tool-changer and interchanged with tools in a machine's spindle, are also becoming popular, but they reduce the time the machine potentially could be cutting metal.

3.3.2 Chip and Coolant Recovery

The major issues involving chip and coolant recovery focus on the question of a centralized chip- and coolant-recovery facility or individual chip conveyors and coolant systems on each machine. The advantages of collecting chips automatically in one spot and the ability to monitor directly the properties of the coolant temperature, water content, foaming, etc., should be considered. Additionally, a wash station for the parts/fixtures/pallets before inspection is easily facilitated with a centralized system, and coolant could be used to wash down the system at the end of each shift.

However, individual chip and coolant recovery units on each machine minimize the machine dependency on a centralized system, allow simultaneous cutting and recovery of different materials on different machines in the system, and do not require the site work and space needed by a centralized system.

3.3.3 Cutting-Tool Room (Tool Crib)

FMS tools can be serviced from an existing tool crib or from a dedicated FMS tool crib. If a dedicated tool crib is chosen, a decision must be made as to the level of complexity that might be appropriate. In general, dedicated FMS tool cribs have proven to be cost effective for a number of reasons:

- The tool crib is under the control of the FMS manager, simplifying communications and supervision.
- The tool setters become familiar with the FMS tools and tool life.
- Tool management is improved.
- Response to tool failures or missing tools is rapid.
- Process or part changes are accommodated more quickly.

This is not to say that an existing tool crib cannot be used; if it is well managed and capable of handling the increased demand for tools due to the FMS, then it might be the best choice.

The complexity of a dedicated tool crib can vary widely, from having simple, manual presetting and sharpening machines to having automated presetting and sharpening machines under computer control that send tool length and diameter information to the machine tool on which the tool will be used. The buyer must work with the vendor to determine the appropriate level of sophistication.

Decide whether the vendor will provide the perishable and durable tooling, but reserve the right to change specifications or purchase unacceptable proposed tooling elsewhere. Tool crib equipment and tool-setting equipment should be described; a tool identification system and pallet specifications must be mentioned. The buyer, the FMS vendor, and the raw material supplier will have to discuss and mutually agree upon the final configuration of the fixtures.

3.3.4 Unmanned Operation

If the intention is to operate the system in an "unmanned" mode for one or more shifts a day, a number of options should be considered:

- Video monitoring of each station from a central control area.
- Various means of adaptive control at each machine, such as spindle- or feed-drive-motor current monitors.
- Tool breakage and wear monitoring at each machine.
- Duplicate tooling at each machine.
- Reduction of feeds and speeds.
- In-process inspection as well as an inspection machine.
- Extra pallet/fixture storage area for preloaded fixtures.

As with the tool room, the buyer and the vendor must determine the degree of sophistication which is both possible and advisable.

4.0 HOW TO EVALUATE VENDOR PROPOSALS

One or 2 months after issuing the RFP, budgetary proposals should have been received from all of the interested vendors. As each vendor's proposal is examined, make entries in a decision matrix indicating the relative score of the proposal for each major topic. The proposals can then be reviewed as a group.

This section describes Step 5 of the FMS implementation sequence and is highlighted in Figure 24 on page 72 and Figure 25 on page 73. Volume IV shows an example proposal.

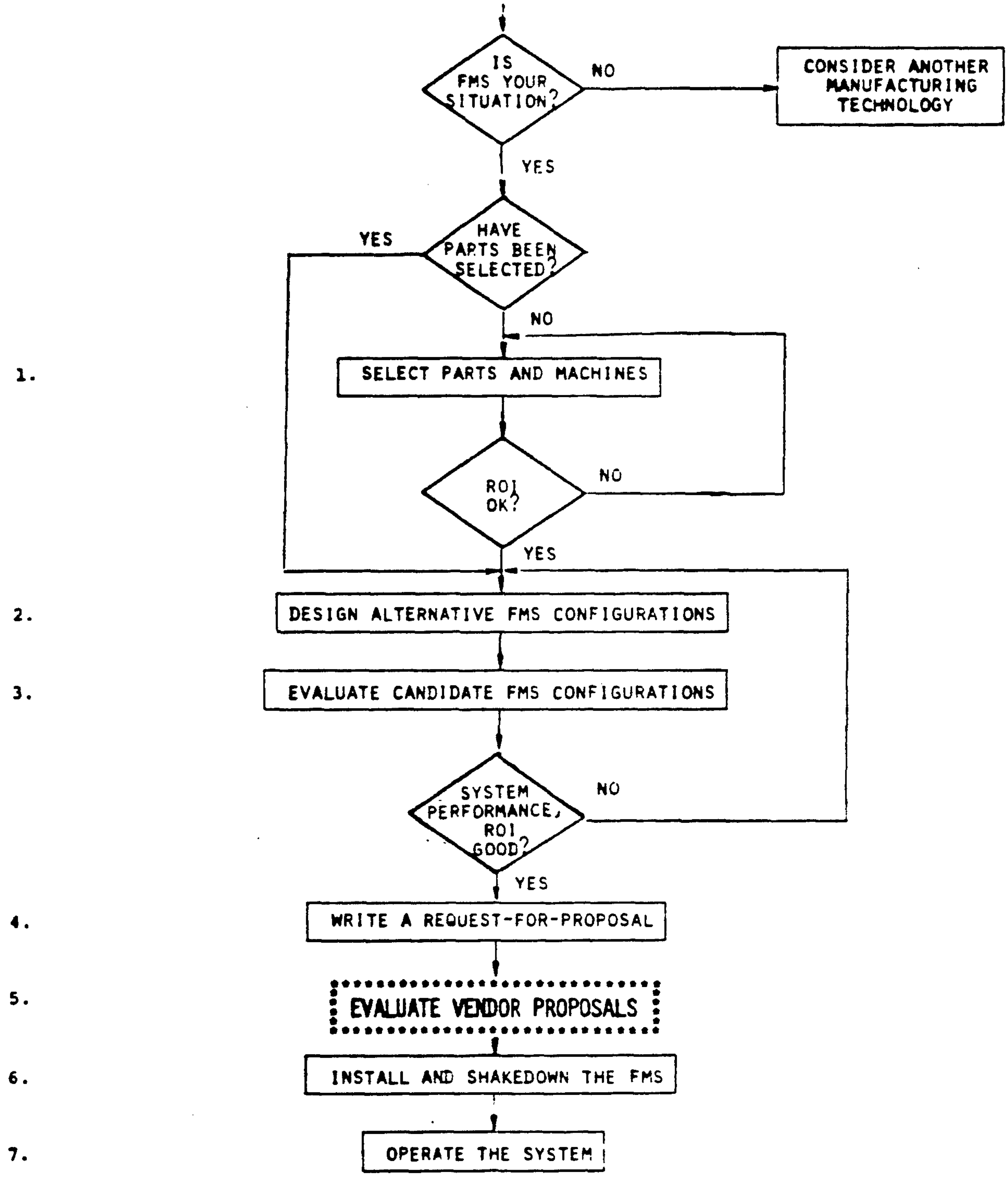

Figure 24. Acquisition of an FMS: Step 5

EVALUATE VENDOR PROPOSALS

- Verify and evaluate vendor proposals using the simulation and economic analysis.
- Evaluate the degree of success each proposal has in satisfying your nonquantifiable requirements.
- Choose the proposal which best satisfies your company's need.
- Work with the vendor to develop detailed specifications and prices.
- Place an order.
- See Volume IV for a sample vendor proposal.

