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FLEXIBLE MANUFACTURING SYSTEMS
PHASE IV
FINAL REPORT

Contract DAAE07-82-C-4040

by The Charles Stark Draper Laboratory, Inc.
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This report is a summary of work performed under contract to the Army Tank-Automotive Command for the fourth phase of a five phase FMS project funded by the Army's Manufacturing Methods and Technology Program. During this phase, computer analysis and simulation tools developed during the previous phases of the project were implemented through support efforts for US Army Rock Island Arsenal, and three Army contractors: General Electric Ordnance Systems Division; Hughes Aircraft Company; and FMC Corporation. The arsenal and three contractor companies were in the process of investigating/imple-

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20. Abstract (Continued)
menting FMS technology and used the Draper Labs support to aide in their system design, analysis, and decision making efforts.

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FLEXIBLE MANUFACTURING SYSTEMS

FINAL REPORT FOR PERIOD

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Prepared for

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Publication of this report does not constitute approval by the U.S. Army Tank Automotive Command of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

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FMS PROGRAM SUMMARY

This document constitutes the Final Report of the mainline FMS Army Contractor support activities performed by The Charles Stark Draper Laboratory under U.S. Army/TACOM sponsorship (Contract DAAE07-82-C-4040).

Final reports for Change Order P00001 (Maremont/Saco plant layout and gun barrel straightness measurement studies) and P00002 (Rock Island 1983 follow-on) are presented under separate covers.

This Final Report summarizes the work performed during 1982 and the period 1 January 1983 through 31 July 1983. The bulk of this document was published earlier as Draper's Intermediate Technical Report for the period 1 June 1982 to 31 December 1982 (Memorandum FMS18762-413); it provides a comprehensive statement of objectives, activities, and results for that period, during which Task 1 (General Electric/Ordnance), Task 3 (FMC/Ordnance), and Task 4 (Rock Island Arsenal) were completed.

The entirety of the Draper effort during January-July 1983 was in support of Task 2 (Hughes Aircraft Company/Electro-Optical Data Systems Group (EDSG)/El Segundo, California).

Major milestones completed during this period were:

Task 1: General Electric Ordnance	
Final RFP issued	July 1982
Task 2: Hughes Aircraft/EDSG	
DSS Specifications Completed	June 1982
MVAQ Module Coded and Debugged	August 1982
BATCHBAL Module Coded and Debugged	September 1982
Installation and Integration of MVAQ and BATCHBAL	October 1982
Installation and Integration of "FMOVE" Scheduler	February 1983
Installation and Integration of "FSIM" Simulator:	
Version 2.0	March 1983
Version 2.1	July 1983
Version 2.2	September 1983
Installation and Integration of "REACT" (to out-of-service equipment)	May 1983
Definition of Functional Requirements of Second-Generation Software Packages (Extensions and Refinements)	May 1983
Installation of "PARSE" (Parts and Machine Selection for expanded FMS utilization)	August 1983
Task 3: FMC Ordnance/San Jose	
System Configuration Design and Evaluation	June 1982
System Simulation	July 1982
Economic Analysis	July 1982
Development of Vendor Selection Criteria	August 1982
Comparison of Head Changer and FMS Technology	August 1982
Review of Vendor Proposals	August 1982

Task 4: Rock Island Arsenal (RIA)

Part Preselection	October 1982
Part and Machine Selection	November 1982
Presentation of FMS Feasibility Study Results	December 1982

SUMMARY OF TASK 1: CSDL/GENERAL ELECTRIC PROJECT

The GE task was in the procurement step for an FMS in 1982. CSDL's role was to help refine the previously prepared RFP and help GE evaluate vendor proposals. The final RFP was not issued due to a reassessment of capital expenditure priorities within General Electric Ordnance Systems Division (GEOS).

SUMMARY OF TASK 2: CSDL/HUGES AIRCRAFT COMPANY FMS PROJECT

Hughes Aircraft Company has installed a Flexible Manufacturing System (called FLEXFAB) in a new plant in El Segundo, California. Under Task 2, CSDL and Hughes are producing a computer-based planning system (called FLEXPLAN) to aid FMS production planning and support its operations in automatic, semi-automatic and manual modes. FLEXPLAN will extend the capabilities of complex manufacturing system management. Lack of such management decision aids can diminish the potential productivity of flexible manufacturing systems (FMS's).

The objective of FLEXPLAN is to reduce costs by improving the quality of decisions required to run an FMS at maximum utilization. Those decisions involve what parts can be processed concurrently on the FMS and how those parts and their associated tooling are allocated to the machines. FLEXPLAN also aids scheduling of the FMS. At the same time, FLEXPLAN recognizes that short- and long-term production needs are often compromised by day-to-day disruptions. Machine and tool failure and emergency changes in production plans all create a need for decision aids that offer a choice of responses and maintain the overall productivity of the line.

Because the operator cannot foresee all consequences of every decision, FLEXPLAN embodies two main functions: it makes decisions and predicts the consequences of those decisions. The first function employs optimization techniques for making decisions, and the second function employs simulation techniques for predicting performance of the FMS.

Work Done in This Period

The focus of the work performed in this reporting period was twofold: to produce a functional specification for the FLEXPLAN system that reflects the major concerns of the Hughes environment; and to follow this with software module design, coding, debugging, and installation. Several coordinating meetings were held between CSDL and Hughes personnel before coding and testing began. Integration of the programs at Hughes was begun in August 1982. By the end of 1982 two major modules (Batch

Planning and Queue Modeling) were in use at Hughes for production planning.

During 1983, Draper installed Scheduling, Reaction to Out-of-Service Machines and Simulation packages onto Hughes facilities. In May 1983, functional requirements for extension and refinement for the following programs were defined by Hughes and Draper personnel:

- "FSIM" (Discrete-Event Simulation)
- "FMOVE" (Scheduling)
- "REACT" (Reaction to Out of Service Machines)
- "BATCHBAL" (Batching and Balancing Work Load)
- "ROLLING BATCH" (Batch-to-Batch Tool Changeover Planning)

Second-generation versions of these programs are being developed under 1983-1984 contract funding and will be installed in January-February 1984.

Hughes personnel are integrating these packages with one another and to other Hughes-developed software, as well as with user interfaces in the form of menu-driven input/output and job launching video screens.

SUMMARY OF TASK 3: CSDL/FMC PROJECT

The FMC Feasibility Study consisted of three major line items or phases. Phase I consisted of two subtasks: (1) Examine the technical and economic feasibility of producing on an FMS, for 14 parts originally chosen by FMC as appropriate for head changer technology; and (2) Examine all 3,200 BFV/CFV "make" parts to determine which, if any, could be produced economically on an FMS (this included the 14 head-changer parts). Phase II encompassed detailed FMS configuration design and evaluation, using simulation and economic modeling, to be undertaken only if one or both of the subtasks of Phase I indicated that an FMS would be economically justifiable. Phase III entailed assisting FMC personnel to prepare a general Request-for-Proposal for the FMS defined in Phase II, contributing to the final proposal specification, and developing an evaluation matrix that FMC personnel would complete in their evaluation of the proposals.

All three phases of the study were completed by the end of August 1982. Phase I showed significant savings by processing the 14 parts on an FMS. Furthermore, review of the 3,200 parts revealed that, while approximately 60 parts could be produced more economically on an FMS, the 14 already chosen had the greatest potential for savings. Thus, the chosen part set and the "ideal" part set were the same, substantially reducing the detailed design effort required in Phase II.

The detailed configuration design and evaluation effort undertaken in Phase II suggested that a five-machine FMS, consisting of four four-axis horizontal machining centers, one vertical turret lathe, and a wire-guided vehicle material handling system would be the most efficient system.

Using average equipment costs and calculating the potential part savings of using an FMS over the conventional method, the economic model showed an acceptable payback period. A direct capacity comparison showed that FMC could avoid purchasing 12 to 16 CNC machining centers and lathes by installing the five-machine FMS due to increases in machine utilization over current shop values. (Note that the term 'utilization' refers to the proportion of its available time that a machine spends 'in process'; this includes being 'in cut', waiting for probing and in-process gauging, and tool positioning. 'Utilization' is expressed as a percentage, e.g.,"a machine is working at a level of X% Utilization"; 'Utilization' is not used interchangeably with the more general term 'use'.)

Midway through the project, FMC assigned a person to be System Manager after the system was purchased. The System Manager decided that initially there should be no turning work in the system, thus eliminating nine of the original 14 parts. These parts were replaced by nine others from the 60 parts indicated as economically acceptable in Phase I. Although less total savings could be expected from this new part set, the FMS now only required three four-axis machining centers, offsetting the savings loss. Finally, the production level used to size the system was increased, requiring one more four-axis machining center in the system. This new production level and part set became the basis for an FMS Request-for-Proposal (RFP).

FMC issued the Request-for-Proposal package first to three American vendors, and then to three foreign vendors. Two American vendors responded. These vendors worked closely with CSDL and FMC to determine process plans and fixturing concepts for the parts, and benefited from joint discussions on desirable system components. The vendors presented their final proposals in August 1982. FMC started the vendor selection process and issued a purchase order for an FMS early in 1983 to Cincinnati-Milacron.

SUMMARY OF TASK 4: CSDL/ROCK ISLAND ARSENAL PROJECT

The Rock Island Arsenal (RIA) FMS Feasibility Study was undertaken to determine the suitability of FMS technology for the production environment at RIA. RIA currently produces approximately 4,200 different part numbers in quantities of one to 500 annually on a mix of approximately 2,000 stand-alone manual and N/C machines. The applicability of FMS technology was judged on the ability to select a combination of parts and FMS-compatible machines that would generate sufficient cost savings over the present production method for those parts to pay for the FMS in a reasonable time. Two part and machine selection algorithms, PAMS (Part And Machine Selection) and PARSE (PARt SElection), were developed. The principal effort in this reporting period was to apply those tools to the RIA part set and determine whether FMS technology had potential for RIA. This study demonstrated that an FMS shows considerable savings over stand-alone N/C machines. Hence, RIA decided to proceed in 1983 with the next phase, Detailed System Design and Evaluation.

TASK 1: CSDL/GE FMS PROJECT

BACKGROUND

An FMS has been designed and evaluated by CSDL for GEOS to manufacture 11 turret stabilization parts for the Bradley Fighting Vehicle. A request-for-proposal was issued to several American and foreign vendors in September 1981.

CURRENT FMS PROPOSAL STATUS

Three FMS vendors presented proposals - Giddings and Lewis, White Sundstrand and Comau. The systems proposed ranged in size from two to three duplicate, four-axis horizontal machining centers serviced by either wire-guided carts or carts on rails as a MHS. A computer-controlled coordinate measuring machine would be integrated into the FMS for part and process verification.

Each vendor was invited to present a proposal to GEOS. After review of each of the proposals, the vendors were asked to describe more fully specific areas of their proposals. The vendors subsequently presented their revised proposals to GEOS for further consideration.

FINAL REQUEST FOR PROPOSALS

After the second round of vendor proposals, GEOS and CSDL reviewed the individual proposals. After this review, GEOS issued a more detailed, final request for proposal (RFP) in July 1982. (The first RFP was issued for a budgetary level of detail.) The final RFP was organized the same as the budgetary RFP. More detail was added to the machine specifications with respect to minimum accuracy requirements, lubrication and maintenance requirements. More information was added on the features and capabilities of individual machine controls. Also included were requests for additional accuracy specifications for the coordinate measuring machine and more details about FMS tool changing and tool management.

GEOS has not issued this RFP to date due to a general reassessment of capital expenditure priorities within General Electric Ordnance Systems Division.

TASK 2: CSDL/HUGHES AIRCRAFT COMPANY FMS PROJECT

INTRODUCTION

The FLEXPLAN system is a component of an integrated manufacturing system in that it assists in controlling the various FMS manufacturing processes. A block diagram in Figure 1 on page 7 illustrates the basic partitioning of the system. In the initial implementation of FLEXPLAN, the part programming function is not directly tied into the facility such that the part programs can be loaded directly into FLEXPLAN files. Thus, the part programs and the data they contain about machining times and tooling requirements are shown connected to the system with dotted lines.

The FLEXPLAN functional modules reside in an HP3000 computer. The system is under the control of the FLEXPLAN Executive. This program uses the Hughes-developed HICLASS data classification system, an effective method for interrelating data and/or programs that can be maintained in hierarchical tree abstractions. The Executive function handles the operator/system dialogue, which serves to bring in input data, invoke system programs and output data to files or displays. The Executive controls and coordinates all the programs and utilities of FLEXPLAN.

The system uses data gathered from a variety of sources. Manual input is needed to supply information on production data, including production quotas, number of castings available, status, failure repair times, priorities, and due dates. FMS status data will be transmitted periodically from the Kearney & Trecker (K&T) FMS computer through a special communications link. These data include machine status, tooling configurations, pallet availability, and work in progress. The link may, in the future, be used for modified control of the FMS as a part of the FLEXPLAN function. The data link may emulate typical actions at an FMS terminal to bring data and status into view, except that in this case, the information will be stored in separate data files for use in the FLEXPLAN system.

The Data Base Management function is an important part of the system. Management of FLEXPLAN data involves creating input and output files for the different system functions. The data files draw from data generated as part of the production planning, run-time operations, and operator inputs.

Integration of the FLEXPLAN modules involves coordinating the access and consolidation of data from the various files into separate input files for the different modules. In turn, output from the FLEXPLAN modules are stored in separate files or displayed on the operator console.

