EFFECTIVENESS ANALYSIS OF FLEXIBLE MANUFACTURING SYSTEMS[*]

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ABSTRACT

A methodology for assessing the effectiveness of Flexible Manufacturing Systems (FMSs) is presented. The methodology analyzes system capabilities in terms of the goals which must be achieved within specific manufacturing, corporate and marketing environments. These environments constitute the context in which the system must operate.

Three example systems, which exhibit different types and degrees of flexibility, are analyzed. Measures are defined to show how effectively the system will be used: and how effectively the goals will be met. The system which best fulfills both criteria within a hypothetical context is then identified. Effectiveness analysis is found to be a useful tool in choosing an appropriate FMS for a manufacturing operation.

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1. INTRODUCTION

Flexible Manufacturing Systems (FMSs) are expected to play a major role in world wide productivity improvements. In order to harness the potential benefits, industry has been installing "flexible" manufacturing equipment such as robots and Computerized Numerically Controlled (CNC) machining centers in rapidly increasing numbers. Although there is little doubt that these systems have the potential to affect the overall manufacturing process in a positive manner, it is not apparent that their use is understood well enough to assure either optimal benefits or successful usage. A gap exists between the status of FMS technology and the ability of industry to assess and use the technology effectively. Development of analytical methods to aid decisions concerning applications of FMS technology is therefore still in the early stages.

There are two basic obstacles hindering the use of FMSs in the U.S. The first obstacle is justifying the capital expenditures required for an FMS. This equipment is typically much more expensive than dedicated manufacturing equipment. Also, management often focuses more on short-term profits, rather than the long-term position of the firm. Justification methods used by industry reflect this concern with short-term gains. FMS usage however, must be justified in terms of both short and long-range benefits. A second obstacle is the problem of implementation. Droy (1983) reports a study which showed that over half of the existing FMSs installed in the U.S. were failures. Essentially all of these failures were attributed to poor planning. However, successes of FMSs are causing recognition of the importance manufacturing processes may have on a company's competitive position. It is becoming necessary to include manufacturing decisions at higher levels of management and to give those decision higher status among a company's priorities. There is a need for assessment methodologies which will help the decision making process in determining where to install and FMS or how to best use existing systems. This necessity becomes more apparent when considering the scope of effects FMS usage may have.

Current methods of assessing manufacturing systems generally culminate in a financial statement. It is not, however, appropriate to assess and FMS solely in financial terms. Flexible manufacturing systems are difficult to assess due to longer life periods, impact on the strategic position of the company, downstream benefits such as incorporation of engineering changes, and other benefits which typically are not expressed in finanical terms. This research addresses the problem of assessing flexible manufacturing systems in such a way that the probability of successful implementation will be greatly enhanced. The approach focuses on analysing the system in terms of the tasks it must accomplish given particular manufacturing, marketing and corporate environments.

Packer (1983) introduces very relevant definitions of efficiency and effectiveness in productivity analysis. Efficiency is defined as how well an enterprise converts its input resources into immediate outputs. Effectiveness is defined as how well the enterprise uses its input resources to meet its ultimate goals and purpose. Presently, U.S. companies tend to look for productivity gains in areas which are related only to efficiency. However, it will be necessary for U.S. industry to make use of FMS technology quickly, efficiently and effectively in order to remain competitive. This will require more emphasis on the long-range effects of manufacturing decisions. Assessment methods designed for FMS technology should be used, and what the implications are for the future. This paper presents a method of making decisions of this type based on the analysis of system effectiveness.

2. DEVELOPMENT OF FMS MISSION AND SYSTEM MODELS

2.1 Flexible Manufacturing Systems

A precise definition of a flexible manufacturing system (FMS) is difficult to compile. Literature tends to identify such systems in terms of their components (i.e., robots, Computerized Numerically Controlled (CNC) machines, automated parts transfer lines,...). For the purpose of

this research, it is appropriate to define FMSs in terms of the flexible capabilities a system may exhibit. For instance, FMSs may exhibit characteristics such as ability to process more than one part or families of parts, production capacity which may be expanded or contracted as needed, ability to process parts in random order, system components which work in different configurations, ability to handle operational problems, and back-up capacity.