Figure 25. Steps in FMS Implementation: Step 5

4.1 REVIEW OF INDIVIDUAL PROPOSALS

Perhaps the easiest way to evaluate the proposals is to use the evaluation matrix technique introduced in "HOW TO DESIGN AND EVALUATE AN FMS" on page 9 and illustrated in Figure 17 on page 44. A simple subjective rating scheme -- say, numbers from one to five -- can be used to evaluate the desirability of each proposal with respect to each evaluation criterion. Each criterion should be given a relative weighting, to indicate which are most important. The matrix is useful for comparing the group of proposals, since the buyer can simply scan a line and ascertain how well a proposal addresses each topic or how well one proposal fares against another.

Although they are difficult to separate during the evaluation process three areas concern buyers the most:

- The cost of each element of the system.
- Performance verification of each element as well as of the system itself.
- The reputation and experience of the vendor.

Cost should not be the only criterion for choosing a system. Each element of the RFP quoted on must be examined thoroughly to determine exactly what it includes. Questions to consider when rating each element with respect to cost are:

- Are engineering costs included clearly in the proposal?
- Are site work costs included?

- What types of support (during and after installation) is the vendor offering at the quoted price?

- Is a training program offered?

- What spare parts are included?

- Can a recommended spare parts package be purchased?

- Is an installation team included in the quote?

- Are all specified elements included, except options?

- Has the system been over-designed? Under-designed?

- Are the costs reasonable with respect to the delivery date and equipment capability?

- What are the operating costs -- manpower, utilities, and off-line operations -- in this proposal?

- Does the vendor have local service capability?

- Can the system be installed in phases?

- Is the system expandable?

Once the costs of a proposal are fully understood, the cost of options can be calculated using the IROI approach described earlier, and in Volume IV. When rating the proposal using the matrix, be aware of the compromise between the price quoted and what is provided; later comparison of all the quotes may show that one vendor is providing significantly more system for the price than another.

Finally, the availability of capital required to purchase a system must be assessed. If the capital requirements are too great, perhaps a phased program, purchasing one or two machines initially and installing the rest of the FMS over a period of time, is a reasonable approach.

Verifying performance is equally important to cost. This includes verification of:

- Machinability data and process planning.

- System throughput.

- The utilization of each system element.

- The effects of machine failure and the MHS.

- The ability to alter the part mix.

- The accuracy of each machine.

System verification is usually performed by the vendor using simulation. However, before rating the proposal on system performance, double-check vendor performance claims with an in-house simulation or, if necessary, pay a consultant to verify the vendor's simulation results. If neither of these approaches is feasible, at the very least study the vendor's simulation to make certain that it is modeling the proposed FMS accurately and completely.

Verifying the performance of the vendor's individual machines is more difficult. If possible, the best approach is to talk to another user of the same machines. This is usually much more realistic than the vendor's estimates of accuracy, since the machine in the shop has had a chance to wear in and sustain normal production punishment.

Do not underestimate the usefulness of vendor reputation as a final guide. It can indicate whether problems in delivery are likely to occur, as well as the likely quality of the long-term support. Personal experience with the vendor's stand-alone machines also should play a part in the evaluation. Remember, however, that a separate division of that vendor's company may be offering the FMS and that division may have an entirely different set of policies.

4.2 SELECTION OF THE VENDOR

After completing the proposal evaluation matrix for all of the potential vendors, the vendor with the highest total score can be selected, and then, contract negotiations begun. Figure 26 on page 76 illustrates a sample vendor evaluation matrix.

4.3 FINAL PROCUREMENT SPECIFICATIONS

After selecting the vendor, the final RFP must be converted into a final specification for the FMS. All parties involved at the buyer's plant should have input to this document and agree to any changes. This specification should be the negotiating vehicle to obtain a final agreement with the vendor. The document must state precisely the content and capabilities of the system, as well as the responsibilities of all of the parties. Upon reaching a final agreement on the specifications, a purchase order can be issued for the system.

	Poor		->		Excellent
Ranking:	1	2	3	4	5

	Not Important		->		Very Important
Weighting:	1	2	3	4	5

Criteria	Weighting	Vendor System A	B	C
•Shipset Production Time/ Throughput				
•Precision/Accuracy				
•System Availability/ Reliability				
•Redundancy				
•Flexibility				
•Material Handling System				
•Option A				
•Option B				
•Option C				
•Inspection				
•Fixture Design Package				
•Tool Package				
•Control Software				
•Decision Support System				
•DNC System				
•Total Investment				
•Return-On-Investment				
•Finance Plan				
•Vendor Reputation				
•Performance Tests				
•Acceptance Tests				
•Warranty				
•Operational Support				

Figure 26. Evaluation Matrix: Vendor Proposal Evaluation

5.0 INSTALLATION AND SHAKEDOWN

The buyer's involvement with FMS implementation does not end with signing the purchase agreement. Although the vendor is supplying all of the parts and will help the buyer put them together, the buyer must prepare for the FMS, assist the vendor in its installation and begin to debug the system. Every effort made to maintain a partnership with the vendor during this phase of the project will provide dividends in the long run.

This section outlines Step 6 of the FMS implementation sequence, summarized in Figure 27 on page 78 and Figure 28 on page 79.