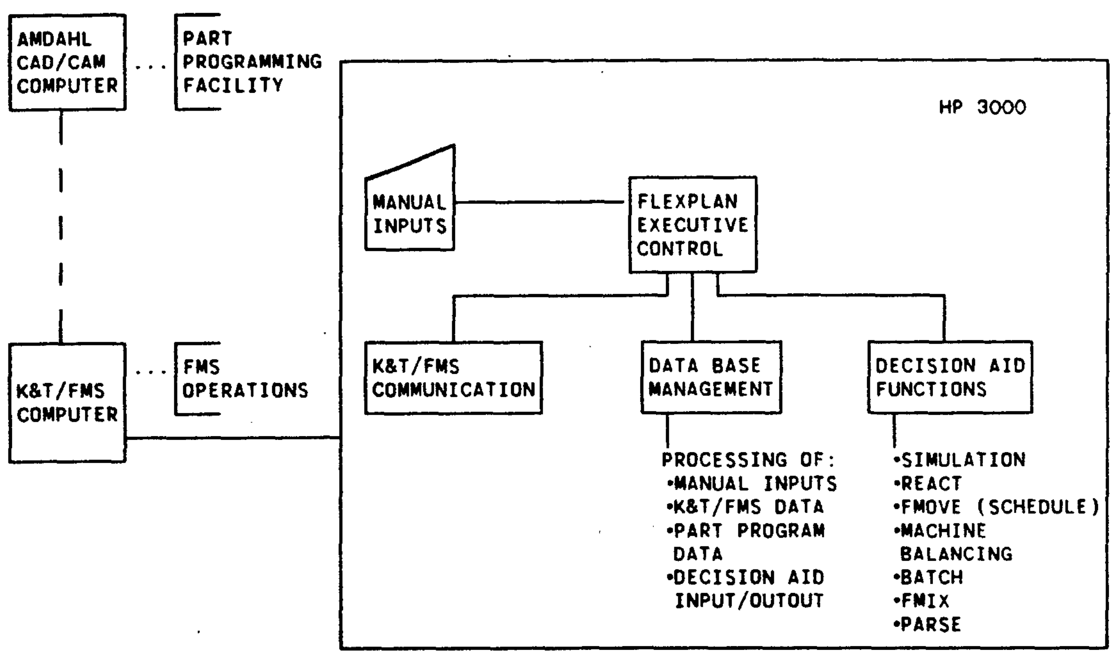

Figure 1. FLEXPLAN Functional Block Diagram

DIVISION OF WORK AND SCHEDULE

FLEXPLAN is being constructed at both Hughes and CSDL. The partitioning of the collaborative effort is illustrated in Figure 2.

Hughes Aircraft is responsible for the design and construction of the FLEXPLAN control software and the data base communications and management. This includes the methods for communicating with the K&T FMS computer for status and output information, as well as route plans, tooling information and production schedule requirements.

CSDL is designing and constructing the functional modules of the system, which are described in detail in subsequent sections. These modules provide management decision support for batch planning, machine balancing and tool allocation, fixture allocation, reaction to failure and system modeling and simulation.

Hughes Portion	CSDL Portion
FLEXPLAN SYSTEM CONTROL AND DATA BASE MANAGEMENT	FLEXPLAN SOFTWARE MODULES
• Executive Control and User Interface	• Simulation and Modeling
• K&T FMS Data Communications	• Failure Reaction
• Route File Generation	• Entry of Parts
• System Status File & Tool Allocation	• Machine Balancing
• Graphical Displays	• Batch Planning
	• Fixturing
	• Part Selection

Figure 2. Apportionment of System Implementation

AUTOMATED DECISION AIDS AND USAGE

In the continuous operation of an FMS there are many intermittent problems that present unique production difficulties. The FLEXPLAN system has grouped these problems into generic sets. Within each of the generic FMS operational problem areas identified, one specific critical problem is addressed and provided with an automated decision aid. The problems occur in the daily and weekly activities and are too complex to be made by the operator without computer aid. They are as follows:

1. Response to Disruptions - Unforeseen contingencies arise and give the operator problems to be solved in real time. In the event of machine breakdown or overload, decisions are required to determine if and how work and tools are to be shifted among machines.

   This program is called REACT. The problem it addresses is as follows: Some machine in the FMS breaks down. Repair will take an amount of time, at least approximately known to the operator. The work which the machine would have done during that time could be performed by other machines in the FMS, possibly at the price of moving some tools. How much, if any, work reallocation should be done, and how many and which tools should be moved from where to where?

   REACT can be used when a breakdown occurs; it will provide an initial check as to whether reallocation of work and tools is required. If queues in place are sufficient to outlast the repair, there is no need to reallocate.

   While REACT is primarily for FMS management during repairs, it could also have a role in normal operations. It could help re-establish balance if there is a sudden change in demand for some part. Also, if, in spite of the K&T software designed to prevent such things, there should develop a longer-than-usual queue somewhere in the system, then the operator should be able to use REACT to reduce it. Declaring a fictitious breakdown and repair time for the overloaded machine may be sufficient.

2. Real-Time Control - The operator can invoke the program FMOVE to help in real-time FMS control and scheduling.

   This program addresses the following problem: A space for additional work materializes in the FMS because: (1) a part is completed and delivered out of the system; (2) some machine becomes vacant and has no queue of work to draw upon; or (3) some other contingency occurs. What, if any, new part(s) should go in, and in what orientation(s)? That is, what fixture do we need next?

   FMOVE can be run normally every time there is an opportunity to enter work in the system. If there are already many fixtures in the system, the risk of cart deadlock may be sufficient to recommend a delay in entering new work. A simple fixture count and comparison to a preset bound is used for this.

FMOVE overlaps somewhat the functions provided by K&T software, and so requires a convenient interface for when it is used. FMOVE also has uses for repair, just as it does in normal operation. FMOVE may be called to feed the system if a machine runs out of work during the repair. FMOVE can also serve to rebuild the queue of the down machine when it is up again, and thus rebalance the system.

3. Batch Planning - Given an overall production requirement for some time period, the part-batching function organizes and optimizes the tool allocation and machine work load balancing in the FMS. This is a non-trivial task when there are many short-run parts, each having a different due date and/or date at which its raw materials become available; there are always limitations on tool capacity and often on pallet storage.

This program, called BATCH, solves the following problem: Management has prescribed a set of parts to be produced. Not all of them can be processed at once because the set of required tools exceeds, even if only slightly, the tool capacity of the system. When should tool changes be made? Which parts should be processed while each tool configuration is on-line?

BATCH is normally used for solving a problem whose time scale is large compared to any repair needed in the system. But BATCH could also have a role in disrupted operations if the breakdown happens to come near the end of the current batch. In that case, redefining the next batch to use only the operational machines makes sense. After the Batch Planning function has determined the parts that are to be simultaneously processed, a detailed allocation of parts and tools to machines must be performed. This task is important because parts often can be processed on a number of different machines with limited tool storage capacities. An intrinsic part of BATCH is a subroutine ("BAL") called to balance the workload among the machines.

The balancing problem is as follows: A part batch has been proposed, either by the BATCH program, management, or the operator. Is it feasible to allocate all proposed operations and tools to machines? If so, what, in detail, is an allocation with the most efficient machine utilization? BALANCE is a subroutine always called by BATCH, since it provides a test for feasibility and makes all the detailed work assignments. But BALANCE is also directly callable by the operator, in case he has a proposed batch that has come about not because of the BATCH program, but because: (1) management has requested that he put a part on the system immediately; (2) at the last moment, castings are not available; or (3) some other unforeseen contingency arises.

Much "what-if" analysis can be done by the operator with BATCH. The operator can: (1) respond to a management request that a particular part be worked as soon as possible; (2) catch up on work not finished on schedule; or (3) integrate new work into the previously planned work. For all of these, the ability to mandate that a few particular parts be included in the first batch defined provides the required capability.

4. Rolling Batch - Given a Batch Planning solution resulting in a number of batches (part groupings), the Rolling Batch concept and program address how to minimize tool changeover at batch-to-batch transitions. The approach is to scan existing tool complements on all machines, look forward to the subsequent tool complement/machine assignments, and to match the tool complements to minimize the tools that need to change from batch to batch. In this way, the time and risk associated with changing substantial numbers of tools from machine tool magazines (chains or drums) can be significantly reduced. This is a particularly important issue in the Hughes K&T system, in which tool changes (into the tool storage chains) are accompanied by manual entry (into a digital keyboard) of the tool offsets associated with the tools. The need to minimize tool handling is a very important issue.

   The program "Rolling Batch" can be run as a postprocessor to BATCHBAL, to anticipate the tool changeover scenarios, and in real-time as a batch completes.

5. Fixturing Requirements - The efficiency of the FMS is affected in part by avoidance of fixture limitation. High-level decisions are required to assure that the correct mixture is provided initially.

   This program, FMIX, addresses the following problem: Finite dollars are available for fixturing. What is the minimum commitment required to assure adequate functioning of the FMS?

   FMIX should be run whenever new parts are added to the inventory that the system produces. It should advise not only what new fixtures may be needed, but also if old fixtures ought to be retired in order to make the system balance well.

6. Simulation - The discrete-event simulation program for the Hughes FLEXPLAN is derived from the existing CSDL Generalized Flexible Manufacturing System Simulator (GFMS). The Hughes FMS Simulator (FSIM) models the Hughes FMS in sufficient detail to simulate accurately the behavior of the system so that reliable answers can be provided to a variety of "what-if" questions.

   FSIM mimics such major FMS activities as: load/unload, machining, and inspection operations; part, fixture/pallet, and cart movements. FSIM does not model details such as tools and part program movement.

   FSIM provides a "cold start" (empty system start) capability. The simulator tracks and reports important performance measures, including: (i)part production rates, and (ii)utilization of loaders, machines, shuttles, carts, and pallets. FSIM is usable stand-alone and in conjunction with the decision aids described above. FSIM is expandable, to reflect future FMS expansion.

   There must be considerable flexibility in how the operator accesses and uses the simulation and decision aids. All programs could be useful under various contingencies in both normal and disrupted operations. Simulation tools like FSIM are useful for "what if" questions that arise in disrupted operations. They also are needed in test-out to confirm the performance of all the decision aids described above. FSIM can reassure the operator on the reasonableness of decisions that he makes under stress in disrupted operations.

7. Simplified FMS Queueing Model - This is the "poor man's" simulation. It models the system using queueing theory to provide an estimate of total system and part-by-part throughput, average machine and conveyance utilization, and lead times. It provides quick answers to "what if" questions (requiring little computational power) but is not as accurate as discrete-event simulation.

IMPLEMENTATION GUIDELINES

Considering that FLEXPLAN is to be used by people concerned with efficient manufacturing and high FMS utilization, and whose experience with computers is probably limited, the following guidelines were followed:

1. Algorithms should be fast. If this is not possible, then algorithms should quickly arrive at a feasible solution and then (at user option) steadily work towards a better solution.

2. The system should give the operator a measure of how good the solutions to decision problems are. Simple comparisons with worst- and best-case scenarios are helpful.

3. All input data items may be manually overridden by the user.

4. The user should be able to make some or all of the decisions made by BATCHBAL and the other Decision Support programs. The algorithm would then make remaining decisions, if any remain.

5. The user should be able to observe the consequences of decisions made by the aids by using the outputs of these programs as inputs to FSIM.

6. The operation of FSIM should mimic as much as practical the actual procedures used to input production data to the FMS so that specialized knowledge of the simulation is not required.

FLEXPLAN'S STATUS

The Queue Modeling and BATCHBAL software modules were delivered to Hughes and installed beginning in August 1982. The programs were tested at CSDL and were subsequently thoroughly exercised at Hughes. The integration of these programs into a system structure with convenient input and output methods was done by Hughes with CSDL assistance through the remainder of 1982.

Hughes developed and implemented the graphical methods for preparing computer runs and outputting results in easily readable form. Extensive use is being made of these features to allocate work and tools on the FMS.

Hughes is also developing the software to store, retrieve and update the input data so that changes can be made readily. They have accomplished the following:

1. Defined input parameters for the modules to reflect the FMS and general manufacturing procedures.
2. Created schemas and data bases for the part routing information.
3. Implemented easy-to-use data entry software.
4. Implemented decision support software graphics to generate ouput charts and graphs.
5. Defined data interfaces between the software modules.
6. Implemented an executive structure for program execution.

TASK 3: CSDL/FMC PROJECT

BACKGROUND

FMC Corporation/San Jose Ordnance Plant's goal was to design and install a flexible fabrication facility in its new plant in Aiken, South Carolina, for the fabrication of components for the Army's M2 and M3 Bradley Fighting Vehicles.

FMC had previously investigated the economics of using head-changers to increase production capacity and requested CSDL assistance in assessing FMS technology as an alternative. A three-phase project was developed. Phase I consisted of two separate FMS feasibility studies. The first was to examine the technical and economic feasibility of producing on an FMS, 14 specific parts originally chosen by FMC as appropriate for a head changer. The study started with the development of cycle times from process plans and machinability data provided by FMC. The number of machines and material handling transporters were estimated using this cycle time information. These components were arranged into alternative FMS configurations, and their operation simulated to gather system performance measures. Finally, an economic comparison based on total production cost was done to see if the present production method, or an FMS, or a head changer would be the most economical production alternative in the long run. The development of cycle times was discussed in the Quarterly Progress Report for the reporting period 1 October to 31 December 1981 (CSDL-R-1535).

The second feasibility study examined all of the IFV/CFV parts to determine which, if any (including the baseline 14 examined in the first feasibility study), are most economically produced on an FMS. Using group technology codes, the 3,200 IFV/CFV production parts were screened for FMS attributes; Then CSDL examined the remaining parts in detail to determine which, if any, could be produced economically on an FMS.

In Phase II, detailed FMS configuration designs were developed and fully evaluated using simulation and economic analysis. In Phase III CSDL assisted FMC to prepare a general Request-for-Proposal for the FMS defined in Phase II and to evaluate vendor responses.

Concurrent with this proposal procedure, FMC personnel requested that three American FMS vendors propose systems for the production of the 14 baseline parts. All vendors were given the same information and asked to prepare a preliminary technical and budgetary proposal for a presentation in October 1982, and firm technical and budgetary proposal for December 1982.