Brown, et al. (1984) define eight different types of flexibility which may be exhibited by an FMS. They are (1) Machine Flexibility; (2) Process Flexibility; (3) Product Flexibility; (4) Routing Flexibility; (5) Volume Flexibility; (6) Expansion Flexibility; (7) Operation Flexibility; and (8) Production Flexibility.

An example of a reasonably flexible system might be computer controlled CNC machining centers with multiple head changing capabilities, automated parts handling and automated machining and assembly. A less flexible system might be a robot performing parts transfer between a drilling machine and a lathe. The given definition may be used to determine not only whether a system is flexible, but also to determine the relative flexibility of systems when differentiating between them.

The general methodology to be used in assessing the effectiveness of FMS of the type defined above can be summarized in the following steps.

Step 1: Define the system (FMS), mission (objectives the system should accomplish), and context (the environment in which the system must achieve the mission).

Step 2: Determine which attributes of the system are of interest in satisfying the mission. Define the mission in terms of desirable attribute ranges. Independently calculate the admissible system attribute ranges by varying the independent variables (primitives) in their formulations.

4

Step 3:   Scale the system and mission attributes so that they may be represented in a common attribute space.

Step 4:   Map the system and mission attribute ranges into the attribute space. This step results in two geometrical loci which describe the desirable and possible system operating points.

Step 5:   Define measures of effectiveness to determine how well the system can fulfill the mission.

The two loci mentioned in step 4, the system locus L_s, and the mission locus L_m, can have one of the following geometric relationships.

1.   The loci have no points in common. In this case, the system does not meet any of the mission requirements and the measure of effectiveness is set equal to zero.

2.   The loci have some points in common, but neither locus is contained in the other. In this case, only some of the mission requirements are met by the system. Several measures of effectiveness could be defined. A possible measure, which maps the effectiveness, E, between 0 and 1 is:

$$E = \frac{V(L_s \cap L_m)}{V(L_s)} = \frac{V_s \cap V_m}{V_s} \tag{1}$$

where V is some measure of the "volume" of each locus. The usefulness of this measure becomes apparent when one looks at the final two categories:

3.   The system locus is entirely contained within the mission locus. The effectiveness measure defined in Eq. (1) yields the maximum effectiveness of 1. This system always fulfills the mission.

4. The mission locus is entirely contained within the system locus. In this case, the resulting effectiveness will be less than 1. Although the system is capable of fulfilling the mission, it may also operate in ranges which do not satisfy the mission.

The measure of effectiveness given by Eq. (1) may represent only one of several measures which are of interest in a common attribute space, or may only represent the effectiveness of a subsystem. Therefore, E may be one of several partial measures of effectiveness. The partial measures may be combined to form a single global measure of effectiveness using utility theory such that:

$$E = u\{E_1, E_2, \ldots, E_k\}$$

where E_k denotes a partial measure and u represents the utility function.

When used for comparing alternative systems, this methodology identifies the system which will fulfill the mission in the most effective manner. In doing so, the method indicates what types of flexibilities are just appropriate and the degree of flexibility which is appropriate. This methodology has been described in detail in Bouthonnier and Levis (1984).

2.2 Context and Mission

Consider the hypothetical case of a printed circuit (P/C) board manufacturing company. The company is interested in installing flexible automation in its assembly operation in order to deal better with the uncertainties of its business. Because the company is a supplier of circuit boards to manufacturers of personal computers, there is great uncertainty in predicting both aggregate sales volumes and demand for specific types of boards. It is imperative that the company survive with its current product line of P/C boards because that is the only area in which management is experienced.

The marketing, finance and engineering departments have identified the major areas in which improvements in the assembly operation must be made. The percentage of defective boards receive by customers must be reduced, the new system must be able to incorporate design changes easily, and the time required for assembly of a board must be shortened. In addition, current cash flow difficulties dictate that the system must be profitable within three years. These objectives may be thought of as the company's "mission" which the new manufacturing system should aid in achieving. A clear and complete definition of the mission of an FMS is one of the most crucial, but often overlooked, steps in its justification.