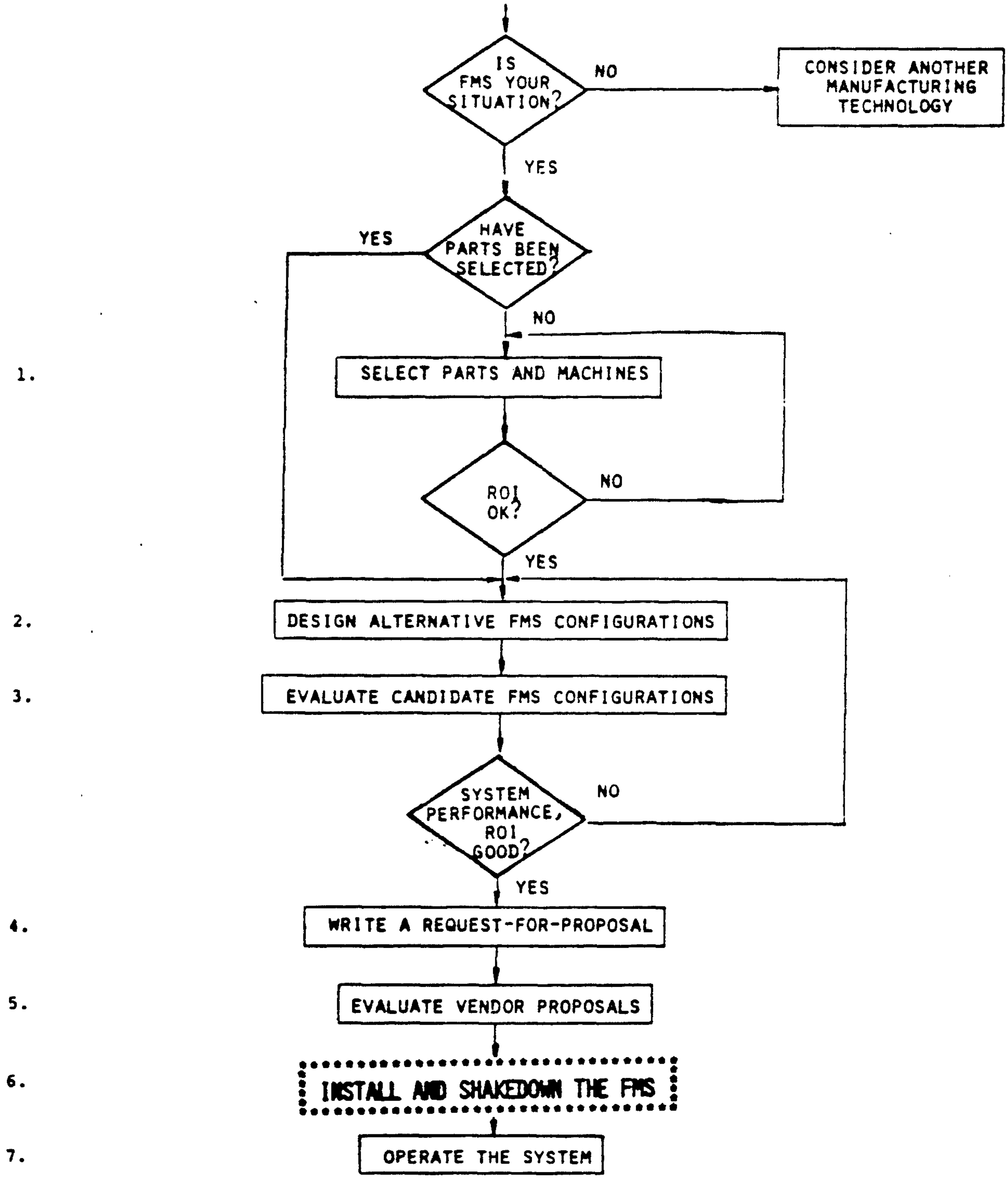

Figure 27. Acquisition of an FMS: Step 6

PREFARE FOR AN FMS

- Select and educate personnel to operate and maintain the FMS.
- Assess the quality control and production control departments' role in the successful implementation and operation of the FMS and develop or augment policies to assure success.
- Develop a preventative maintenance plan and spare parts list for the FMS.
- Prepare the FMS site.
- Assist vendor with installation and shakedown.
- Perform FMS acceptance tests.

Figure 28. Steps in FMS Implementation: Step 6

5.1 PREPARING TO TAKE DELIVERY OF AN FMS

5.1.1 Labor

FMSs are a relatively new approach to manufacturing and can result in a significant change in many plant operations. As such, they affect people on all levels of responsibility, from the shop workers and supervisors up through the ranks of management. The FMS will be regarded with different perceptions, ranging from a grave threat to a remarkable opportunity.

Do not overlook the necessity to remove, as much as possible, negative reactions to the installation. The threat of job displacement or job elimination is most obvious. In addition, new technology often appears overwhelmingly complicated to those who have not been schooled in the basics. Thus, it often has a psychological effect of diminishing the self-confidence that motivates skilled workers and supervisors.

The FMS can present an opportunity to generate new skills in promising employees, and it should be used as such to enhance career possibilities. It can be a motivational force to develop new skills for workers whose previous roles are eliminated by the new technology. Consider an educational period for all involved to familiarize them with the intent and facts of the installation, and any effects it will have on them.

An FMS is a "system", and as such it requires a team of skilled people to make it work properly. The range of skills begins with the operators and includes maintenance, programming, scheduling, performance analysts, and on up through the ranks of management. Communications across the lines of responsibility require that each level of skill overlap the next in the hierarchy.

The labor movement in the U.S. is undergoing attitude changes with regard to new technology. Union leaders are increasingly recognizing the necessity for manufacturing innovation in order to maintain competitiveness in world markets. Labor also recognizes that it is better to lose some work categories than to lose an industry.

What is required is that management cooperate with labor in implementing new technology. Labor should be invited to participate in the planning and be kept aware of the goals and anticipated gains in productivity to the point that no threat can be perceived and a net improvement for all concerned is the ultimate objective.

5.1.2 Staffing the FMS

Essentially, two skill levels are required to operate FMSs. In the unskilled classification, there is the loader/unloader. The most demanding elements of his job entail making sure that part and fixture mounting surfaces are clean so that parts register properly, and sometimes clamping parts at prescribed torque levels to prevent excessive part strain.

In general, highly skilled machine operators attend machines during the shakedown of an FMS. They are a logical choice for start-up because they can readily identify problem areas associated with the machine tools. Often, they will not physically operate the equipment, but monitor it to determine whether its operation is satisfactory. Their value continues beyond this initial phase, because it is very important to keep the machines running, but they are treated more like consultants, called only when a problem arises that is too difficult for the line foreman to take care of.

In the skilled classification, there is the line foreman, typically a manufacturing engineer with machining and systems engineering background. He is responsible for maintaining production on the line and must make decisions affecting raw part orders, manpower placement when failures (machines, computer, controllers) occur, and perhaps even part routing in the event of such failures.

The number of loaders depends on the number of load/unload stations and the part cycle times. A loader should be able to work several stations; the exact number requires a time study for the particular FMS in question. Similarly, the number of machine operators required will depend on the particular line. One operator per machine is not required, as the "operator" does not normally operate any machine, unlike common practice for stand-alone machines. Under normal circumstances, one worker per six machines may be adequate.

Some users have found that there are significant benefits to be gained when most personnel running the system have the skills needed to do the other jobs as well, from fixturing parts to supervising the system. Aside from the obvious advantage that absentees can easily be covered by others, users find that surges can be handled better. For example, there may be a sudden need to load eight parts on their fixtures. It is very helpful if all "hands" can respond to the need. In addition, this a method to provide job enrichment, especially if the FMS team is allowed to assign their work on a revolving basis by group agreement.

The ability to operate in this manner depends strongly on union policies. It may require that the same job description, pay, and ranking, etc., be given to everyone.

5.1.3 Quality Control

An FMS is a relatively untended system, and there will be no operators to visually inspect the parts for missing holes, cracks or other material defects. Nor will the NC programs accommodate large casting variations as a skilled machinist can. So there is a need to adequately evaluate the casting vendor, and incoming inspection is most important.

One company, expecting its FMS to be installed "turn-key", relied on its old approach: if a casting, chosen at random once a year, passed a layout inspection, the vendor was accepted, and castings were brought into the factory with nothing more for incoming inspection than an occasional visual check. This policy had been satisfactory when skilled machinists could be counted on to accommodate excess stock and check for missing cored holes and other defects. The FMS, however, had no way of inspecting the parts, and machine crashes and scrapped parts set production back more than 1 year. Confidence in the system was destroyed, and only after a detailed examination did the company realize that its inspection policy and not the FMS needed improvement.

The quality control and production control personnel will need to decide whether rework, part program proofing, and fixture/tool verification would better be performed on-line or off-line with duplicate machines. For FMSs, the decision to go off-line is usually preferred. There are a number of reasons:

- Reintroducing the part back into the system may be disruptive.
- The tooling required may no longer reside at the machine.
- There is usually only one feature out of tolerance; running the part completely through the system would be a waste of time and rescheduling the part on one machine would not be worthwhile.
- Off-line rework equipment can be pallet-compatible with the FMS. (Additional pallets and fixtures may be needed.)