PHASE IA: FOURTEEN PART FMS FEASIBILITY STUDY

The collaborative CSDL effort to process plan the 14 baseline parts for the FMS and calculate FMC cycle times is discussed in detail in Flexible Manufacturing Systems Quarterly Progress Report for Period 1 October 1981 to 31 December 1981 (CSDL-R-1535). A comparison of the estimated cycle times and FMC standard times for each part is presented in Figure 3 on page 15. Seventeen individual parts were examined because two of the 14 parts are actually assemblies; each component of the assembly is machined in the FMS, then assembled to form the end product, which is also machined in the FMS. Because these parts' data are proprietary, no part numbers or actual times are illustrated. Instead, the times are presented as ratios, with the FMS cycle time defined as "1.0". Based on the significant potential production time savings shown by the cycle time comparison, plus the potential reduction in fixtures and perishable tools, FMC decided to begin Phase II, Detailed Configuration Design and Evaluation, for these 14 parts.

Part Number	Estimated FMS Cycle Time	Current FMC Cycle Time
1	1.0	1.59
2	1.0	1.53
3	1.0	2.22
4	1.0	1.15
5	1.0	2.04
6	1.0	1.19
7	1.0	1.09
8	1.0	1.36
9	1.0	1.98
10	1.0	2.25
11	1.0	1.73
12	1.0	2.50
13	1.0	1.28
14	1.0	1.48

Figure 3. FMS Part Cycle Times (Relative Scale)

PHASE IB: PART SELECTION FEASIBILITY STUDY

The part selection feasibility study was conducted concurrently with the 14-part feasibility study in order to see if there were parts for an FMS better than the original 14 chosen and, if so, put those parts in the part set to be considered in Phase II. This would prevent designing and evaluating FMS configurations for two part sets and trying to merge them to obtain the best part/machine combination in Phase II.

FMC personnel defined approximately 3,200 "make" parts in the IFV/CFV project. All of these parts had been coded according to a group technology classification scheme developed at FMC and illustrated in Figure 4 on page 17. The first part selection step was to preselect parts from the 3,200, based on those coding parameters mutually agreed to be likely FMS part attributes. These parameters are indicated by stars in Figure 4 on page 17. In general, acceptable parts had a machining envelope size from 6" to 36", and could be flat, prismatic or short round. The material could be wrought, cast, forged or welded; the final geometry could include holes, threads, and any type of finishing operations. Approximately 350 parts were selected.

FMC then matched the 350 part numbers with their computerized part routing and manufacturing time data bases. This provided all the operations necessary to manufacture each part (in the proper sequence), an indication of what machines were used to fabricate each part, how long it took to set up the equipment, and the cycle time in standard hours. The parts were also listed in descending order of total manufacturing hours per part number per vehicle.

Review of the manufacturing hours per vehicle in conjunction with the manufacturing routings indicated that parts with less than 18 minutes of manufacturing time per vehicle had no machining work content. These were small parts stamped with an identification number or that had some other minor modification. Elimination of these parts reduced the part set to approximately 250. Subsequently, further parts were eliminated if their routings showed:

1. No machining work content, such as assemblies, parts only being finished treated, or weldments.

2. Machining work content more appropriately performed by dedicated machines, such as parts requiring routing or parts with just a few holes drilled in them.

Approximately 60 parts had FMS machining center or turning center work content. Fourteen of these parts were those originally chosen for the head changer. This set of 14 also had the most manufacturing hours per vehicle. Investigation of the process plans of the 46 other parts indicated that while the potential for significant cycle time reduction through the use of an FMS existed, it was not as great as the potential indicated by the baseline 14 parts. Based on this, it was agreed to proceed to Phase II using the baseline parts. The remaining 46 parts could be used to fill idle time on the FMS or substitute for parts deemed unsuitable during Detailed Configuration Design and Evaluation.

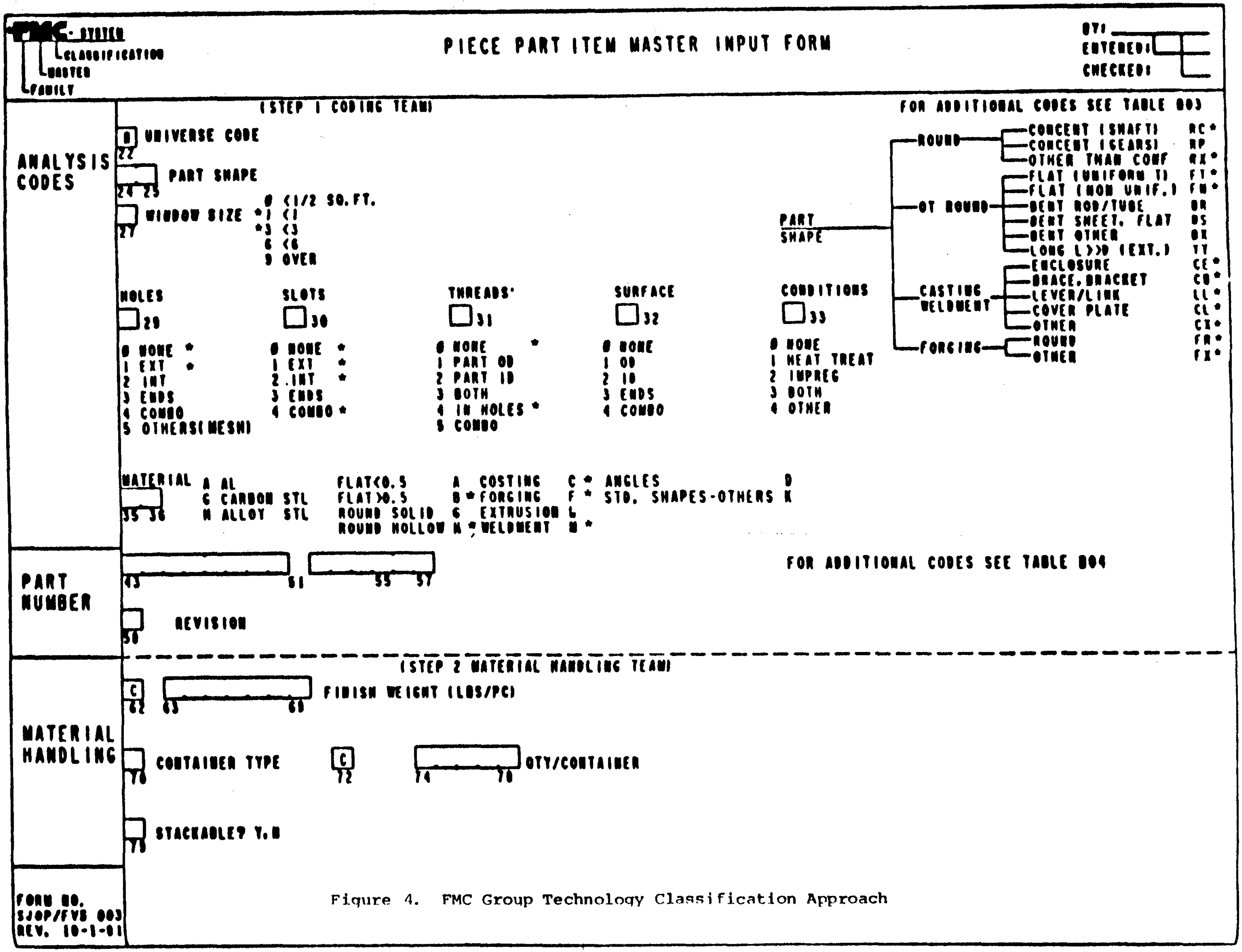

Figure 4. FMC Group Technology Classification Approach

PHASE II: DETAILED CONFIGURATION DESIGN AND EVALUATION

Production Alternative Evaluation Methodology

There were three possible production methods from which FMC personnel could choose for the 14 parts. The first alternative was to continue the present method of manufacturing. The second was to purchase a head changer with up to 88 heads, tool it for the 14 parts, and complete conventionally whatever operations could not be done on the head changer. The third alternative was to purchase an FMS, tool it for the 14 parts, and, as with the head changer alternative, complete non-FMS operations conventionally.

The following design and evaluation methodology was adopted:

1. Develop process plans and calculate part cycle times.

2. Rough-size the production system using calculated cycle times. Give San Jose Ordnance the production parameters.

3. Allocate parts and tools to specific machines.

4. Balance workloads across the machines.

5. Simulate the system for final sizing, total shipset flow time.

6. Determine economic parameters.

7. Evaluate the systems using economic models.

8. Evaluate intangibles.

FMC personnel were investigating the head changer alternative at that time, and it was agreed that they would complete the head changer evaluation through Step 6. CSDL would evaluate the FMS and perform the economic comparison of all three production alternatives. Figure 5 on page 19 illustrates the software tools that CSDL used for system design and evaluation. Each step is discussed below.

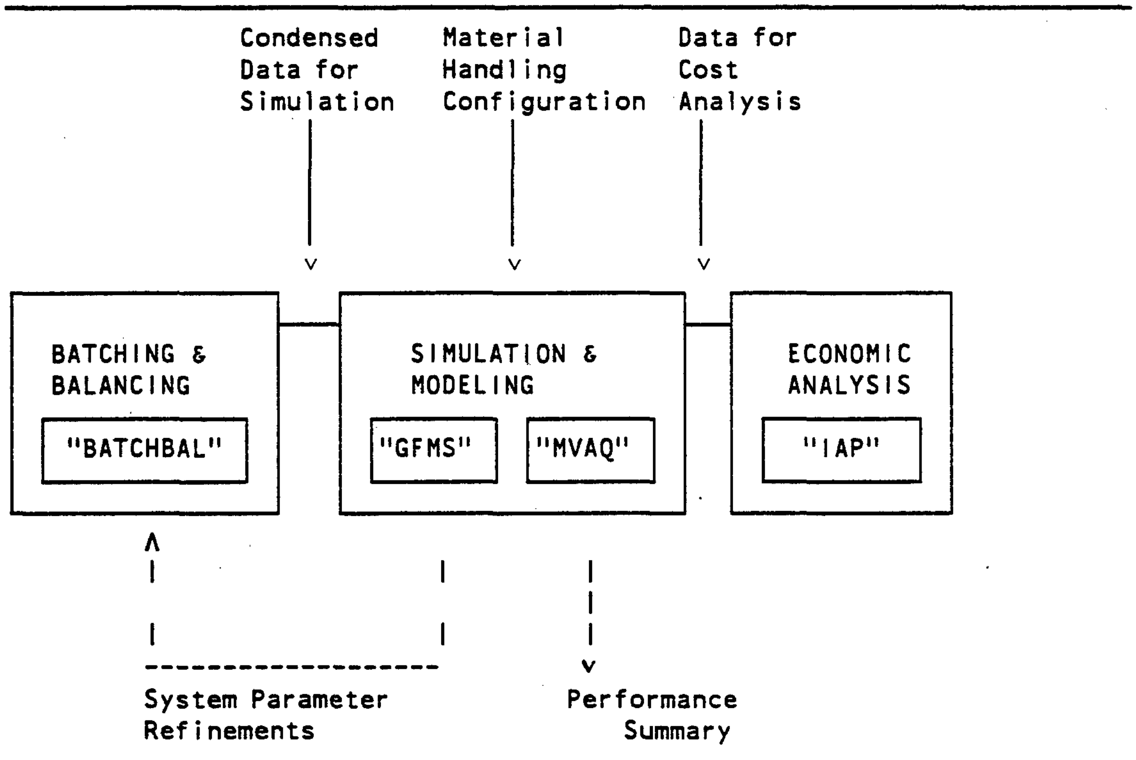

Figure 5. Configuration Design and Evaluation Tools

Rough-Sizing the System

FMS process planning and cycle time calculations were completed as a task in Phase I. The choice of equipment for these parts was: four-axis horizontal machining centers and vertical turret lathes since they were best suited to the FMS work. Representative models from the chosen vendors were investigated, and their parameters were used to calculate part cycle times in Phase I. System configuration (calculation of the number of each class of machine and the combining of those machines with the appropriate MHS(s)) was the next task.

FMC personnel adopted a working hypothesis that the system would operate five days a week, 24 hours each day, with estimated 70% efficiency. Continuous five-day operation would reduce start-up and shut-down problems, maintain higher and more consistent accuracy, and reduce shift-to-shift confusion. A general system efficiency of 70% was chosen as representative of current average FMS operating efficiencies. Scheduled and unscheduled maintenance, tool replacement, and other operating inefficiencies were assumed to be included in the 30% non-cutting time figure. On average, there are 20 working days per month. Thus:

MONTHLY OPERATING HRS. = 20 DAYS x 24 HRS. OPERATION x 70% OPERATING EFFICIENCY

= 20 x 24 x .7 = 336 HOURS

The expected maximum time an FMS machine can be used to process parts is 336 hours/month. Dividing the total hourly machining time per month per machine class (in this case, either machining center work content or vertical turret center work content) by the expected processing hours gave an estimate of the required number of machines. The FMC system was initially sized for an expected production level of 60 vehicles per month. Four horizontal machining centers and one vertical turret lathe could theoretically produce sets of the chosen parts for this number of vehicles.

$$\text{HORIZONTAL MACHINING CENTERS} = \frac{\text{MONTHLY MACHINING CENTER WORK CONTENT (HOURS)}}{\text{AVAILABLE MONTHLY PRODUCTION HOURS}}$$

$$\text{HORIZONTAL MACHINING CENTERS} = \frac{1157.78}{336} = 3.45 \rightarrow 4$$

$$\text{VERTICAL TURRET LATHES} = \frac{\text{MONTHLY TURRET LATHE WORK CONTENT (HOURS)}}{\text{AVAILABLE MONTHLY PRODUCTION HOURS}}$$

$$\text{VERTICAL TURRET LATHES} = \frac{227.28}{336} = .83 \rightarrow 1$$

Allocation of Parts and Tools to Machines and Machine Balancing

Part and tool assignment to specific machines and the balancing of the assigned workload between machines was done simultaneously using BATCHBAL. BATCHBAL is a program developed by CSDL to optimize part and tool allocation, machine balancing and batch work content (if batching of production is required due to tool or casting limitations). These three concepts are interrelated (e.g., a change in batch work content or tool allocation alters the machine balance) and they are difficult to optimize manually.

Figure 6 on page 21 presents the part and tool allocation and machine tool balance for all fixturings of the 14 parts on the four horizontal machining centers. There is only one vertical turret lathe, and all turning work content can be loaded on that machine. Sufficient tool storage at each machine and casting storage allow all of the parts to be produced randomly in one batch. BATCHBAL required approximately ten seconds to generate the balanced workload in Figure 6. A manual attempt at optimally allocating and balancing the same workload without using BATCHBAL required 15 hours.