Although there are many P/C boards types which are offered by the company, there are two types - Part 1 and Part 2 that represent the extremes of simplicity and complexity in the manufacturing operation. It is possible that demand in subsequent years may be as high as 100% for either part type. Marketing has split on predictions for sales volumes during the next few years. The optimistic projection is that sales will fall between 40,000 and 60,000 units annually. The pessimistic projection is that sales will fall between 28,000 and 42,000 units.

The scenario describes the context in which any proposed manufacturing systems must be evaluated. The marketing environment, and the unwillingness of the company to change to a different product line are examples of constraints placed on the proposed systems by the context. For an FMS, the mission may be represented by the following attributes: In-Process Lead Time (time interval beginning when a part enters a system and ending when the finished part leaves the system), Market Response Time (time required to incorporate design changes), Strategic Response Time (time required to change product lines), Product Quality, and the Net Present Value (measurement of economic feasibility). Desirable ranges of each of these attributes may be set by the company's knowledge of customer needs, competitor capabilities, and the firm's strategic position. For the hypothetical company, the mission is expressed in the following requirements:

In-Process Lead Time

$$22 \text{ mins.} \geq T_L \geq 8 \text{ mins.} \tag{2}$$

Market Response Time

$$90 \text{ mins.} \geq T_M \geq 6 \text{ mins.} \tag{3}$$

Product Quality

$$Q \geq 0.94 \tag{4}$$

Net Present Value

$$NPV > 0 \quad \text{within three years} \tag{5}$$

The attribute, Strategic Response Time is not applicable within the given context since a change in product line is not a mission objective.

2.3 Representation of Systems

The following systems are under consideration for the assembly operation. Each of the systems has been chosen to exhibit only one type of flexibility in order to stress the methodology rather than the analytical formulation of the attributes. In a more demanding context, several complex FMSs might be under consideration.

The major components of each system are listed and described below:

Transportation Elements – Rotary elements rotate parts in 90-degree increments with each increment requiring a fixed time for rotation, t_R. Linear elements transfer parts between two points. There is also a fixed time, t_E, required to transfer a part between any two elements.

Variable Center Distance Inserter (VCD) – This device inserts components

8

which have two leads (such as resistors). The insertion process is similar to a stapling action.

Dual-In-Line Package Inserter (DIP) - This device is used for insertion of integrated circuits (ICs).

Robot - The robot is used primarily for insertion of non-standard components. The more flexible insertion characteristics of a robot are required when component types are used infrequently or are somewhat problematic to insert.

Wave Solder (WS) - Upon entrance of a board, this process generates a wave of solder which passes underneath the board and solders its components. For the purposes of illustrating the methodology, it will be assumed that this step of the process is run in a continuous manner.

Automatic Test Equipment (ATE) - It checks the connections of components to the board. In addition, there are some logic checks performed to ensure that the board is functioning properly.

Buffers - Buffers are included between processing steps to hold boards whenever the next processor is occupied.

Each of these system components may be referred to as a processor. Loading and unloading of the processors will not be modeled as part of the system. In all analyses, it is assumed that each processor is manned by one attendant; in cases of processing error, the attendant is responsible for removing the affected part from the process flow.

2.3.1 Computerized Automated Line

A schematic of System 1 is shown in Figure 1. Computer control and sensors are used to establish the part type that is entering the system. The computer allows storage of a library of programs for different part types. Once the board type is established, each processor is switched to

the correct program to follow for component insertion or inspection. The process flow is as follows:

$$VCD \rightarrow DIP \rightarrow Robot \rightarrow WS \rightarrow ATE$$

The robot's gripper in this system must be able to handle the various non-standard parts without a gripper change. This system exhibits part-mix flexibility in that it can simultaneously process several different part types. The system also allows quicker changeover between batches.
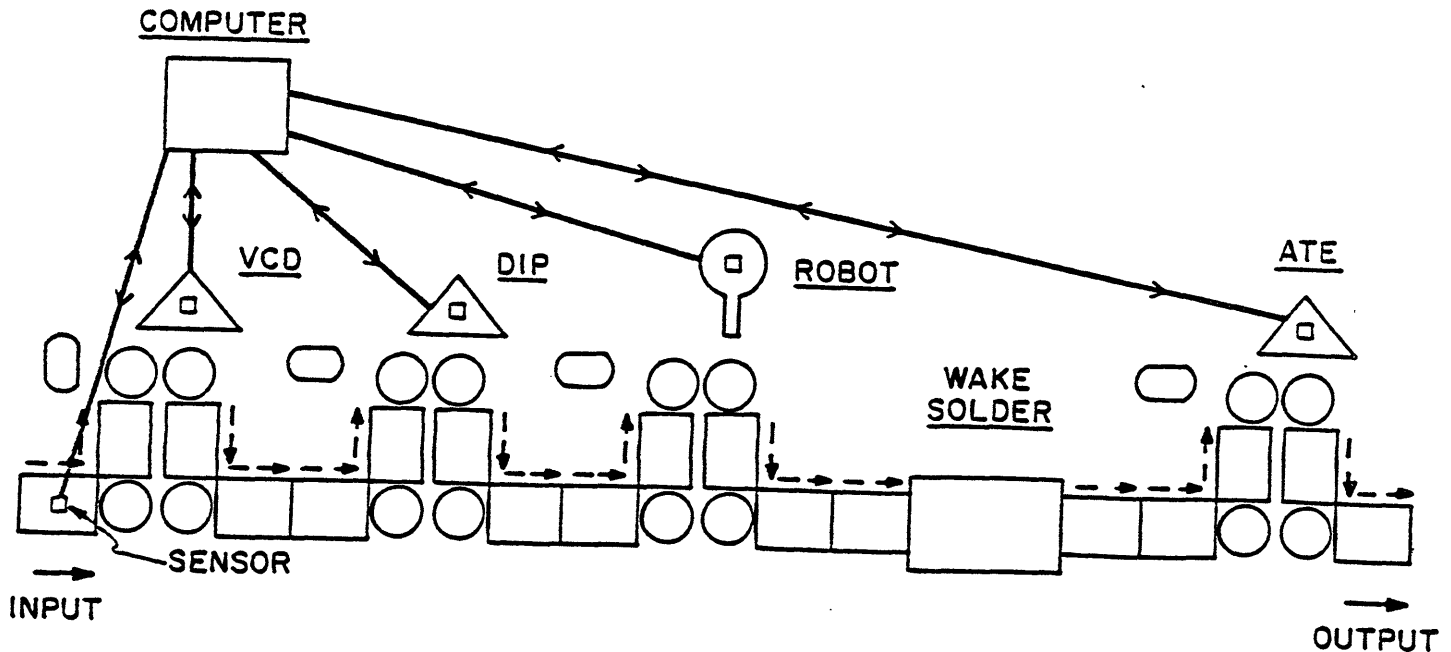

Figure 1. System 1 – Computerized Automated Line

2.3.2 Automated Line/Potential Routing Flexibility

System 2 (shown in Figure 2) includes what Brown, et al. (1984) call potential routing flexibility. In the case of DIP breakdown, this system will automatically reroute parts to the robot for insertion of both standard and non-standard components. The possible process flows are:

(1) $VCD \rightarrow DIP \rightarrow Robot \rightarrow WS \rightarrow ATE$

(2) $VCD \rightarrow Robot \rightarrow WS \rightarrow ATE$

It will be assumed that the DIP attendant continues checking for defective parts so that overall quality levels remain unchanged in either process flow. The robot gripper in System 2 must be able to handle variety of part types as in System 1.
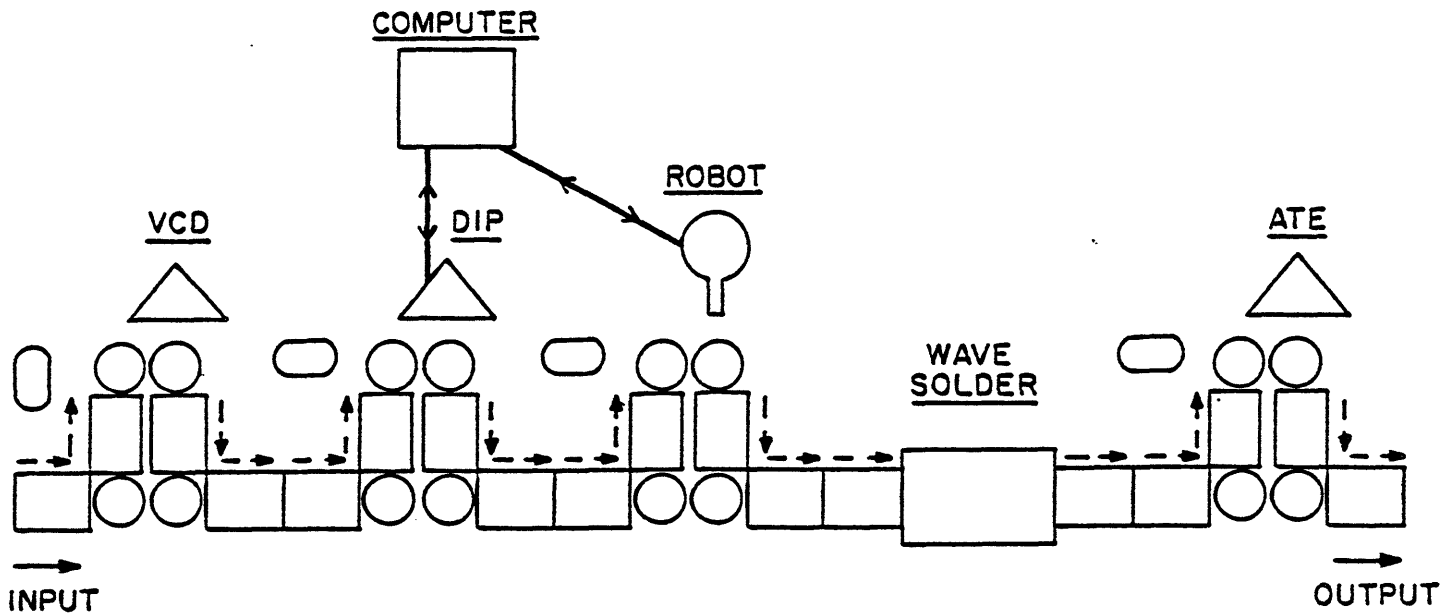

Figure 2. System 2 - Automated Line/Potential Back-up Capacity

2.3.3 Automated Line/Actual Back-up Capacity

System 3, as shown in Figure 3, is an example of actual routing flexibility. Redundancy of the VCD and robot provides several possible paths through the system in the case of processor failure. In this system, the robot performs only non-standard part insertion. The possible process flows are:

(1) VCD#1 → DIP → Robot#1 → WS → ATE

(2) VCD#2 → DIP → Robot#2 → WS → ATE

(3) VCD#1 → DIP → Robot#2 → WS → ATE

(4) VCD#2 → DIP → Robot#1 → WS → ATE

In addition, process flows 1 and 2 may occur simultaneously. Since there are two more processors in this system, additional personnel are required.
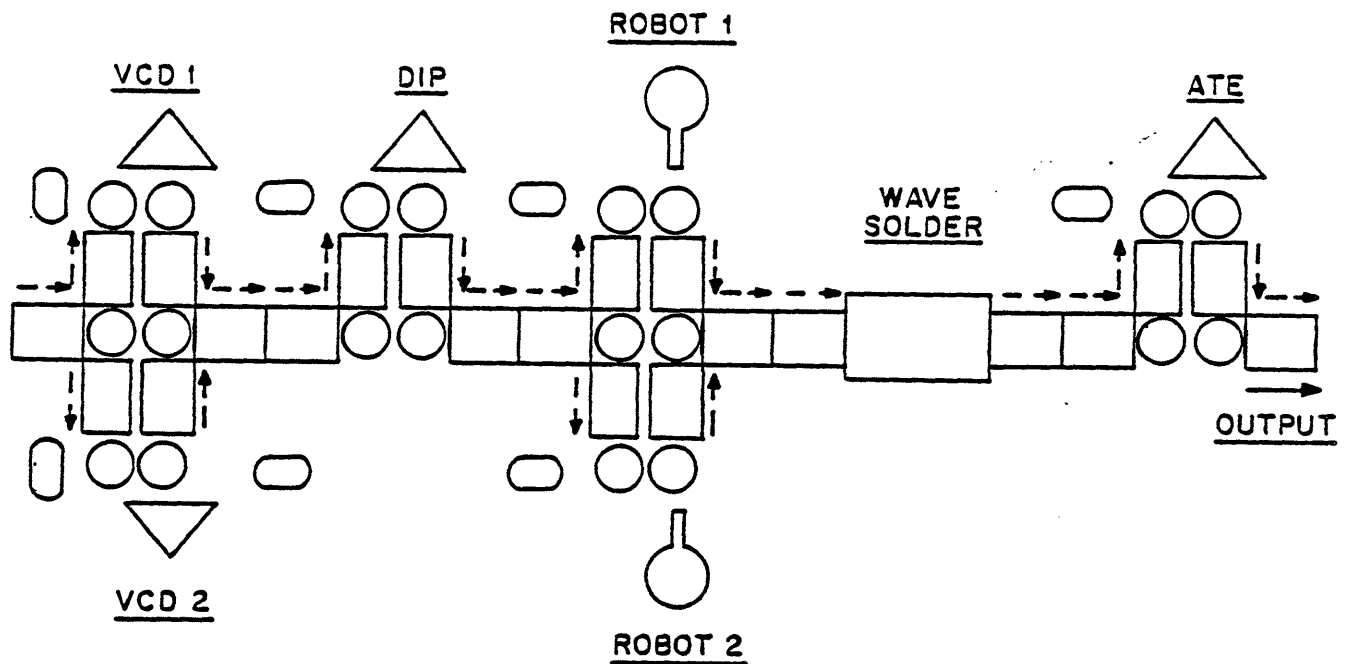
Figure 3. System 3 -Automated Line/Actual Back-up Capacity

2.4 System Attributes

This section presents an overview of system attribute calculations. Detailed analysis of the attributes for each system can be found in Washington (1985).

In-Process Lead Time, T_L: There are two major components of the in-process lead time, total transportation time, Δt_t, and total service time (waiting time in buffers and processing time), Δt_s.

$$T_L = \Delta t_t + \Delta t_s \tag{6}$$

The total transportation time, Δt_t is fixed by the number of transportation elements in the system. For each of the systems under consideration, the transportation time is given by

$$\Delta t_t = \sum_{k=1}^{n_L} \left(\frac{S_k}{V_k} \right) + (n_L + n_R) * t_E + n_R * t_R \qquad (7)$$

where

s: length of linear elements

v: velocity of linear elements

n_L: number of linear elements

n_R: number of rotary elements

t_E: transfer time between elements

t_R: time for rotation

The service time varies with the processor and part type. For each processor in Systems 1, 2 and 3, the service time may be determined using either the M/M/1 or M/M/c models found in queueing theory. The M/M/c (with c=2) is appropriate for System 3 where duplicate processors are available. Calculation of the service time component requires several primitives; including the part input rates, processor component insertion times, and number of components inserted per processor. When comparing the system attribute ranges, only the in-process lead time when a system is fully operational is considered. For each system, the range of in-process lead times is formed by the range of part types which may be processed.

Market Response Time, T_M: This is the time increment beginning when a system ceases producing a given part type, in order to change to a new type, and ending when the system begins production of a new part type. This attribute is also known as changeover time. The lower bound of the market response time is assumed to be the average changeover time when all input primitives fall in expected ranges. A company may, however, take a infinite amount of time for changeover. Therefore, since a maximum system market response time will be needed, it will be defined as the maximum market response time allowed by the mission (in this case, 90 mins.).

If scheduling of production runs is done in advance (as it usually the

13

case), then the minimum market response time, T_{Mmin}, consists of three components:

$$T_{Mmin} = \sum_{i=1}^{5} (\Delta t_{rpi} + \Delta t_{fxi}) + \Delta t_{wu} \qquad (8)$$

Δt_{rp} — reprogramming time

Δt_{fx} — time to mount and test fixtures

Δt_{wu} — warm-up time

These three parameters are the primitives for this attribute. The minimum market response time will vary with each proposed system depending on the portion of changeover which is performed manually versus that which is performed automatically.