Determining the source of an "out of tolerance" problem in an FMS is often not easy. The error may be a result of any one or a combination of factors, e.g., tool wear, interface misalignments (tool/spindle, part/fixture, fixture/pallet, pallet/machine), etc. FMSs that incorporate redundant tooling present an additional problem. The computer must keep track of which tools on which machines were used on which workpieces. If inspection is done on a sample basis, workpieces traveling different routes should be sampled frequently.

5.1.4 Production and Inventory Control

Lot-size calculations are important because they give some idea of how much support the FMS will require from inventory. It is important to estimate the number of casting producers necessary, warehouse space, and time for material handling.

Lot sizing is a two-fold problem. First, determine the optimum production lot size based on:

- Machinability and tool life.
- Set-up costs.
- Scheduling requirements.
- Planned system capacity.
- Average machining time.
- In-process inventory carrying costs.

Second, estimate the optimum inventory lot size, considering:

- Warehouse space.
- Carrying costs.
- Ordering costs.
- Demand requirements.

Calculate inventory lot sizes twice -- once for raw castings and once for finished castings -- to determine total space requirements.

An in-place manufacturing resource planning (MRP) system, or some other kind of scheduling system, will be greatly influenced by the introduction of an FMS. Consider providing a direct communication link between the production/inventory control computer and the FMS control computer, allowing the production control department to schedule the FMS. This integration can promote smoother work flow, reduce lead times, and assure that raw materials arrive when the FMS needs them. Reductions of four-to-one of work-in-process inventory are not uncommon with the introduction of an FMS. However, integrating the two systems is not a trivial task.

5.1.5 Preparations for Maintenance

Because of an FMSs complexity compared to stand-alone machines, maintenance planning is a necessity. A competent FMS maintenance organization should be created when an FMS is contracted, not after it is delivered. Every effort to contact and work with other current users of FMSs from the manufacturer will pay great dividends.

Each of the many disciplines of an FMS must be addressed in creating a maintenance force. These include specialists in computer hardware and software, controls, machine tools, tooling, and manufacturing. A strong emphasis should be placed on programming and computer operations because FMS software will be new to the organization. FMSs have not been turn-key installations, in the sense that users have historically experienced long learning curves due to underestimating the maintenance skills necessary.

Development of a spare parts list should be pursued with the FMS vendor at contract time, and it is useful to discuss it with users of similar FMSs. The vendor is in a delicate situation. On one hand, he is trying to sell the reliability of his system; on the other, the buyer will need the spare parts and the vendor will profit from their sale. It is natural to delay investing in spare parts because the total cost can be considerable. But the lead time for these parts may be large, and ultimately many of them will be needed.

5.2 INSTALLATION PREPARATIONS

5.2.1 On-Site Preparation

Foundation design for the FMS differs from those of stand-alone machines by the sheer extent of the system and by the potential need to integrate coolant and chip handling subsystems over the full set of machines.

Foundations should be designed to achieve excellent stability. Since the MHS interconnect machines and have some nominal component positioning accuracy requirements in order to function, there are greater demands on the stability of the system as a whole than there are for stand-alone machines. The foundations should be installed long before delivery of the FMS to allow them to settle and stabilize.

An often-forgotten issue at the design stage is the accessibility of the equipment for preventive maintenance and repair. Especially in an automated system, thought should be given to providing sufficient access space around the machines and MHS. Consider these points when developing configuration layouts and, for example, consider MHSs that also could be run manually.

Power requirements for an FMS are considerable when machine tools, MHSs, and computers are grouped. FMS components may be susceptible to moderate voltage variations, and the FMS may affect other equipment on the same supply bus. Computers are particularly sensitive to power conditions and warrant good supply practices.

5.2.2 Off-Site Preparation

After a vendor is chosen, form a liaison team to work with the vendor to fine-tune the system design and gain assurance that the system will do the job intended. The team will aid in developing the physical interface with the manufacturing plant and oversee installation preparations.

If the FMS is a multivendor design, the team can make certain that the vendors are working together. (Usually this is not a problem since one of the vendors will have prime responsibility.)

5.2.3 Other Preparations

In order to become familiar with the dynamics of FMS operation, exercise the computer simulation model of the system, investigating part changes, part-mix changes, and machine and MHS failures.

Presumably, at least a tentative part mix and its attendant tool complement will be chosen long before the FMS is installed. This in itself serves to define tool room requirements. If the machinability of the parts is low, extra tooling should be stocked to offset anticipated breakage.

If during FMS construction you change parts or part mix, the changes should be finalized before the system is delivered. While the FMS is progressing to a fully productive state, keep other operating factors stable.

A training program should be used to introduce the FMS to the operating and maintenance staff. The vendor may provide all of this service or just parts of it. Its extent should be defined in the original contract.

5.3 INSTALLATION AND SHAKEDOWN

5.3.1 Machine and System Acceptance Tests

There should be at least two levels of acceptance tests called out in the RFP and subsequently agreed to in the contract. The first measures the performance of machines and perhaps other subsystems on a stand-alone basis. The second is the acceptance test for the entire system.

Stand-alone machine acceptance tests can take two forms. The most common one, known as a "qualifying" test, is some type of test demonstrating the ability to manufacture to production accuracy specifications. The test pieces may not be actual production parts, but are representative in shape, material, and machining operations. They usually are simpler than production parts and might take the form of a box-like weldment; they incorporate all the significant operations associated with production parts, such as face and pocket milling, drilling, tapping, boring, and turning.

Test cuts directly show the performance of a machine tool in producing a tangible product. However, the machine's inherent accuracy may be partially masked by sharp new tools, nonoptimum process plans, etc. The second common acceptance method is known as the master part trace or "performance" test. A fully machined and inspected part is clamped on the pallet and traced with a probe using a special NC program for that part. Probe deflections are a direct measure of machine positioning errors. This technique presumes finish-cut machining does not impose significant loads on the part and, therefore, machining errors essentially are the result of positioning errors. This method will, therefore, not measure errors due to lack of machine rigidity, lack of part/fixture rigidity, etc.

It is usually impractical to use actual production parts to qualify the machines because the NC programs are incomplete, the specific tooling and fixtures are not available, etc.

The complete system acceptance test is a demonstration of the full system functioning in production mode producing an agreed-upon number of parts within a specified time. Sometimes the entire system -- or perhaps each individual component -- must remain free of all failures for some minimum percentage of the time.

5.3.2 Typical Shakedown Problems

Every installation is plagued with start-up problems. Most FMSs are custom-designed and built; although the machines and MHSs are usually standard off-the-shelf items, many of the problems are completely new with each installation.

In multivendor systems, lead times for machine delivery may be quite different, and only a portion of the FMS may be installed for some time. This can be an opportunity to learn the operation of and check out certain elements of the system under less pressure. However, if some key elements are missing, it may not be possible to do anything but treat machines as stand-alones until the full system is integrated.

Software "bugs" can range throughout the computer-controlled system. Some examples of the kinds of problems that occur are a sudden inability to read tapes despite having done so before, an incomplete control-software checkout that only reveals itself under certain operating conditions, conflicts in control logic, etc. The buyer's software people should work with the vendor's programmers to solve these problems.

MHS interface hardware may develop mechanical problems that were thought to be engineered out during system design. Once again, it must be emphasized that the uniqueness and complexity of the system promote growing pains that are not circumvented just by good design practices.