Allocations of Operations and Tools to the Four Machining Centers in the Proposed FMC/FMS

Part	Setup	Total Shipset Operation	Req. No.	Part Assignment to Station (Machine Number)			
No.	No.	Time (Min.)	Tools	4	5	6	7
1A	1	15.19	9				X
1B	2	36.11	14			X	
2	3	38.55	26				X
3	6	42.67	3		X		
4	9	121.63	6	X			
5A	10	58.92	15	X			
5B	11	60.03	13		X		
5C	12	59.90	13		X		
6	14	107.96	26	X			
7	16	28.12	3		X		
8	19	7.92	6				X
9	20	47.99	10		X		
10	22	456.46	17			X	X
11	25	26.85	13		X		
12A	26	2.94	3	X			
12B	27	8.51	9	X			
13A	28	8.04	9				X
13B	29	31.18	23			X	
14	30	42.50	6		X		
Total No. of Tools:			224	59	61	54	67
Total No. of Minutes per Shipset:			1201.47	299.96	308.06	295.52	297.93

Figure 6. Part and Tool Allocation for the FMC FMS

Material Handling System (MHS) Selection

Three different MHSs had the weight capacity and travel capability required by the FMC FMS. These were a floor-mounted, powered roller conveyor system, a chain-in-floor cart tow-line system, and a wire-in-floor guided electrical cart system. The floor-mounted conveyor system was eliminated because it would interfere with machine maintenance. The tow-line system was rejected due to the difficulty in expanding or re-routing the system and the obstructions required in the floor. The tow-line did offer an advantage, however, because the carts are inexpensive and are not hindered by chips and coolant spilled on the floor. After investigation of the wire-guided carts' functioning in a manufacturing environment, AGV's were chosen for FMC's FMS. Wire-guided cart advantages include:

- Easy expansion and re-routing around machines.
- Easy connection to remote material storage area.
- Complete access to machines for maintenance.
- High speed.
- Independent, bi-directional cart operation.

Simulation of the Proposed FMS Configuration

An FMS configuration is simulated to see how the system will react when manufacturing parts, quantifying specific production parameters used to evaluate the operation and investment potential of the configuration. The simulation model written for the FMC FMS was developed using the CSDL "General Flexible Manufacturing System" (GFMS) simulation language. The simulation was used to represent one month (336 hours) of production. It collects the following statistics:

- Number of each part type and fixture set-up scheduled during the period.
- Number of each part type and fixture set-up completed during the period.
- Utilization, in percent, for each work and load/unload station.
- Busy and idle time, minutes.
- Average time each part type spent in the system.
- Average cart utilization.

The effects of changing the material handling system configuration or the number of carts in the system, or the number of fixtures available for each part type can be observed by changing these parameters in subsequent runs of the model.

Figure 7 on page 24 illustrates the FMS material handling system configuration for the five-machine FMS. This represents the working hypothesis adopted during the pre-RFQ phase of the project. Boxes one and two represent load/unload stations. Due to the number of parts in the system and their average processing time, one load/unload station was insufficient to handle the load/unload demand. Box three represents the vertical turret lathe (VTL). The remaining boxes represent the four horizontal machining centers. The 37 points around the material handling system indicate cart stop points. These are in the simulation to keep track of in-transit carts. This also permits insight into system performance degradation when carts flow is blocked, by other carts loading or unloading machines or waiting to enter a load/unload zone, for example. Flow around this system is counterclockwise. The lines drawn across the main circle allow carts to bypass machines between the load/unload stations and their assigned machines, reducing waiting time and shortening cart travel paths.

Simulation model runs for 20,160 minutes or 336 hours (one month) of system operation were performed. A short period of time was allowed for "run-in"; the system starts empty, is loaded for the first time, and operates until the transients caused by the initial loading have essentailly disappeared. At this point the system is considered to be at steady state, and data collection begins for the 20,160 minutes. Input to the simulation model includes:

- Part Data: for each fixturing (orientation of the part), routing through the FMS and processing time at each station.
- Number of fixtures available for each fixturing.
- Maximum number of pallets allowed in the system at one time.
- Queue sizes at each station.
- Material Handling Information: number of active transporters, transporter speed, distance between check point or stations, shuttle time to move a pallet onto or off a station.
- Production Information: monthly production quantity of each part, total operation time to be simulated.
- Probability of station failure.

The simulation was run several times to optimize variables, such as MHS configuration, number of transporters and pallets in the system, machine locations, and the number of load stations required. Figure 8 on page 25 and Figure 9 on page 26 show the simulation findings for the best FMS configuration (shown in Figure 7 on page 24). Figure 8 on page 25 indicates that all production requirements can be met by this configuration in the production time allowed (336 hours/month, 70% of the actual available hours). Figure 9 on page 26 lists the utilization of each station during the production period. Average flow time to produce one set of 14 parts was about 345 minutes (5 hours 45 minutes).

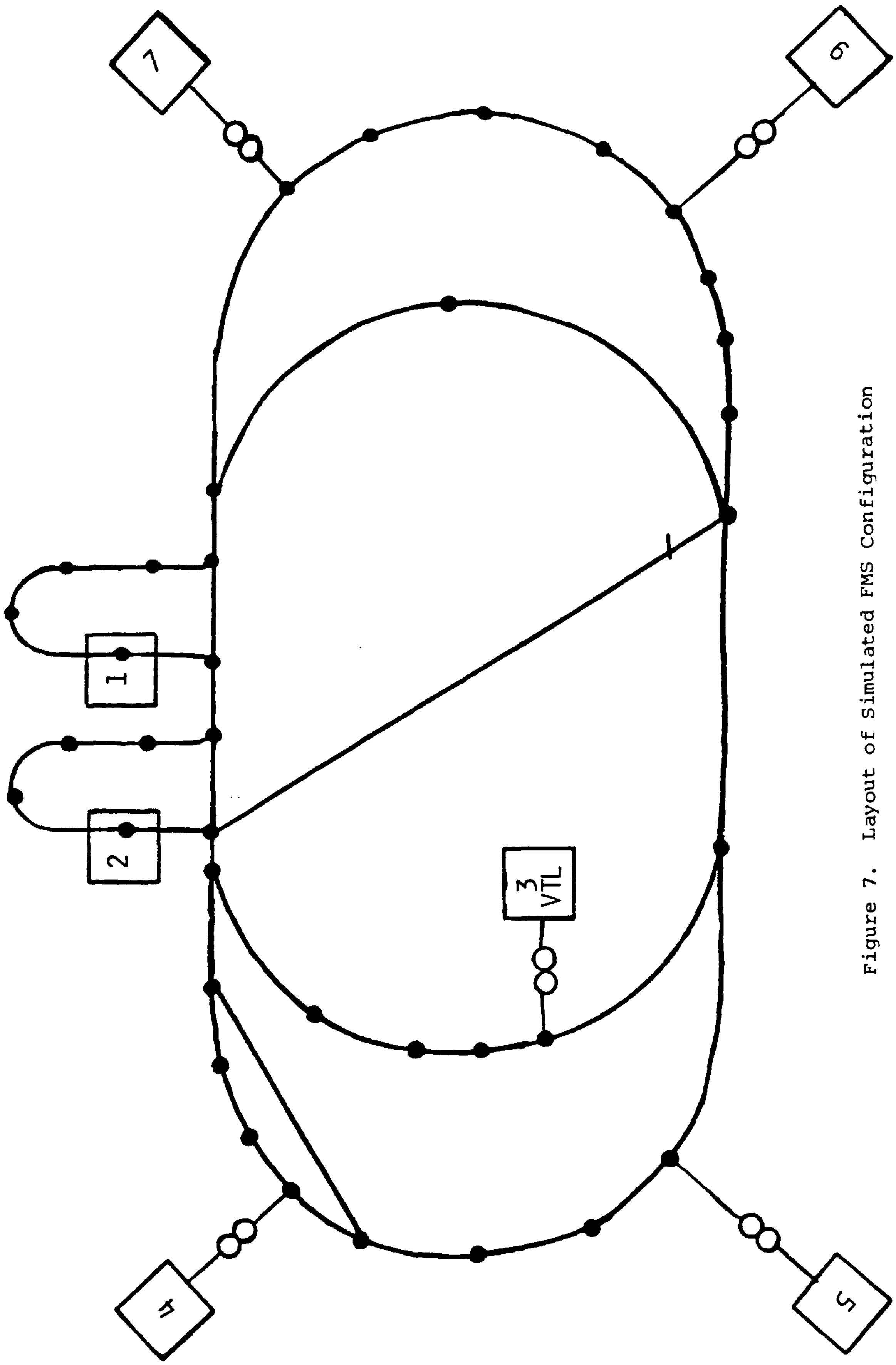

Figure 7. Layout of Simulated FMS Configuration

PART	--PART PRODUCTION--				SIDE	--SIDE PRODUCTION--				SIDE TIME IN SYSTEM			AVE. NUM.
TYPE	REQD	SCHED	COMP	PCT	TYPE	REQD	SCHED	COMP	PCT	AVE	MIN	MAX	IN SYSTEM
1	120	119	120	100.0	1 2	120 120	119 120	120 120	100.0 100.0	44.08 51.48	17.50 27.96	89.73 118.31	0.26 0.30
2	30	30	30	100.0	3 4	30 30	30 30	30 30	100.0 100.0	98.44 36.44	87.00 18.82	119.79 53.56	0.14 0.05
3	240	239	240	100.0	5 6	240 240	239 240	240 240	100.0 100.0	30.95 45.55	16.89 20.78	53.60 110.80	0.36 0.53
4	120	120	120	100.0	7 8 9	120 120 120	120 120 120	120 120 120	100.0 100.0 100.0	32.08 38.15 89.71	25.66 24.23 70.97	62.96 58.56 154.79	0.19 0.22 0.53
5	120	120	120	100.0	10	120	120	120	100.0	69.60	39.61	125.24	0.41
6	120	120	120	100.0	11	120	120	120	100.0	55.70	40.12	134.55	0.33
7	120	120	119	99.2	12	120	120	119	99.2	70.96	42.36	114.54	0.41
8	60	60	60	100.0	13 14	60 60	60 60	60 60	100.0 100.0	33.11 128.50	24.28 118.11	51.67 175.69	0.10 0.39
9	120	120	120	100.0	15 16	120 120	120 120	120 120	100.0 100.0	41.72 49.21	24.81 24.28	61.66 93.25	0.24 0.29
10	60	60	60	100.0	17 18 19	60 60 60	60 60 60	60 60 60	100.0 100.0 100.0	32.73 29.77 43.36	13.39 17.54 17.82	53.16 45.84 120.48	0.10 0.09 0.13
11	60	60	60	100.0	20	60	60	60	100.0	79.98	58.10	123.41	0.23
12	720	693	689	95.7	21 22	720 720	693 692	692 689	96.1 95.7	32.65 62.97	18.91 47.95	69.75 142.59	0.10 1.12
13	60	60	60	100.0	23 24 25	60 60 60	60 60 60	60 60 60	100.0 100.0 100.0	36.64 25.89 55.80	27.46 16.89 36.96	50.90 39.41 101.78	0.11 0.08 0.16
14	60	60	60	100.0	26 27	60 60	60 60	60 60	100.0 100.0	110.44 72.55	32.38 32.38	158.78 117.31	0.32 0.21
15	60	60	60	100.0	28 29	60 60	60 60	60 60	100.0 100.0	49.17 39.60	17.95 10.00	94.09 102.13	0.14 0.12
16	120	120	120	100.0	30 31	120 120	120 120	120 120	100.0 100.0	23.08 33.07	10.00 19.07	73.32 48.60	0.14 0.19
Total		2161	2158				4143	4140					

Figure 8. Simulation Results: Monthly Production Rates

Station Number	Time Busy	PCT	Time Idle	PCT	Time Trans Out	PCT	Time Trans In	PCT	Down	PCT	Percent of Time Busy During Time Available
1	17064.76	83.2	3236.71	15.8	99.76	0.5	98.77	0.5	0.00	0.0	84.21
2	16698.00	81.5	3614.54	17.6	94.11	0.5	93.35	0.5	0.00	0.0	82.37
3	17545.61	85.6	2925.74	14.3	14.33	0.1	14.33	0.1	0.00	0.0	85.73
4	17997.28	87.8	2495.88	12.2	3.34	0.0	3.46	0.0	0.00	0.0	87.82
5	16910.08	82.5	3577.35	17.5	6.29	0.0	6.29	0.0	0.00	0.0	82.55
6	16794.52	81.9	3697.09	18.0	4.19	0.0	4.20	0.0	0.00	0.0	81.97
7	17095.29	83.4	3394.71	16.6	5.00	0.0	5.01	0.0	0.00	0.0	83.44

Figure 9. Simulation Results: Resource Utilization

Simulation of "steady state" FMS operation over long periods, such as 20,160 minutes (one production month), can overstate the performance that can be expected of the system in normal operation. This is because disruptions in production, such as shutdown for the weekend or two-shift operation produce transients in production just after start-up and just before shutdown. To investigate the effects of these transients on expected production, the configuration shown as most efficient in the first simulation runs was simulated, both with weekend shutdowns and with a five-day, two-shift operating strategy for the same amount of production time - 20,160 minutes total. The more accurate five-day, three-shift simulation indicated that performance was only slightly degraded by the weekend start-up/shutdown cycle. No adjustments in equipment levels were required to achieve the desired production level. However, simulation of the five-day, two-shift operating strategy indicated that system performance degraded significantly due to daily start-up/shutdown cycles. An additional four-axis machining center was required to achieve the required production level in 20,160 minutes. These results reinforced the decision for five-day, three-shift operation. They also showed that simulation of "steady state" FMS operation may not represent actual system performance with sufficient accuracy. When possible, actual operating strategies should be simulated for reliable results.