Product Quality, Q: This attribute is entirely dependent on the type of part which is being manufactured by the FMS. In the manufacture of P/C boards, may be defined as the percentage of output boards which are not defective. At any inspection, a part may pass inspection or not pass inspection, and may be defective (bad), or not defective (good). If each attendant checks the components inserted at the current processor, and possibly notices defects which have passed through previous inspections, the probability that a good part will pass through the system's inspection system and on to the customer is given by:

$$Q = \frac{P_{1G}P_{2G}P_{3G}P_{5G}}{P_{1G}P_{2G}P_{3G}P_{5G} + P_{1G}P_{2G}P_{3G}P_{5B} + P_{1G}P_{2G}P_{3B}P_{5B} + P_{1G}P_{2B}P_{3B}P_{5B} + P_{1B}P_{2B}P_{3B}P_{5B}}$$

with $P_{iB} = 1 - P_{iG}$ \qquad (9)

Variation of each of these probabilities over admissible ranges results in a product quality range. Since each system has the same inspection process, the quality ranges are identical.

14

Net Present Value, NPV: The general formula for calculating NPV is as follows:

$$NPV = C_0 + \sum_{i=1}^{n} \frac{C_i}{(1+r_i)^i}$$ (10)

C_0: initial cash flow

C_i: annual cash flow

r_i: annual discount rate (opportunity cost of capital)

n : system lifespan or other limit in years

Cash outflows (such as capital equipment costs or installation and maintenance costs) are negative. Cash inflows (such as sales revenues or salvage value) are positive. The cash flows are discounted to reflect inflation, risk and the time value of money. The formula given in Eq. (10) is a simplified version of NPV which assumes that all cash flows occur at the end of the year.

For the given systems, the following cash flows are of interest. In this list, the desired profitability period is three years ($t = t_3$).

Cash Outflows   Cash Inflows

$t = 0$ $t = t_1$
    Capital Cost   Investment Tax Credit
    Plant Floor Space
    Other Costs (OC($t=0$))

$t = t_1, t_2, t_3$ $t = t_1, t_2, t_3$
    Labor Costs   Sales Revenues
    Materials Costs
    Inventory Costs
    Tax Liability
    Other Costs (OC(t))

<u>Materials Costs, CM</u>: In order to calculate the costs of materials, it is necessary to know the sales volume and the system yield. The possible ranges of sales volumes were established in the mission. The system yield, is the ratio of the number of output boards to the number of input boards. As shown in Figure 4, a board may be passed to the next stage or may be rejected. A portion of those boards which are rejected may be fixed and returned to the process flow. If there are five processors in the process flow, the system yield, Y, is the ratio of the output of the first processor and is given by:

$$Y = (r_s + c_s(1-r_s))(r_4 + c_4(1-r_4))(r_3 + c_3(1-r_3))(r_2 + c_2(1-c_2))(r_1 + c_1(1-r_1)) \quad (11)$$

where r_i is the probability that a part moves to the next stage and c_i is the probability that a rejected part is corrected and returned to the process.
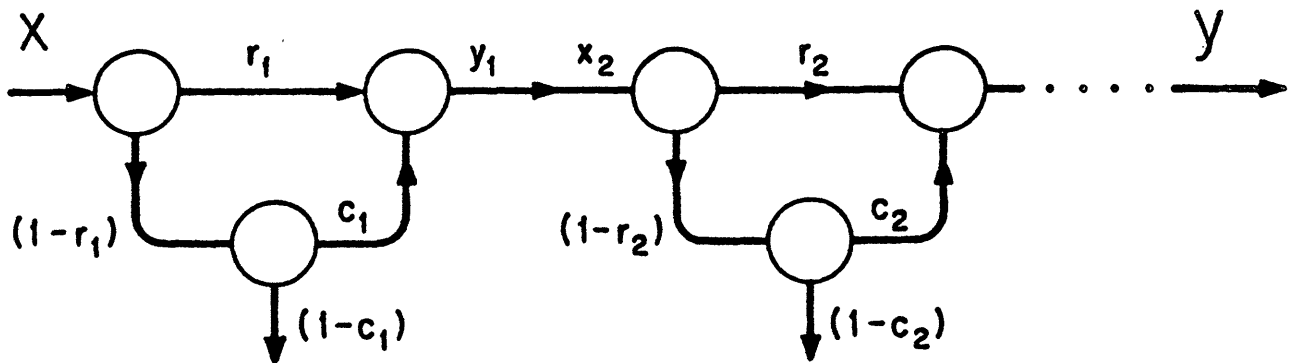