Normal manufacturing problems, like machinability, can be compounded in an FMS because of the interdependence of machines. What was believed to be the line's pace-setting machines, may not be so after their speeds or feeds are adjusted to achieve adequate tool life.

Part changes should be minimized during shakedown. It is much easier to learn to operate an FMS with a fixed set of parts than to have to change part programs, which may unbalance the line and require extensive changes in the part/machine mix. In this view, it also is better not to load a new FMS to capacity during a start-up period. Checking out all the systems with just a few parts should be easier and will reveal major problem areas.

The lack of well-established maintenance schedules tends to be self-correcting in time as the needs of the system are assessed through experience. The supplier, of course, should recommend some basic schedule.

Diagnostic and management information systems aid in locating problems and recording performance measures during operation of the system. Both also can be extremely useful when debugging a system during installation and shakedown. The diagnostic system will pinpoint problem areas such as overlooked connections, mechanical malfunctioning, incorrect start-up or shutdown of the system, and so on. This information may be difficult to obtain otherwise during installation. The management information system (MIS) can continuously record performance statistics, providing a complete record of shakedown problems and progress.

This section discusses the operation of an FMS and is the final step of the FMS implementation process. (Figure 29 on page 88 and Figure 30 on page 89 summarize this step.)

An FMS is a complex system consisting of many interconnected components of hardware and software, as well as many limited resources such as pallets, fixtures, and tool capacity. Operating an FMS efficiently can be difficult since any decision to allocate some resources to production of one workpiece necessarily affects the resources available to produce all other workpieces. Furthermore, this interaction can be rather complex and not easy to predict. It is, therefore, important to structure this difficult task in a manner that leads to good decisions. This section will help provide such a structure to aid in FMS operational decision making.

For the design and installation phases of FMS implementation, the importance of involving all levels of the organization has been stressed already. Similarly, you should be aware that once the FMS enters the operational phase, successful functioning of the FMS will require ongoing activities at all levels of the organization. The various activities required are best understood in terms of the classical three-level view of organizational operation.

The first level consists of long-term decision making, typically done by higher management. This involves establishing policies, production goals, economic goals, and making decisions that have long-term effects. The second level involves medium-term decisions, such as setting the production targets for each part for the next month. These decisions are typically made by the FMS line supervisor, aided by decision-support software. The third level involves short-term decisions, such as which workpiece should be introduced next into the system. Under normal circumstances, these decisions are made by the FMS control computer(s). However, when an exception occurs, such as a machine failure, the FMS line supervisor may decide to take over some of this decision making, again aided by the decision-support software.

A summary of the three levels of decision making, and associated software, hardware, and management tasks, is given in Figure 31 on page 90. The remainder of this chapter will describe these tasks. The primary aim here is to give an understanding of the issues involved in operating an FMS and the typical software decision aids that should be available to the FMS managers/supervisors. The architecture of the software and hardware components will not be discussed here; this architecture is described in Volume II of this handbook, and Volume V presents the details of the software.

A key point is the importance of software decision aids in successful FMS operation. The complexity of the FMS operation task should not be underestimated: even experienced shop-floor supervisors find that running an FMS efficiently can be very difficult. In reading the following sections, take note of the role played by software decision aids so that the devel-

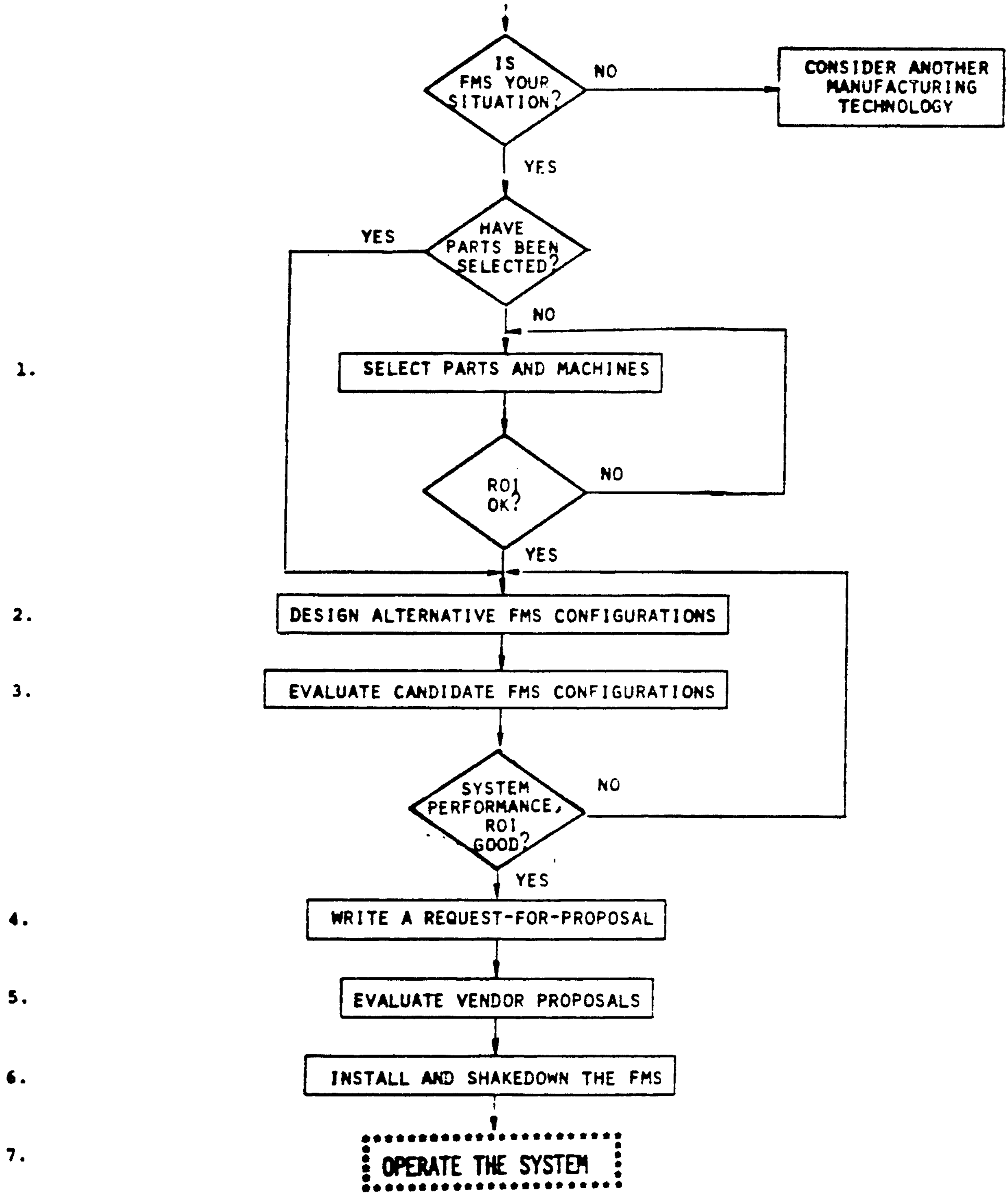

Figure 29. Acquisition of an FMS: Step 7

OPERATE THE SYSTEM

- Schedule parts.
- Batch production if necessary.
- Allocate parts and tools to machines.
- Balance machine loads.
- Use a decision support system to optimize daily operations in the face of machine failure and changing part requirements.