Economic Evaluation of the Three Production Alternatives

Economic analysis is the final quantitative step in the FMS configuration design and evaluation process. Concurrent with the CSDL FMS configuration design and evaluation effort, FMC conducted their head changer evaluation. FMC corporate personnel provided an interface to assure that the input data for the economic model would allow an "apples-to-apples" comparison between the projects. The time and cost figures for the conventional production method were developed jointly between FMC and CSDL. It was also mutually agreed that the economic comparison would be twofold. The projects would be compared as though they would be instituted at San Jose or at FMC's new "low cost manufacturing facility" under construction at Aiken, South Carolina. The difference in the analysis would be the lower overall production costs at Aiken for all three manufacturing alternatives due to different pay scales and overhead bases.

IAP, the Investment Analysis Program, was developed by CSDL to evaluate production alternatives from three different investment viewpoints, as indicated in the flow chart for IAP illustrated in Figure 10 on page 29. These three investment categories are Replacement, Capacity Expansion and Displacement. In each of these categories, the annualized acquisition cost of an alternative 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, either to 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 the introduction of 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 in the future. This approach can be used when no additional capacity is needed now, but will be needed in the future, shifting the analysis emphasis from Replacement to time-phased Expansion or Cost Avoidance. FMS justification using standard cost accounting procedures is most easily accomplished when more capacity is required.

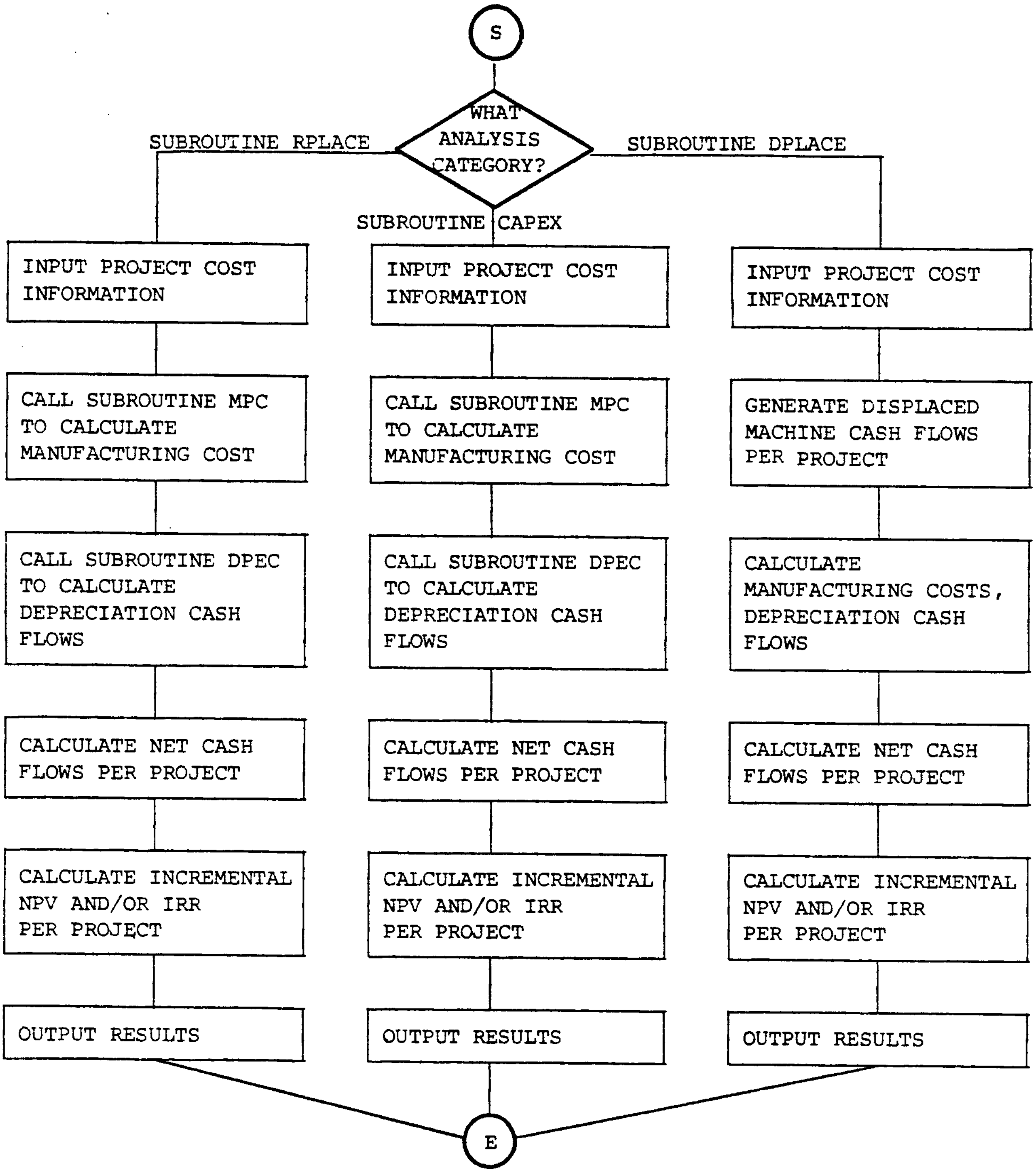

Figure 10. IAP (Investment Analysis Program) Flow Chart (Part 1 of 3)

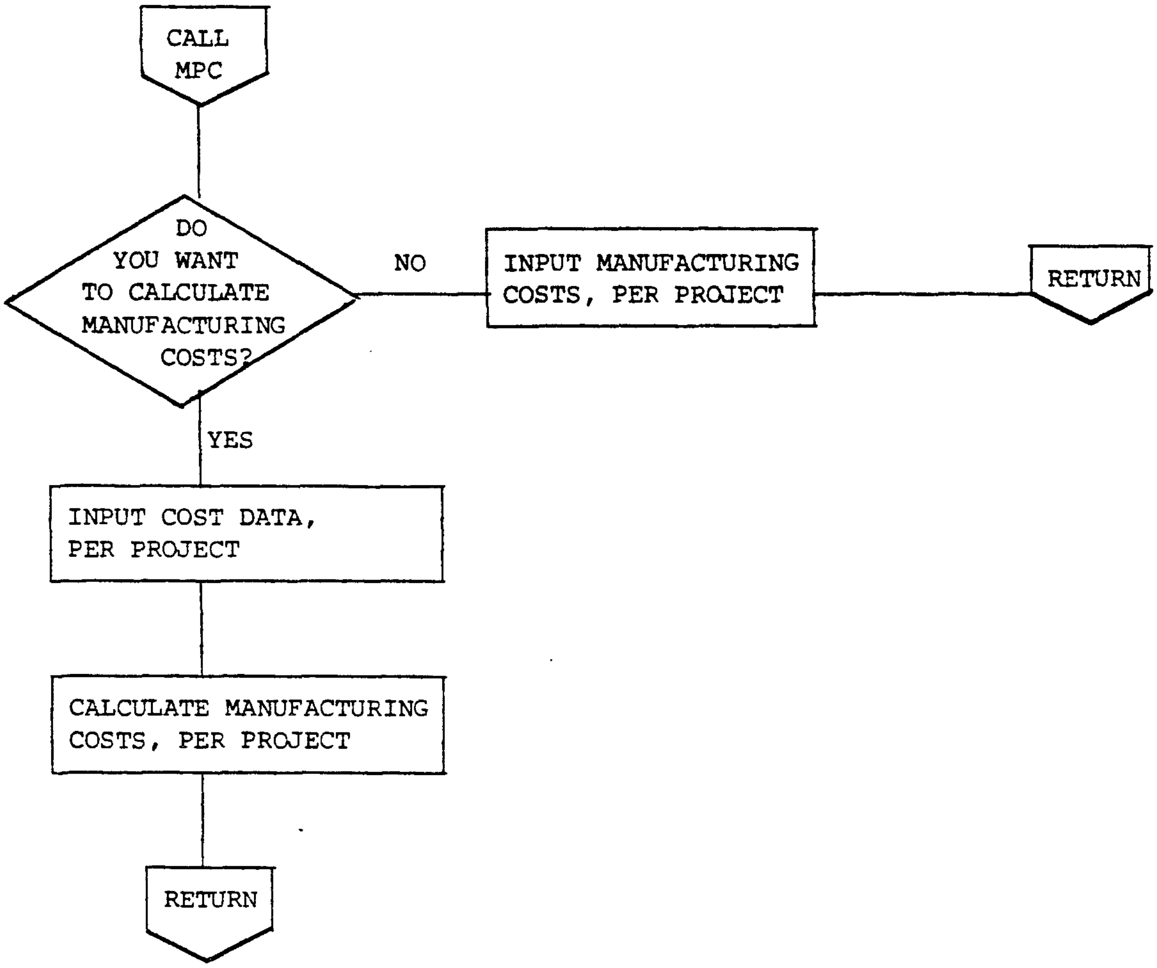

Figure 10. IAP (Investment Analysis Program) Flow Chart (Part 2 of 3)

SUBROUTINE DPEC

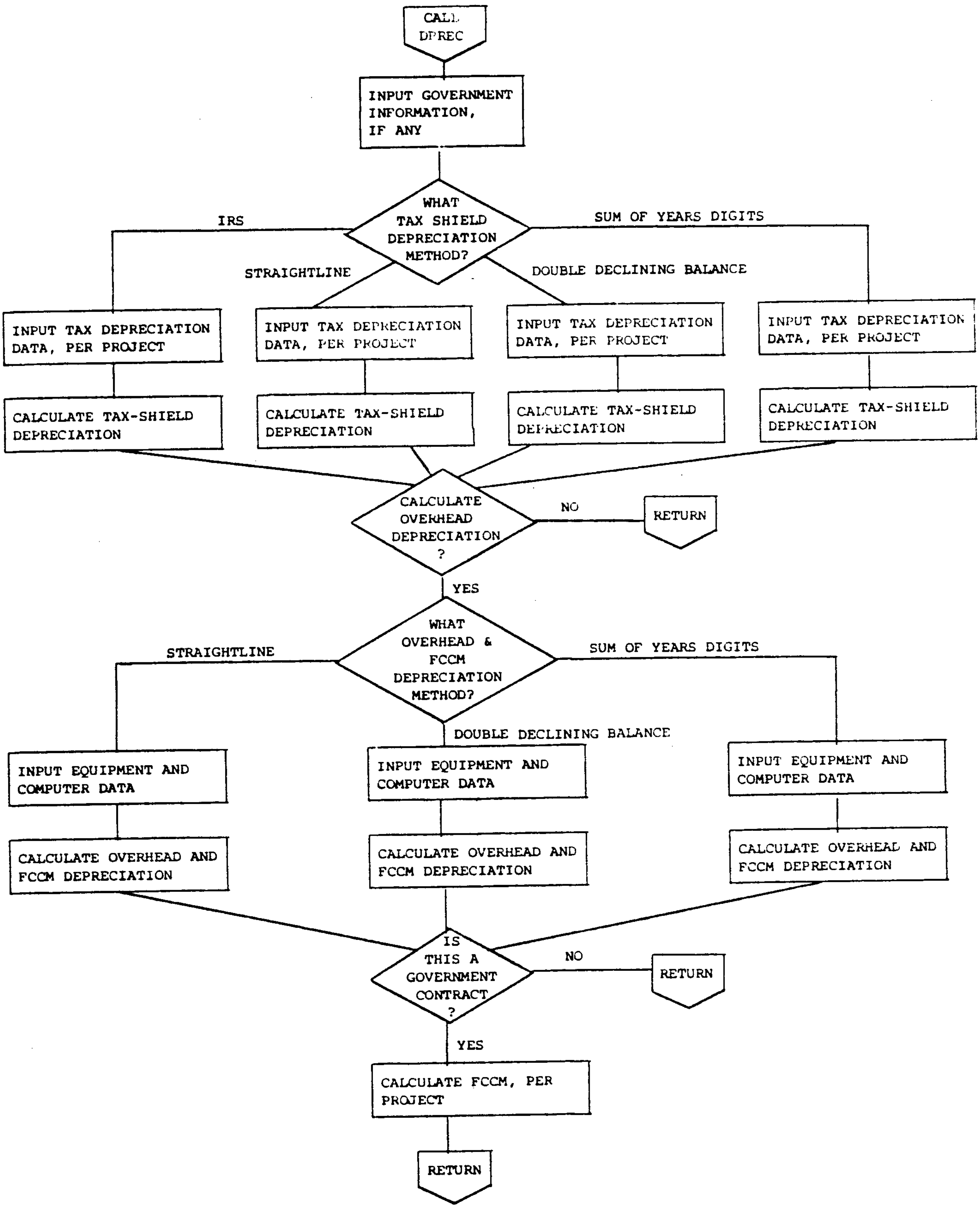

Figure 10. IAP (Investment Analysis Program) Flow Chart (Part 3 of 3)

Two economic modeling techniques, each with its own advantages and disadvantages, can be used by IAP to perform the economic analysis regardless of the category chosen. The "Net-Present-Value" (NPV) technique estimates the present values of all savings and expenditures for the FMS over its useful life, discounted back to the "present" by a value which represents the Opportunity Cost to a company for making that investment. In other words, if money could presently be invested by the company 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 investment on 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 the same as the NPV techniques, except that it estimates the discount rate instead of starting with it as a given. The project's internal-rate-of-return 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 resources available rather than in an FMS. The rate specified in the NPV technique is the investment rate that the company believes is likely during 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, when this discount rate is calculated to be much larger than the threshold rate, it is unlikely that in reality the rate would be realizable.

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 by which to compare different projects; it can indicate the best project on a relative scale. It is more difficult to tell from the NPV techniques which project makes the best use of the invested capital.

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 a 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 stand-alone N/C machines, and then compare both alternatives to 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 can be eliminated by the FMS is considered a cash in-flow in Year One.) This is then compared to the savings generated by using an FMS instead of those machines 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 cost of purchasing the necessary standard equipment and purchasing an FMS. This is again compared to the savings or costs of producing the parts on an FMS instead of on the conventional machines. Because of the higher utilization of machines in an FMS, the investment of an FMS is often less than purchase of additional conventional equipment. In this situation, the FMS can be beneficial, even if it costs more to produce the parts on the FMS. Generally, however, the projected costs of FMS production will be less than those with a conventional approach.

Finally, for displacement analysis the FMS investment is compared to the investment over time in 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 on conventional machines, plus a cost for storing and not using the conventional machine(s) while waiting 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 concept of incremental analysis is automatically performed by the economic modeling software. The alternatives are reviewed in ascending magnitude of investment, and each increment of additional capital is either justified of rejected.

Figure 11 on page 34 lists, per alternative, the production time (on the equipment desired and in the machine shop, where necessary), per shipset; the production cost per shipset (including prorated setup costs); the total installed cost of the alternative; and the number of workers required. The time and cost values are presented as ratios due to their proprietary nature. This information forms the basic input data to IAP. Additional data concerning monthly production quantities, monthly operating time and tax structure are also required.

The alternatives were analyzed from two viewpoints, replacement and capacity expansion. Displacement did not apply because additional capacity was needed immediately. Review of the work load of the machines used in the conventional method indicated that the FMS could be used to replace or avoid buying 16 machining centers and lathes. The head changer would replace approximately seven machining centers. It was also decided that the head changer would need to operate only two shifts daily; the FMS was to operate three shifts per day. Analysis indicated that, from a replacement and capacity expansion standpoint, the FMS was the most economic production method.

	Shipset Time		Shipset Cost.		
Alternative	On the New Equipment	In the Machine Shop	Direct Labor and Overhead	Capital Investment	Direct Labor Required Per Shift
1. Conventional Method	-	9.57	1.54	-	17
2 Head Changer	0.93	4.92	1.12	0.82	2
3. FMS	1.00	1.00	1.00	1.00	3

Figure 11. Summary of Relative Economic Data, Per Alternative

Evaluation of Intangibles

Economic analysis indicated that it would be advantageous for FMC to produce the 14 selected parts on an FMS. Manufacturing the parts on a head changer, though less advantageous than the FMS, also would be a great improvement over the conventional job shop production approach. The final area of evaluation to assist in the correct choice of a manufacturing method was evaluation of intangibles.

Intangibles are areas of concern that cannot be quantified, such as system "flexibility" or the impact of redundancy during machine failure. Figure 12 on page 35 lists the intangibles reviewed. The FMS satisfied or positively impacted most of the intangibles. Additionally, Figure 13 on page 36 presents a comparison of FMS and head changer technology on a number of topics (both tangible and intangible) developed by FMC personnel with experience in both technologies. Again, FMS is the more favorable technology.

SUGGESTED INTANGIBLES AND STUDY FORM

FACTOR/CONSIDERATION	WT.	RATINGS AND WEIGHTED RATINGS, PER ALTERNATIVE A	B	C	D	E	COMMENTS
1 MINIMIZE FUTURE TOOLING AND FIXTURE INVESTMENT							
2 REACT TO MARKET CHANGES							
3 MINIMIZE INDIRECT LABOR							
4 REACT TO ENGINEERING CHANGES							
5 MINIMIZE LEADTIME							
6 MINIMIZE WIP INVENTORY							
7 MINIMIZE SPINDLE TOOLING DESIGN							
8 MINIMIZE SOFTWARE REQUIREMENTS							
9 COMMONALITY OF MACHINE TYPE							
10 PART DEBUG TIME							
11 PART SELECTION FLEXIBILITY							
12 MINIMIZE EFFECT OF MACHINE DOWNTIME							
13							
14							
TOTALS							

Figure 12. FMS Intangibles

Concern	FMS	HCT
Commonality of Machine Type	Normally composed of standard CNC machining centers that have been modified to accept automatic transfer of pallets with modifications to CNC controls hardware and software to support system communications.	Each machine is a special-purpose machine tool that has been designed and built to meet specific unique requirements. It likewise must meet the automated pallet transfer and control communication requirement to function within a system environment.
Machine Accuracy	Modest	Higher accuracy
Machine Costs	Equivalent to any CNC machine tool.	Very expensive as is any highly sophisticated interactive special-purpose machine. Can be 5 to 10 times as expensive, as a function of number of heads.
Software Requirements	Highly sophisticated in order to establish and operate the various components in an interactive systems environment.	Simpler than FMS requirements.
Spindle Tooling Design	Standard machining center tooling with minor exceptions, thereby keeping tool design effort to a minimum.	By virtue of the special-purpose machine approach to these systems, the tooling in most cases is likewise special-purpose. This does not preclude the use of single spindle tooling, but, rather, utilizing these machines in a single spindle application is both uneconomical and contrary to HCT intent. Requires extensive tool design effort.
Spindle Tooling Costs	Low to moderate in keeping with costs normally associated with machining center tooling.	Costs are substantially greater than FMS tooling and are more in line with those multiple-spindle process head type tooling.
Fixture Design	Practices that normally are incorporated into machining center fixtures are acceptable. However, due to fixture load/unload being performed by relatively unskilled labor, they should be simple and sturdy.	Normally subscribe to FMS requirements; however, often there are guide bushings or pilot holes designed and mounted directly onto the fixtures to help retain proper alignment of the head during machining.
Fixture Costs	Low to moderate and in keeping with costs associated with N/C-types figures.	Moderate to expensive, depending upon depending upon design requirements.
Part Programming	Equivalent to programming requirement for any CNC machining center.	Similar to FMS requirement, although a reduction in programming time may be evident due to multiple-spindle applications
Part Debug Time	Similar to techniques used for machining center debug.	Equivalent to or less than FMS requirement as fewer programmed tools are used. However, as most of the geometric relationships on the part are controlled by the design and manufacturing of the head used for machining, debug may be significantly more complex.

Figure 13. General Comparison of FMS and Head Changer Technology (Part 1 of 2)

Concern	FMS	HCT
In-Process Gauging	Required for all operations, rough or finish as operators must be cognizant of part quality in order to correct quality deficiencies and to minimize exposure to discrepant in-process inventories.	Same as FMS requirement.
New Product Introduction Time	Short; product can be brought on stream in term frame normally allotted to CNC machining center.	Slow; time requirement is equivalent to special-purpose machine acquisition.
Engineering Change Incorporated	Rapid compliance to ECO's; most changes can be incorporated with part programming revision only.	Time-consuming and equivalent to ECO changes in hard process machine environment.
ECO Incorporation Costs	Minimal; majority of changes can be accomplished through revisions in the part program without design changes or tooling modifications.	Moderate to expensive as practically every change requires some design and tooling modification to incorporate.
Part Selection	Parts with complex geometric relationships and low- to mid-volume requirements are ideally suited for system manufacturing. However, in many instances, less complex parts with a high manual labor content can be justified as their tooling requirements are virtually non-existent.	Confined to complex inter-related geometric configuration with mid- to high-volume requirements because of the high cost of equipment and tooling. The economics are simply not there to justify the use of these in a single-spindle operational mode.
Machine Down Situation	As all machines are similar and to the extent that tooling is common across machines, downtime can become a matter of reassigning critical operations from the down machine to others within the system. There are obviously some effects on system productivity during this time.	By virtue of its design and intent, there are few, if any, alternatives available when a machine down situation is encountered other than repair of the down machine. During the repair procedure, system output has all but ceased due to the domino effect that the down machine has set into motion.

Figure 13. General Comparison of FMS and Head Changer Technology (Part 2 of 2)

Selection of Manufacturing Technology

A review meeting attended by personnel from FMC Corporate Offices (Chicago), Ordnance Division (San Jose), and Aiken was held to examine the manufacturing alternatives evaluation. They agreed to pursue FMS technology and install the resulting system in Aiken, South Carolina. A System Manager, who would be responsible for writing the final specification and move to Aiken concurrent with FMS installation, was chosen at this time.

Part Mix Change and Redesign/Re-evaluation of FMS Configuration

The new System Manager examined the data collected during the configuration and evaluation phase. He decided that, due to the risk in integrating vertical turning equipment in a prismatic FMS and the difficult features of the turned parts, turning work content and machines would be excluded from the FMS. This work content will be added later by expanding the FMS to include vertical turret lathes. This is to take place after Aiken operational and support personnel have become thoroughly familiar with the initial FMS.

FMC corporate personnel also reviewed production projections. They agreed that the initial production requirement of 60 vehicles per month would be surpassed by the time the FMS is installed and has completed its shakedown. A new production level of 100 vehicles per month was chosen as a realistic production requirement for the post-shakedown time frame (1984). (This has subsequently been reduced to 75.)

Removal of the nine parts with turning work content reduced the overall work content to approximately 40 percent of the original total, or slightly less than two fully utilized machining centers. To improve the return on investment of the FMS, FMC and CSDL agreed that more parts should be added to those remaining on the FMS. After review of the proposed system complexity, support capability, and storage space, it was decided that initially the FMS would have no more than 15 individual part numbers. More could be added later. Two production levels would be examined: 100 and 140 vehicles per month, to account for variability in projected demand.

The 46 parts remaining from the Phase I part selection study were examined; 19 had turning work content and were eliminated from further consideration. Seven parts having the most cost savings over their conventional processing method were selected to complete a new FMS part set. This part set has 14 individual parts (twelve part numbers, two of which are assemblies).

The FMS configuration required to produce this new part set differs only slightly from the original. After developing the process plans and cycle times for the additional parts, the work content for 100 vehicles per month required four four-axis machining centers. Five machining centers were required for 140 vehicles per month. The VTL was eliminated. The number of material handling transporters and load/unload stations remained the same as in the original configuration (two each). Batching and balancing of this new work load was performed using BATCHBAL. The output from BATCHBAL was used to simulate the new FMS configuration for FMC. Based on the very positive economic benefits indicated by economic modeling of the original FMS configuration, FMC did not request that CSDL perform economic analysis of the new configuration. Instead, they relied on the economic analysis of the alternatives performed by FMC corporate financial personnel, required for review of all major capital equipment purchase requests. The evaluation of intangibles remained the same.

PHASE III: DEVELOPMENT OF A REQUEST FOR PROPOSAL AND INTERACTION WITH FMS VENDORS

Preparation of a Request for Proposal Package

The final phase of this project was to assist FMC in the development of a Request-for-Proposal (RFP) to issue to each vendor chosen by FMC to propose an FMS. This package, designed to assist each vendor in preparing a proposal and speed the proposal response, contained the following:

- Letter of introduction and statement of intent from FMC.
- Production requirements.
- Fixture concept sketches for each part.
- Process planning data and cycle times; both were generated by the CSDL-developed analysis package CTIME for specific vendor equipment.
- Part drawings keyed to the process plans.
- General machine, MHS, and components (hardware and software) desired.

Two sets of RFP packages were issued; one pertaining to the original part set, and one for the revised part set.

Selection of Vendors to Receive an RFP

FMC initially chose three American FMS vendors that they felt could produce the parts in question as recipients of the RFP packages. Subsequently, FMC corporate management requested, on the basis of FMC's international corporate status, that foreign FMS vendors be included. Three foreign vendors were thought capable of building an FMS to produce the parts. RFP packages were sent to them approximately two months after the American vendors' packages. Two proposals (American) were deemed acceptable by FMC.

Vendor Proposals

The proposals received from both vendors were quite similar. For the initial 14 part set selected by FMC, Vendor A's proposal presented an FMS with four four-axis horizontal machining centers with tool changers and one vertical turret lathe with a tool changer. Vendor B's proposal called for three four-axis horizontal machining centers with tool changers and two proprietary turning machines in the development stage at the time of the proposal. A tow chain MHS (MHS) was proposed by Vendor A while Vendor B incorporated a wire-guided vehicle system. Automated coordinate measuring machines (CMM's) were also incorporated into each vendor's FMS. Both proposed using the same computer (DEC 11/44) for their system control software. Vendor B also proposed incorporating their proprietary decision support software into the system control software, to allow the system manager to make more intelligent short-term decisions. Each system had approximately the same lead time from the issuance of a purchase order to completion of FMS installation.

In addition to general system design information, each vendor provided process plans for each of the 14 parts, including cutting time, tools used, and fixture concepts. The vendors each began their proposal process immediately after receipt of part drawings and production requirements from FMC. The full request for proposal, with part fixturing concepts and cycle times generated by CSDL, arrived after the vendors had completed their first system designs. This lag allowed an honest comparison of process plans developed by CSDL, in cooperation with FMC, to those produced by each vendor. This comparison is most beneficial. Historically, many FMS problems during shakedown and operation are the result of incomplete process planning by the vendor and customer during the design phase.

The process planning done by both vendors agreed in general with CSDL plans. However, both vendors had overestimated the machinability of the material, and were not aware of some of the unusual features of the parts which did not allow processing in the usual manner. After a series of very open and fruitful meetings among CSDL, FMC and each vendor (including numerous tours of the shop floor to examine part production and associated machining processes firsthand), the vendors adjusted their process planning. Although significant planning changes were made, corrections of overestimates and underestimates resulted in machine loads that were very similar to the first system designs, so the system size and content remained the same. Even though the new individual part cycle times estimated by the vendors varies as much as five percent from those times estimated by CSDL, overall process planning times were within one percent of CSDL's estimate.

Next, the four parties reviewed the MHS's and integration of coordinate measuring machines with the remainder of the system. Due to the ease of reconfiguration, simplicity of installation and maintenance, and minimum impact on machine maintenance, a wire-guided vehicle MHS was deemed more desirable than a tow chain system, and Vendor A proposed a new system design using wire-guided vehicles. Upon careful examination of both the vendors' experience with integrating coordinate measuring machines (CMM's) with their FMS's, the state of the art of various available CMM's, and FMC's ability to operate and maintain a CMM, it was decided that a CMM would be added to the installed FMS after it was debugged and operating personnel were familiar with it.

The vendors prepared their final proposals after these meetings. During this period, FMC altered the desired FMS part set to eliminate turning work and to substitute relatively simple parts to machine early in the system's life in place of some of the more intricate parts initially considered. CSDL calculated cycle times and developed fixturing concepts for these new parts, and worked closely with both vendors to minimize the impact of these changes on their final proposals. Both vendors responded within the allotted time as a result of these cooperative reviews.