Figure 30. Steps in FMS Implementation: Step 7

opment or acquisition of an integrated Decision Support System (DSS) can be considered to aid in the efficient running of the FMS.

6.1 FIRST-LEVEL OPERATIONS

These should 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 typically will 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 DSS computer.

The activities that need to be performed in each of the operational areas are now described further. In the descriptions that follow, we assume that the FMS is part of a larger manufacturing environment, so the following functions are already being performed at the corporate (or plant-wide) level:

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

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

Time Horizon	Management Level	Typical Tasks	Typical Decision Support Software Used	Hardware Used
Long Term (Months/Years)	Upper Management	•Part-mix changes •System modification/ expansion	•Part Selection Program •Queueing models •Simulation	•Mainframe Computer or DSS computer
Medium Term (Days/Weeks)	FMS Line Supervisor	•Divide production into batches •Maximize machine utilization •Respond to disturbances in production plan/ material availability	•Batching and Balancing Programs •Simulation	•DSS Computer or FMS Computer
Short Term (Minutes/Hours)	FMS Line Supervisor (exceptions only)	•Work order scheduling and dispatching •Tool management •React to system failures	•Work order dispatching program •Operation and Tool Reallocation Program •Simulation	•FMS Computer

Figure 31. Levels of FMS Decision Making

6.1.1 Strategic Decisions

Even after the FMS is operational, upper management will continue to make FMS-related decisions which have far-reaching consequences. Examples of such decisions are:

- Parts-mix changes, e.g., allocating a new part type (or part types) for production on the FMS.

- System modification/expansion, e.g., adding a new machining center or changing the MHS layout.

These decisions typically involve complex tradeoffs between economic investments and resulting changes in system performance. A framework and methodology for studying these decisions has been given earlier in this volume, and typical software tools that aid in this decision making process are described in Volume V.

6.1.2 Evaluating FMS Performance

It is important to have a system for monitoring the performance of the FMS relative to management goals and to ascertain the economic (and other) returns from FMS operations. Real-time FMS monitoring takes place at the third level; here we are concerned with summary indicators of system performance. This is best done by using an MIS that periodically receives detailed performance information from the FMS computer. Analyzing and summarizing this detailed information can then be done according to the wishes of upper management, using the standard capabilites of an MIS.

6.1.3 Ancillary Support

The ancillary support services described here involve all three levels of the hierarchy. However, it is appropriate to consider them as part of level-one operations, because they are primarily concerned with developing new applications for the FMS, and hence have a longer time horizon. Such support services include:

- Extended part programming facilities.

- Part-program verification tools.

Upper-level technical support for an FMS is an ongoing task because each time a new part type is allocated to production (e.g., using the Part Selection Software in Volume V), it requires considerable further analysis and preparation to be included in the FMS part repertoire. It is also necessary to refine methods as operational data is accumulated.

Part-program production uses almost every computer in the system. Part design and manufacturing analysis is an effort that must be supported by a variety of utility programs on the mainframe computers. In particular, a part programming language processor is used to create the part programs from drawings and specifications. To ensure that the programs do what is intended, extensive part-program verification aids must also exist. These usually involve some form of graphic analysis and tool path plotting. In an FMS where parts may be partially produced on dissimilar machines, separate part programs will have to be used for each machine. Thus, the total effort for part programming can be a lengthy process.

6.2 SECOND-LEVEL 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 that maximizes resource utilization.
- Responding to changes in upper-level production plans or material availability.

The main issues involved in each of these tasks are described in the following sections. Also mentioned are software tools that the FMS supervisor should use to aid in decision making. These software decision aids typically would reside on the FMS computer, or if this is not feasible, then on a DSS computer (as defined in the previous section).

6.2.1 Batching and Balancing

Since an FMS is usually part of a larger manufacturing environment, the inputs and outputs of material to the FMS must match the overall plant MRP and master production plan. These plans specify various availability dates for raw material and various due dates for completed pieces, as well as quantities to be produced. At the same time, in trying to keep to the overall plans, the FMS manager must satisfy many other constraints, such as limited numbers of fixtures and pallets, tool capacity, available machine time, amount of work in process, etc. The task of meeting all the production requirements, while using the FMS resources efficiently, is often complex, and is divided into two stages.

The first stage (which is typically done off-line, once a week or once a month) takes the output of the MRP/production plan for the next week (month) and divides the FMS production into batches. This is necessary since tool capacity limitations usually prohibit simultaneous processing of all candidate parts. Each batch should be designed to have a balanced mix of parts, i.e., makes even and efficient use of all FMS resources.

The second stage of work order dispatching (usually done on-line, by the FMS control computer) uses the targets set by the batching and balancing stage to decide when to introduce the next workpiece into the system and which part type that workpiece should be. This decision is part of the third-level of operations, described in "Level-Three Operations" on page 94. In this section, the first stage introduced previously, which involves batching and balancing the workload on the FMS, will be discussed in more detail.

6.2.2 Batching Parts on an FMS

The need for batching in an FMS can arise for a variety of reasons. Prime among these are the tool capacity constraints that exist for each machine. If the parts to be produced require more tools than will fit on the machines, they will have to be divided into batches, with tool changes between. In addition, batches could be mandated because internal pallet storage is insufficient to handle all parts at once or because part due dates and casting availability dates are widely staggered.

Assuming that there is enough machine capacity to process all desired parts by their due dates, then it must be possible to split the group into a number of smaller batches. However, questions immediately arise as to how many batches must be formed and what parts should comprise each batch. The problem is complicated because you are trying to process parts efficiently, on schedule, while minimizing in-process inventory and staying within tool capacity constraints.

If the batching is performed solely using manual procedures, it may take a considerable investment of time to produce workable solutions, for example, solutions where tools needed at each machine do not exceed the machine's tool storage capacity. However, this task can be done much more efficiently using automated decision aids, such as those described in detail in Volume V.

The main criterion the batching procedure should satisfy is to minimize the total time it takes to process all parts. This translates to the following two issues:

- Minimize the number of batches required to process all parts. (This minimizes the time associated with batch changeovers.)

- Maximize the average utilization over all machines. (This minimizes the time required to work through an individual batch.)

The second of these issues highlights the need for balancing the work evenly among the machines. This problem is addressed next.

6.2.3 Balancing the Workload on an FMS

The need to arrive at balanced allocations of parts and tools to FMS machines arises from economics. It is important that the expensive resources represented by FMS machines not be allowed to stand idle. Workloads must be balanced so that all machines finish their work for each batch more or less together and a new batch can start immediately.

Typical constraints that influence the allocation of parts and tools to machines are tool-capacity constraints, tool costs, fixturing limitations, in-process inventory, system workload, and machine-failure statistics. As with batching, there is a complex problem to solve, and manual solution is both difficult and very time-consuming. Again, this task can be expedited by use of software decision-aids such those detailed in Volume V.

Two main issues should be addressed by the balancing procedure. They are:

- Minimize the differences in time required for workload assigned to different machines.

- Be sure all the work for each batch is in fact assigned to some machine in the system.

The second issue here brings up the possibility of conflict. Due to individual machine tool capacity constraints, it might in fact turn out to be impossible to assign the work prescribed for a given batch. This would depend on the batching procedure used. For example, the batching procedure used by the software described in Volume V is designed to minimize the chance for such an outcome, but it cannot absolutely prevent it. So there has to be a mechanism for iteration: if balancing fails, batching must be tried again, with some modification to its inputs. In recognition of these interdependencies between batching and balancing, in Volume V the two problems are treated together, with one subordinated to the other, in the same software package.