Proposal Review and Selection of the FMS Vendor

In accordance with CSDL's policy to maintain an unbiased third-party status, CSDL did not participate in the final proposal review nor the final selection of vendor. This was done by FMC personnel from San Jose, Aiken, and the corporate staff, using the design evaluation information and intangibles criteria provided by CSDL. FMC corporate finance personnel prepared the final economic analysis (with input from CSDL's simulation and investment analysis programs), and prepared the final FMS acquisition report for presentation to FMC's Board of Directors in early 1983. Cincinnati-Milacron was chosen as the FMS vendor. Installation of the FMS in Aiken is planned for spring 1984.

TASK 4: CSDL/ROCK ISLAND ARSENAL FMS PROJECT

BACKGROUND

The Rock Island Arsenal (RIA) FMS Feasibility Study was undertaken to determine the suitability of FMS technology for the RIA production environment. RIA currently produces approximately 4,200 different part numbers in quantities of one to 500 annually on approximately 2,000 stand-alone manual and N/C machines. The applicability of FMS technology would be judged on the ability to select a combination of parts and FMS-compatible machines that would generate sufficient cost savings over the present production method for those parts to pay for the FMS in a reasonable time. The Part-and-Machine-Selection algorithms, PAMS (Part And Machine Selection) and PARSE (PARt SElection), used in these studies, have been documented in Volume V of the FMS Handbook. The principal effort in this reporting period was to apply those tools to the RIA part set and determine whether FMS technology had reasonable potential for RIA. The results of this study show that an FMS can give considerable savings over stand-alone N/C machines. Hence, RIA decided to proceed in 1983 with the next phase, Detailed System Design and Evaluation.

CLASSIFICATION AND CODING OF THE RIA PART DATA BASE

RIA personnel reviewed all 4,200 active production part numbers to classify and code them using the MICLASS Group Technology coding scheme. This review revealed numerous errors and omissions in the old data base. A decision was made to apply the part and machine selection procedure to the new part data base.

PRESELECTION OF FMS-COMPATIBLE PARTS USING THE MICLASS CODING SYSTEM

A tape with the MICLASS code, part number, part name and production data for each of the 4,200 parts was sent to CSDL for part preselection. A program was developed that scanned these data for parts with FMS attributes, using predetermined values that represented FMS attributes for each digit of the MICLASS code for each part. In general, the parts could:

- Be prismatic or short cylindrical.
- Have a machining cube of between 6 and 36 in.
- Be aluminum, steel or brass.
- Have tolerances greater than ± 0.001 in.
- Have any number of machining axes.

The MICLASS scan found about 600 of the 4,200 parts with such attributes. Chosen parts with fewer than 40 hours of annual production time were rejected because they usually had little or no machining time--they were weldments and part assemblies. This reduced the part set to approximately 300 parts. Drawings for each of the 300 parts were reviewed to eliminate parts which would be better produced on existing dedicated equipment.

This preselection process resulted in a part set of 243 part numbers. These parts were from end items listed in Figure 14. Those end items in the right-hand column were determined by RIA as unlikely to be in production in two years. The parts associated with these end items were eliminated from the data set, reducing the preselected part data set to 144 parts.

243 parts were selected from the following end items:

M1	M39
M45	M8C
M102	M85
M140	M101
M174	M101A1
M178	X198
	XISC

Figure 14. End Items

Although part preselection greatly reduces the amount of computation effort necessary by PAMS and PARSE, PAMS could have reviewed all 4,200 parts quickly and selected parts and machines to satisfy a desired system size. However, the user would have had subsequently to review the chosen parts to assure that no unacceptable parts were included. If some were, they would be eliminated from the initial data set (manually); PAMS would be applied to this reduced part set to choose another set of parts and machines. This select/review/reselect procedure would be repeated until no unacceptable parts are chosen. The preselection effort allows the user to avoid this process. PARSE, on the other hand, could not have reviewed all 4,200 parts without great computational expense. For the most efficient use of PARSE, the input data set should have fewer than about 100 parts.

PREPARATION OF THE PART DATA FOR PAMS

RIA prepared and forwarded a computer tape with specific manufacturing processing data for all 144 preselected parts. These data included for each part:

- Process sequence and routing.
- Machine group code for each step of the sequence.

- Cost center code for each machining group.
- Annual production quantity.
- Number of production lots required annually.
- Number of hours to set up equipment in each machine group to produce one lot of parts.
- Number of hours to produce a part in each machining group.

A typical set of data for one part is illustrated in Figure 15 on page 45. Computerized process planning information showing the tools required to manufacture each part and the fixtures necessary to hold it, and part drawings for all parts were sent to CSDL.

RIA machine group codes were analyzed to determine which represented FMS-compatible machines. Ten FMS machine classes could be constructed from the different machines associated with the machine group codes. The RIA machine group code/FMS machine class relationship is presented in Figure 16 on page 46. About one-third of the RIA machine group codes listed represent N/C machine tools. The remainder represent stand-alone, manual machine tools ranging in age up to about 50 years.

The processing planning summaries for each part were then scanned for the appropriate RIA machine group codes to estimate the total number of tools necessary to produce that part on FMS machines, and to estimate the number and complexity of the fixtures required to hold the part during machining. In general, about half the parts required only one relatively simple fixture because they could be machined on one FMS machine and did not require access to all six sides during machining. The remaining parts required at least two fixtures to: allow access to all sides during the machining process; allow machining on different FMS machine classes (machining centers and VTL's, for example); or both. For simplicity, two fixture assumptions were examined: one fixture per part and two fixtures per part. The impact of the second amortized fixture would be analyzed to see how sensitive the part selection process is to changes in part-related costs, such as number of fixtures or tools.

Yoke Rear (mach.) MICLASS CODE 7997512561402586150000000000000

5	6	7
252	0008	105

1	2	3	4
27	6420	5.100	1.483
2535	6420	5.800	1.550
2251	6420	8.000	2.550
9999	6420	0.500	0.374
8130	5633	0.000	0.333
2535	6420	7.900	2.274
2195	6420	4.400	1.454
2251	6420	4.100	0.683
2251	6420	8.600	4.333
9999	6420	0.500	0.312
2251	6420	11.000	5.200
9999	6420	0.500	0.377
2520	6310	8.000	0.202
2220	6330	3.700	0.438
2220	6330	4.200	0.800
3050	6310	1.500	0.100
2385	6420	16.000	5.366
2385	6420	12.000	0.976
2385	6420	12.000	0.976
2385	6420	12.000	1.674
2820	6750	2.000	0.816
2820	6750	8.000	3.500
2820	6750	8.000	3.500
2820	6750	2.000	0.733
9999	6750	2.000	1.500
8710	7300	0.000	0.417
8710	7300	0.000	0.250

1. Machining Center Code
2. Cost Center Code
3. Hours per Machine Set-up for Next Batch (Lot)
4.* Hours per Piece
5. Pieces per Year
6. Number of Set-ups per Year
7. Multiplier for Scrap Factor

* Aggregate of machining time, L/UL time, fixturing time.

Figure 15. Example MICLASS Data For a Part From End Item M45 (Recoil Mechanism)

Type (Approximately:)	Small (12")	Medium (24")	Large (36")
Machining Center	2010-2040,	2045-2060,	2090-2140,
	2070,	2105,	2185
	2100,2110,	2165-2180,	2188,
	2150-2160,	2190,	2196-2210,
	2270-2290,	2220,	2222-2224,
	2700,	2241-2242,	2245-2261,
	2820,3010,	3020,3030,	2420,2520,
	3040,3050,	3055,	2750,
	3060,3118	3065-3080,	3095,3105
		3100,	3115,
		3112,3113,	3120-3160
		3180-3200	
Precision Boring	2720	2730	2710,2715
			2725
Multi-Spindle	-	3220,3221,	3230,3250,
		3240	3260
Vertical	-	2533,	2531,2535,
		2540-2567	2570-2620

Figure 16. FMS-Compatible RIA Machine Codes by Appropriate FMS Machine Class

To calculate the annual production costs using each method, both the annual production time and hourly operating cost must be given. The production time, hourly direct labor rate and applied overhead were provided by RIA for the current production method. The FMS hourly operating cost was estimated as follows. RIA N/C machines have a cost center cost of CNC per hour per machine. This is the rate that is charged a part machined in this cost center for one hour. Assuming that in practice there is one operator per machine, with a direct labor rate of DL per hour, this leaves CNC-DL as the hourly component of overhead resulting from indirect costs attributed to that piece of equipment.

FMS overhead was assumed, for simplicity, to be equal to the RIA overhead rate on a machine-by-machine basis. This is extremely conservative, as overhead usually includes the cost of material handling to and from the machine (which is greatly reduced with an FMS), the cost of rework and scrap (which should also show improvement), supervisory salaries, and so on. Two men doing loading ('loaders') were assumed to be the maximum necessary for the size range of systems reviewed (4 to 15 machines). In reality, systems with fewer than ten machines would probably require only one loader. One supervisor was assumed for both cases, and that cost was ignored. To complete the calculation of FMS operating cost, the hourly rate for the loaders, who usually are machine operators, was divided by the number of machines assumed to be in the system and added to the hourly rate for a machine in that size system. Thus, the FMS operating cost was at a maximum for a four-machine system and at a minimum for a 15-machine system. An average hourly FMS machine rate was used for all of the systems because the smaller systems would require only one loader.

A computer program, FORPAMS, was developed to calculate: (i) annual production time for each part in each FMS machine class, and (ii) the cost savings (if any) expected by machining that part on FMS rather than conventional machines. FORPAMS first scans the computerized part routing for each part for acceptable RIA machine group codes. When it finds one, FORPAMS calculates the annual:

- Setup time, current method.
- Production time, current method.
- Production time, FMS machining method.
- Production cost, current method.
- Production cost, FMS machining method.

FORPAMS prepares this information for each acceptable code for each part, and organizes it in the format shown in Figure 17 on page 49. A summary, including the potential cost savings, is provided for each part. This cost savings equals the current cost less the FMS cost, less the amortized cost of the fixtures and tooling required to produce the part on the FMS. If there is no cost saving for a part, it is rejected. Additionally, if the part has to be refixtured more than three times (i.e., it leaves the FMS and returns frequently or it goes to different types of machines in the FMS a number of times), it is eliminated due to the difficulty in tracking and controlling its production. FORPAMS creates the part data for PAMS from this summary, providing total potential cost savings and production time in each FMS machine class.

The assumptions used by FORPAMS are listed in Figure 18 on page 51. Both current and FMS costs were based on annual production cycle times for the applicable operations and the setup time for that operation. To be conservative, the cycle times for the FMS were assumed to equal the conventional times. A more realistic value, because fixturing the part is done off the machine table and fewer times in an FMS, would be approximately 75% of the current cycle time. Setup is virtually eliminated in the FMS because of dedicated fixtures and preset tooling; however, since one part was assumed to be completed in the setup procedure, the cycle time for one part was added to the FMS time for every setup eliminated.

To complete the data needed by PAMS, cost estimates of representative machines in each FMS machine class were prepared. Additionally, the cost of the remaining elements of an FMS-automated MHS, control computer and installation, were estimated.

Yoke Rear (Mach.)

Annual Production Quantity = 252.

Number of Setups Annually = 8

Scrap Factor = 0.050

Total Number of Operations = 27

1. Machining Center Code
2. Cost Center Code
3. Annual RIA Cycle Time@
4. Annual RIA Set-up Time
5. Annual FMS Cycle Time, Adjusted for FMS Efficiency*
6. Annual RIA Cost, Adjusted for RIA Efficiency (45% assumed)
7. Annual FMS Cost, Adjusted for FMS Efficiency*

@ Total annual production time, in hours.
* i.e., 75% utilization assumption.

1	2	3	4	5	6	7
2220	6330	112.39	29.60	154.53	13451.24	5408.41
2220	6330	205.28	33.60	282.24	22629.87	9878.38
3050	6310	25.66	12.00	35.28	3567.65	1234.80
2820	6750	209.39	16.00	287.88	22768.92	10075.95
2820	6750	898.10	64.00	1234.80	97193.31	43217.93
2820	6750	898.10	64.00	1234.80	97193.31	43217.93
2820	6750	188.09	16.00	258.60	20617.37	9051.06

Figure 17. Example Cost Summary (Part 1 of 2)

Total Operation Time (Hours) and Cost ($), Small Machining Centers	3,051.36	=	134,542.81
Total Operation Time (Hours) and Cost ($), Medium Machining Centers	436.77	=	20,794.31
Total Current Annual Cost to Produce this Part		=	277,421.56
Total FMS Annual Cost to Produce this Part		=	126,481.31
Tools and Fixtures Account for 4396.95 of this Cost			
Expected Part Savings Annually due to FMS		=	150,940.25
Selected Part Number 27			
This Part Needs 1 Fixture			
This Part Needs 1 Fixturing			
This Part Leaves the FMS 1 Time			

Figure 17. Example Cost Summary (Part 2 of 2)

PART AND MACHINE SELECTION USING PAMS

The part cost savings and production time for each FMS machine class were then used by the Part and Machine Selection Program (PAMS) to determine the proper selection of parts and machines for various maximum system sizes. After the first runs, it was apparent that four machine classes could be eliminated. Small and medium boring machines were not used; medium and large multiple-spindle machines were used so little as to always be uneconomical. The part savings were recalculated without these groups, and PAMS reexecuted. No combination of parts could justify vertical turning equipment, nor the large boring machines. They were eliminated and the part savings recalculated.

This left three machine classes: small, medium and large machining centers. PAMS was used to analyze both this combination and just small and medium machining centers, the latter to see if a system with no large machining centers would have a better return on investment (ROI). The small/medium combination had an ROI a few points better, but it was not a vast improvement. Figure 19 on page 53 through Figure 22 on page 56 summarize the results for four combinations of assumptions, from worst case to the best examined, for both the two-machine class and three-machine class cases. All parts chosen are listed in Figure 23 on page 57 and keyed to the four summary figures.

These parts are not necessarily machined completely in the FMS; only the work content for those parts that can be performed on the selected FMS

- FMS Cycle Time = 100% of RIA Cycle Time. (75% was used in the calculations for one case to examine the sensitivity of the FMS justification to cycle time -- see Figure 22 on page 56 for this "Best Case" Scenario Results.)
- One or two fixtures will be required for every part.
- Fixture Cost = $10,000 each.
- Tool Cost = Average $75 each for a tool and holder combination.
- Amortization Period = Average part life of five years.
- Amortization Rate = 18%.
- Available Annual Production Time = 240 days, 2 eight-hour shifts = 3840 hours/year.
- FMS Production Efficiency = Ranges from 70% to 80%; use 75% as an average and 80% for one case to examine the sensitivity of FMS justification to production efficiency.
- RIA Shop Efficiency = 45% (average shop efficiency).
- FMS Operating Cost = $/hour.
- RIA Operating Cost = Respective cost center rates.
- System Sizes = Minimum of four machines, maximum of 15 machines.
- System Manning = 1 or 2 load/unload persons, depending on system size.
- One part completed during RIA setup procedure.
- On-line setup time is eliminated using the FMS.
- Parts requiring more than three refixturings are not considered for FMS as too difficult to control.

Figure 18. Assumptions

machine classes is computed. Additional machining required could be performed more economically using RIA's current approaches.

PAMS indicated that the FMS has economic potential with all assumptions and system sizes investigated. These systems had ROI's varying from 23% to 54%, depending on the system size and the specific assumptions made. These findings were presented to RIA. After RIA review, CSDL was authorized to begin the second phase of the RIA FMS study, Detailed FMS Configuration Design and Evaluation. Phase II is being conducted during calendar year 1983 under subsequent contract funding.

	No. of Machines:	4		5		6		7		8		9	
A	Machines in each class: S / M / L	1 3	0 3 1	2 3	1 3 1	2 4	1 4 1		1 4 2	2 6		2 7	
B	Total Investment ($M)	2.665	2.970	2.94	3.255	3.33	3.645		4.245	4.11		4.50	
C	No. of Parts with Potential Savings	55	93	55	93	55	93		93	55	93	55	
D	No. of Parts Chosen	9	10	16	18	16	20		16	20		23	
E	Annual Savings ($M)	0.692	0.677	0.812	0.839	0.911	0.983		1.118	1.298		1.438	
F	Return on Investment (%)	26	23	27.6	25.6	27.4	27		26.3	31.6		32	

CHART KEY: S = Small machining center.
M = Medium machining center.
L = Large machining center.

In Row A:

- Each column of numbers represents the two-class and three-class cases, respectively.
- A blank indicates that no machines were chosen or that combination was not investigated.

Nine (9) machines is the maximum size FMS for the two-class case under these conditions.

Seven (7) machines is the maximum for the three-class case.

Figure 19. Summary of Part Selection Results (A): Worst Case Situation - FMS cycle times equal current cycle times. Two fixtures are required for every part. The FMS has an efficiency of 75%.

	No. of Machines:	4		5		6		7		8		10	
A	Machines in each class: S M L	1 3	0 3 1	2 3	1 3 1	2 4	1 4 1	2 5	1 5 1	2 6	1 5 2	2 8	2 5 3
B	Total Investment ($M)	2.655	2.970	2.94	3.255	3.33	3.645	3.72	4.035	4.11	4.635	4.89	5.52
C	No. of Parts with Potential Savings	82	119	82	119	82	119	82	119	82	119	82	119
D	No. of Parts Chosen	12	10	21	19	24	23	20	30	22	30	32	37
E	Annual Savings ($M)	0.728	0.709	0.926	0.897	1.046	1.052	1.154	1.183	1.366	1.273	1.659	1.675
F	Return on Investment (%)	27.4	23.4	31.5	27.6	31.4	28.9	31	29.3	33	27.5	33.9	30.3

Figure 20. Summary of Part Selection Results (B): FMS cycle times equal current cycle times. One fixture is required for every part. FMS efficiency equals 75%.

	No. of Machines:	4	5	6
A	Machines in S each class: M	1 3	2 3	2 4
B	Total Investment ($M)	2.655	2.94	3.33
C	No. of Parts with Potential Savings	86	86	86
D	Chosen No. of parts	12 (12)*	23 (21)*	28 (24)*
E	Annual Savings	0.802	0.974	1.151
F	Return on Investment (%)	30.2 (27.4)*	33.1 (31.5)*	34.1 (31.4)*

* From Figure 20.

Figure 21. Summary of Part Selection Results (C): FMS cycle times equal current cycle times. One fixture is required for each part. FMS efficiency = 80%. Done only for two-class case to determine effect which system efficiency has on no. of parts selected and return on investment.

	No. of Machines:	4		5		6		7		8		9		13
A	Machines in each class: S	1	1	1	1	1	1	1	1	2	1	2	1	2
	M	3	2	4	3	5	3	6	4	6	4	7	4	5
	L		1		1		2		2		3		4	6
B	Total Investment ($M)	2.655	2.97	3.045	3.255	3.435	3.855	3.825	4.245	4.11	4.845	4.50	5.445	7.32
C	No. of Parts with Potential Savings	91	129	91	129	91	129	91	129	91	129	9 1	129	129
D	No. of Parts Chosen	12	24	17	33	20	19	33	33	52	37	72	40	83
E	Annual Savings ($M)	1.181	1.114	1.577	1.457	1.784	1.825	2.014	2.063	2.217	2.369	2.408	2.664	3.55
F	Return on Investment (%)	44.5	37.5	49.8	44.8	52	47.3	52.7	48.6	53.9	48.9	53.5	48.9	48.5

Nine (9) machines is the maximum system size for the two-class case.

Thirteen (13) machines is the maximum for the three-class case.

Figure 22. Summary of Part Selection Results (D) Best Case: FMS cycle times equal 75% of current cycle times. One fixture required for each part. FMS efficiency equals 80%.

Part No.	Name	End-Item	Case A: Figure 19, 2 Classes					Case A: Figure 19, 3 Classes				Case B: Figure 20, 2 Classes						Case B: Figure 20, 3 Classes						C: Fig. 21, 2 Classes			Case D: Figure 22, 2 Classes						Case D: Figure 22, 3 Classes						
			4	5	6	8	9	4	5	6	7	4	5	6	7	8	10	4	5	6	7	8	10	4	5	6	4	5	6	7	8	9	4	5	6	7	8	9	13
10884271	Bracket	M140																			*		*								+	+	*	*					*
10888787	Nut	M178							*	*					+				*	*	*		*		*						+	+	*	*					*
10891787	Nut	M178																														+							
10891945	Gear	M174																																					*
10892028	Housing	M174		+	+	+	+		*	*	*		+	+		+	+		*	*	*	*	*		+	+	+		+	+	+	+		*	*	*	*	*	*
10892140	Cover	M174																													+	+		*					*
10892141	Cover	M174																													+	+		*					*
10895603	Follower	M178		+		+									+																+	+		*					*
10895627	Housing	M178																																				*	*
10895673	Housing	M178					+	*		*	*			+			+	*		*	*	*	*						+	+	+	+	*	*	*	*	*	*	*
10895694	Cover	M178																																				*	*
10895695	Sleeve	M178																																			*	*	*
10895696	Sleeve	M178																																				*	*
10909285	Key	M178	+			+	+	*				+	+	+		+	+	*				*		+	+	+	+	+	+	+	+	+				*	*	*	*
10909315	Retainer	M178																														+							
10923025	Lever	M178		+	+	+	+						+	+		+	+					*	*		+	+		+			+	+							*
10923030	Gearshaft	M178											+		+	+			*	*	*	*	*		+						+	+	*	*					*
10930330	Breech	M178	+	+		+	+	*	*	*	*	+	+	+	+	+	+	*	*	*	*	*	*	+	+	+		+	+	+	+	+		*	*	*	*	*	*
10933931	Breech	M178		+	+	+	+		*	*			+	+	+	+	+		*	*	*	*	*		+	+	+	+	+		+	+	*	*	*	*		*	*
10933931	Breech	M178							*	*			+	+	+	+			*	*	*	*	*		+	+		+			+	+		*					*
10933932	Bracket	M140					+			*	*						+			*	*	*	*	+		+			+	+	+	+	*	*	*	*	*	*	*
10934876	Yoke	M174								*																													*
11590764		M1																																				*	*
11636055		M1													+								*								+	+		*					*
11636292	Manifold	M178																																			*	*	*
1164330	Piston	M174																																					*
1183184	Cap																																						*
12000726	Regulator	M102																				*															*		*
12007602	Cap	M45																														+							*
12007649	Collar	M45							*	*			+		+				*	*	*		*		+	+					+	+		*					*
12007690	Adaptor	M45																											+		+					*	*	*

+ = 2-machine class
* = 3-machine class

Figure 23: Part Numbers Chosen by FMS Case (Part 1 of 3)

Part No.	Name	End-Item	Case A: Figure 19 — 2 Classes 4 5 6 8 9	Case A: Figure 19 — 3 Classes 4 5 6 7	Case B: Figure 20 — 2 Classes 4 5 6 7 8 10	Case B: Figure 20 — 3 Classes 4 5 6 7 8 10	C: Fig. 21 — 2 Classes 4 5 6	Case D: Figure 22 — 2 Classes 4 5 6 7 8 9	Case D: Figure 22 — 3 Classes 4 5 6 7 8 9 13
12007692	Cap	M45						+	•
12007719	Yoke	M45							•
12007723	Yoke	M45	+ + + +	•	+ + + + + +	•	+ +	+ + + + + + +	• • • • • •
12007721	Body	M45	+ + + +		+ + +			+ + + + + + +	
12007765	End	M45							•
12007772	Clamp	M45		•				+ + +	• • • • •
12007782	Nut	M45	+ + + +	• •	+ + + + +	• • • •		+ +	• • •
12007784	Collar	M45			+			+ +	•
12007790	Lever	M45				• •		+ +	• • • • •
12007856	Insert	M45						+ +	• •
12007859	Regulator	M45							•
12007865	Collar	M45						+	
12007872	Housing	M45			+ +	• • •		+ +	• •
12012132	Cover	M178							• •
12274291		M1						+	• • •
12274293		M1			+	•	+	+ + +	• • • •
12274327		M1	+ +	• •		• • • •	+	+ +	• • • • •
12274331		M1	+ + + +	• •	+ + + +	• • • • •	+ +	+ + + + +	• • • • • • • •
12282084		M1		• •	+ +	• • • • •		+ + +	• • • • • •
12287139		M1		•		•	+	+	• •
5507255	Guide	M174	+ +	• • •	+ + +	• • • • •	+ +	+ + + +	• • • • • •
5509262	Trunnion	M174						+	•
5509263	Trunnion	M174						+	•
5568984	Head	M174	+ + + +	• •	+ + + + +	• • • •	+ + +	+ + + + + + +	• • • • • •
6105141	Nut	M174		• •	+	• •		+ +	• •
6109576	Liner	M174		• • •	+	• • • •		+ + + +	• • • • • • •
6507039	Yoke	M174	+ + + + +	• •	+ + + + +	• • • • •	+ + +	+ + + + + + +	• • • • • • •
6536154	Bdy Reg.	M174		•	+ + + +	• • • •	+ +	+ + + + +	• • • • • • • •
6505782	Cap	M174	+ + + + +		+ + + + +		+ +	+ + + + +	
6505788	Cap	M174	+ + + +		+ + + + +		+ +	+ +	• • •
7119400	Body	M174						+ +	• •
7133213	Body	M174						+ +	• •
7133219	Body	M174				•		+ +	• •

Figure 23. Part Numbers Chosen by FMS Case (Part 2 of 3)

Part No.	Name	End-Item	Case A: Figure 19 — 2 Classes 4 5 6 8 9	Case A: Figure 19 — 3 Classes 4 5 6 7	Case B: Figure 20 — 2 Classes 4 5 6 7 8 10	Case B: Figure 20 — 3 Classes 4 5 6 7 8 10	C: Fig. 21 — 2 Classes 4 5 6	Case D: Figure 22 — 2 Classes 4 5 6 7 8 9	Case D: Figure 22 — 3 Classes 4 5 6 7 8 9 11
7119399	Body	M174						+	
8382228	Head	M140						+	
8427051	Box	M174				•		+	•
8427052	Follower	M174							•
8430397	Head	M174	+ + + +	• •	+ + + +	• • • • •	+ +	+ + +	• • • •
8432438	Lever	M162						+	
8432783	Frame	M102		•				+ +	• • •
8432870	Yoke	M102	+ +	•	+ + + +	• • •	+ + +	+ + + + + +	• • • • •
8432874	Body	M102			+ +	• •	+	+ + +	• •
8432887	Yoke	M102	+ + + +	• •	+ + + + +	• • • • •	+ + +	+ + + + + + +	• • • • • • •
8432888	Yoke	M102	+ + + + +	• • •	+ + + + +	• • • • •	+ +	+ + + +	• • • • • • • •
8432951	Housing	M102		•	+ +	• • • •		+ +	• • • • •
8432977	Brocket	M102						+	•
8432978	Hub	M102						+ +	• •
8433001	Subassy	M102							•
8433206	Trail	M102						+ + +	• • •
8433535	Bracket	M102		•		•		+ +	• • • •
8433536	Bracket	M102						+	•
8433578	Housing	M102			+			+	
8433634	Support	M102							• • •
8433635	Support	M102							• • •
8433678	Bracket	M102						+	
8433716	Yoke	M102	+ + +	• • • •	+ + + + +	• • • • • •	+ +	+ + + + + + +	• • • • • • • •
8433724	Housing	M102			+ +	• • •		+ + +	• • • • •
8433752	Cam	M102				•		+ +	•
8433797	Housing	M102	+ +	• •	+	• • • • •	+	+ + + +	• • • • • • • •
8436432	Base	M102							•
8436564	Housing	M102				•		+ +	• • • •
8447496	Housing	M102		• •	+ + +	• • •	+ +	+ + + +	• • •
8449308	Bracket	M140			+			+ + +	• •
8449309	Bracket	M140	+ + + +		+ + + + +		+ +	+ + +	•

Figure 23. Part Numbers Chosen by FMS Case (Part 3 of 3)