6.3 LEVEL-THREE OPERATIONS

This level is concerned with the detailed decision making required for real-time operation of the FMS. The time horizon here is typically a few minutes or hours, and the decisions involved are:

- Work order scheduling and dispatching (which part to introduce next into the FMS, and when).

- Movement of workpieces and MHS (which machine to send this workpiece to next, which cart to send to pick up this workpiece, etc.).

- 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 (depending on the system architecture). However, when an exception occurs, such as failure of a machine, the FMS supervisor will usually take charge of the decision making. If a machine is going to take a long time to repair, he may, for example, decide to reallocate its production to other machines. This involves a complex sequence of tradeoffs between part production rates and machine and tool capacities. Again, the FMS supervisor's task can be simplified considerably by employing various software decision aids. More will be said on these below. These decision aids should typically 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 above.

6.3.1 Work Order Scheduling and Dispatching

This task controls the flow of workpieces into the system. It takes as input two sets of parameters. The first set of parameters are those the batching and balancing function in the second level decides, which defines the overall allocation of system resources to production of each type of part. The second set of parameters are supplied by the system manager or the FMS control computer, and they specify the current status of the system, such as failed machines, types of pallets/fixtures currently available, raw material available, deviations from desired production rates, etc. The work order dispatching function takes into account all these inputs to decide when to introduce the next workpiece into the system and which part type that workpiece should be.

While this task is usually carried out by the FMS computer, the actual division of decision making between the supervisor and the computer can vary, depending on the supervisor and on the particular FMS. Typical systems have the FMS computer making the decisions, but they allow the supervisor to supply various inputs that can influence those decisions. An overview of the usual "control inputs" available to the supervisor follows:

- Total number of pallets in the system. Generally, increasing the supply of pallets will increase the rate at which parts flow through the system and vice versa. This is because having more pallets increases the probability that a part will always be ready for processing when a machine becomes idle. There is, of course, a point of diminishing returns. In fact, as more and more pallets are added to a system with limited storage capacity, the resulting congestion may actually reduce throughput.

- Total number of each pallet-type. Most FMSs operate in a "closed system" mode; when a pallet comes out of the system, a part is chosen that can be fixtured on the pallet and the pallet is then sent back in. If more than one part type can use a given pallet type, the part that is most behind in production is usually chosen.

- Part priorities. Some control systems allow the operator to fine-tune part priority above and beyond allocation of resources to it -- machines, pallets, etc. The basic mechanism is to alter the processing order so that certain parts waiting to be processed by a particular machine can be processed first. This is in contrast to arrangements that force a first-come/first-serve processing.

- Scheduling interval. Some systems allow a time interval to be specified between successive introductions of workpieces of a particular part. In this case, even if the resources required for a workpiece (pallets, fixtures) become available, the system will not introduce that workpiece until the specified interval is over. (Of course, if the interval is over but resources are not available, the introduction will have to be delayed until the resources become available.)

In the case of each of these "control inputs", it is not easy to predict precisely how changing the value of an input for a part will affect production of that and other parts. Here again, software decision aids can prove very helpful to the system supervisor. The most reliable software tool for predicting the consequences of any change in inputs is a detailed simulation program. However, if many different options are to be tested, this can sometimes take a lot of computer time. Alternative software tools which give more rapid results, but are less accurate, are based on the network-of-queues theory. Both types of software tools, i.e., simulation and queueing network models, are described in depth in Volume V.

6.3.2 Movement of Workpieces and Material Handling System

The decisions as to which machine (or machine choices) is (are) available for a particular operation of a part are made in the batching and balancing stage (level two). However, the real-time movement of workpieces around the system is controlled by the FMS computer and/or the MHS computer, in conformance with the decisions made at the batch/balance stage. Under normal circumstances, this workpiece/MHS decision making should be transparent to the FMS supervisor, and will not be discussed here, although some details can be found in Volume II. When an exception occurs, the supervisor may intervene in this decision making level, as described in a later section.

6.3.3 Tool Management

This operational area is concerned with three functions:

- Collecting and updating data regarding the tools on each machine.

- Keeping track of tool wear, and replacing tools.

- Reacting to tool breakage.

The first function involves an interface between the tool crib and the FMS computer. Tooling data is generated in the tool crib and entered by the tool setters into the computer through a terminal located in the tool crib. Alternatively, tool gauging data can be sent directly to the machine-tool controller by an automatic tool-gauging station. This latter feature can reduce tooling cost by reducing the possibility of manual data transcription errors.

A software module in the FMS computer usually can perform the second function directly. When tooling data is entered for a new tool, a conservative estimate should also be included to initialize the limit at which the tool should be replaced/resharpened. A history of tool utilization will be kept and the tool replacement point adjusted either up or down, based on the results of periodic workpiece inspection. When the use of a particular tool has exceeded its anticipated lifetime, a warning will be issued to the system operator and operations will be prevented until the tool is changed or the warning is overriden. Each time a tool is used, a tooling data file is updated so that current reports on tooling status are available.

It should be noted that coordination of the tool replacement task, the activities of the tool crib, and the delivery of tools from the crib to an FMS machine is a complex task. The system supervisor should devote some planning to this task since the successful operation of the FMS, that is, meeting the production schedules, depends as much on tool management as it does on management of other FMS resources.

The last function is discussed in a later section devoted to reacting to failures.

6.3.4 System Monitoring and Diagnostics

These functions are essentially performed under FMS computer control (and/or MHS computer control) and do not require the FMS supervisor. They are discussed further in Volume II. It should be noted, however, that good monitoring and diagnostics are important for the successful operation of an automated system such as an FMS, since they indicate areas where intervention may be needed. To the extent that diagnostics show the need for corrective action, the FMS supervisor's role is discussed in "Reacting to Disruptions."

6.3.5 Reacting to Disruptions

Disruptions in system operation are certain to arise and will require the FMS supervisor to take corrective action. Examples of such disruptions would be:

- Machine failure.
- Tool failure.
- Tool replacement warning.
- MHS failure.

In the case of a tool failing or needing replacement, the action to be taken is clear. This is not so in the case of machine failure.

There are two courses of action possible when a machine fails: either shift the production of affected parts to another machine or temporarily stop their production. If alternate tooling already exists elsewhere in the system, a shift is easily performed and may automatically be handled by the vendor-supplied control software. If the tooling is not available, work can still be transferred from one machine to another, but so must the tools. The problem is that shifting tools from a failed machine will often displace other tools and their associated parts from a working machine. Some of the many questions that must be considered when making a tool-change decision are:

- How will the production of other parts be affected?
- How long will it take to change tools?
- How long will the machine be down?
- Is there enough room to store semifinished parts?

As before, software decision aids can prove very useful in answering these and other questions and in helping the supervisor arrive at a good decision. In this case, the software tools required would be simulation and/or queueing models, both of which were discussed earlier in this chapter and details of both can be found in Volume V.

Similarly, in the case of MHS failure, if the repair is going to take a long time, the supervisor can decide whether to operate a subsection of the FMS to produce a subset of the parts. This decision would also be enhanced by use of appropriate software decision aids.

A barrage of such disruptions can force the supervisor into a "fire-fighting" mode. The software decision aids described, while useful in predicting the effect of any decision, do not automatically find a good decision. Thus, the supervisor may sometimes have to make many attempts before a satisfactory decision is found.

6.4 INTEGRATION OF FMS OPERATIONAL LEVELS

The preceding sections described the various levels of decision making relevant to successful and efficient FMS operation. Figure 32 on page 100 summarizes summarizes the decisions involved at each level (only the major decisions are shown, for clarity).

Of equal importance as the decision making within each level, is the question of communication between the levels. Be sure of the answers to the following questions before becoming "locked in" to a particular system architecture:

- How will data (such as part programs) be moved from the mainframe computer to the FMS computer?
- How will information (such as system performance) be communicated from the FMS computer to the mainframe computer?
- Will a separate DSS computer be used, and if so, how will it communicate with the above two computers?

From the descriptions of the tasks in each level, the importance of software decision aids for enabling a supervisor to run an FMS efficiently is obvious. If an FMS is not supplied with an adequate DSS, the creation of one should receive top priority.

Integration of the operational levels is also an important ability to be incorporated within the DSS software to be used with the FMS. For example, it should be possible to test any decision made at a higher level (e.g., part selection) by trying out all the lower levels (such as batching and balancing, and detailed simulation) and thus evaluating that decision in detail. In this respect, it should be noted that all the decision aids for lower-level decisions are part of the decision aids for a higher level. Thus, for example, simulation should also be thought of as a decision aid for the batching and balancing problem, even though this was not mentioned explicitly in the section on batching and balancing.

6.5 OTHER ISSUES IN OPERATING AN FMS

This section highlights those additional issues users have found to be most important in running an FMS. These are not mathematically quantifiable decision problems; they are people problems. They cannot be neglected, for the impact they have on performance can be quite high.

6.5.1 Manning an FMS

"Preparing to Take Delivery of an FMS" on page 79 elaborated on the various skills required in running a system.

One point to reiterate here is that some users have found that there are significant benefits to be gained when most personnel running the system have the skills needed to do the other jobs as well. Of course, union policies may be a problem, because operating in this manner may require that

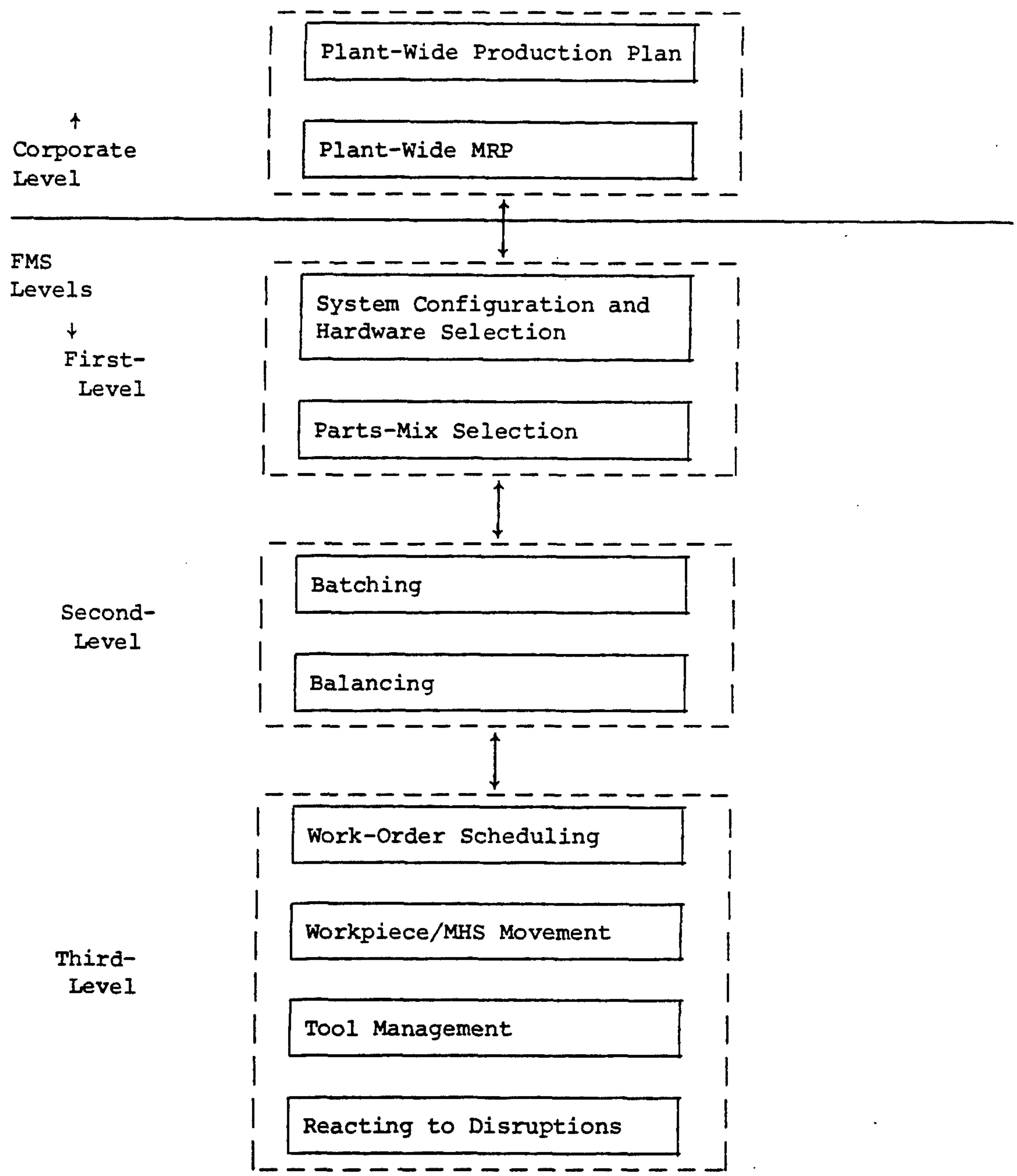

Figure 32. Integration of FMS Operational Levels

the same job description, pay, etc., be given to everyone. If these problems can be solved, the results should be worth the effort.

6.5.2 Shift-to-Shift Cooperation

An FMS generally must run on multiple shifts to justify itself economically. This creates a need for the cooperation of personnel between shifts. Users have found this to be an important area and one which is often overlooked.

It is most important to share information such as production attained during the shift, problems encountered, and problems that may occur on the following shift. It is also desirable that similar system operating policies be followed from shift to shift. For example, it is usually detrimental to the achievement of overall production goals if the first- and second-shift operators try to optimize production by continually changing part priorities when the third-shift operator adopts a "hands-off" approach and allows the system to run itself.

6.5.3 Real-Time Part Programming

Eventually, an on-the-shop-floor change to a part program will be needed to prevent a temporary reduction in part production. It may happen, for example, that the third shift finds an extra half inch of stock on its castings. Unless personnel on hand are authorized to make necessary changes, the castings would not be machined.

The risks associated with having a number of people making changes to a program are well known. Success depends upon the cooperation of all involved. Changes have to be approved and recorded.

At this time, there seems to be no clear direction to take for real-time part programming. Users have adopted both approaches, where FMS operators have been allowed to make real-time changes to the part program and where they have not, with varying degrees of success.