Figure 4. System Yield

The materials cost range may then be calculated using Eq. (12)

$$CM = V * CB/Y \qquad (12)$$

where, CB is the cost per board and V is the number of boards (volume of production).

<u>Labor Costs</u>: In order to calculate labor costs, it is necessary to know

the system capacity. This requires several preliminary calculations including the probability that the system is operating, the annual available machine hours and the average annual input rate.

Probability that the System is Up: The probabilities of the various systems operating in the possible states (fully operational, or partially operational when there is back-up capability) are calculated using the probabilities that the individual machines are operating along the possible part routes. For System 1, where there is no back-up capacity, the probability that the system is up is given by:

$$PS_1 = p_1 * p_2 * p_3 * p_4 * p_5 \qquad (13)$$

P_i = Probability of processor i being operational

Similarly, summing the operational probabilities of the System 2 process flows yields:

$$PS_2 = PS_1 * p_1 (1-p_2) * p_3 * p_4 * p_5 \qquad (14)$$

In the case of System 3, where there are five possible ways for the system to be operable, the probability that the system is up when all processors have the same operating probability, P, is given by:

$$PS_3 = p^6 + 4 * (1-p)p^5 + 4(1-p^2)p^4 \qquad (15)$$

Annual Machine Set-up Time: The annual time required for machine set-up, MS, is given by:

$$MS = N * TM \qquad (16)$$

The maximum machine set-up time is found when the maximum possible market response time occurs for each set-up, and the minimum machine set-up time is found when the minimum possible market response time occurs for each setp-up.

17

Total Available Machine Hours: Since there are approximately 2000 working hours per shift in a year, the total number of available machine hours, AMH, is given by:

$$AMH = 2000 * PS * \gamma - MS \qquad (17)$$

where γ represents the efficiency of the scheduling algorithm which is used. The range of possible available machine hours is determined by the maximum and minimun annual machine set-up time.

Average Annual Input Rate: It will also be necessary to know the average annual input rate of both part types for each system. Given a system and part, the average annual input rate is found by weighting the possible input rates by their respective probability (i.e., probability that the corresponding process flow occurs). Therefore, the average input rate (under operating conditions) is given by:

$$Av \ IR_j = \frac{p_f * IR_f}{PS} + \sum_{k=1}^{m} \frac{p_p * IR_p}{PS} \qquad (18)$$

where
IR_f - input rate during full system operation

IR_p - input rate during partial system operation

m - number possible partial operating states

System Capacit: The capacity per shift is given by:

$$C = AMH * IR \qquad (19)$$

The shift capacity is partially dependent on both the in-process lead time, and the market response time. Since each of these attributes varies independently, there are four limiting values of C which correspond to the possible limiting combinations of in-process lead times and market response times. Assuming the possibility of partial shifts yields the following expression for the required number of shifts:

$$NS = \frac{V}{C} \tag{20}$$

At this point, the analysis will yield eight possible values of the number of shifts, since C may vary between four scenarios, and the anticipated sales volume also varies between a maximum and minimum.

Finally, the possible labor costs, CL, per shift for each of the eight scenarios is given by:

$$CL = NS * SL \tag{21}$$

Inventory Costs: The amount of inventory held, C_I, is assumed to vary linearly with the annual machine set-up time. This is a very simplified model of inventory patterns:

$$C_I = CB * r \ (SS + N * T_M) \tag{22}$$

where r is the cost of capital and SS is the minimum average annual inventory. The safety stock requriment is assumed proportional to the sales volumes. Possible inventory costs are determined for the four possible scenarios by varying the sales volume and market response time.

Other Cash Flows: The investment tax credit may be taken as a fixed percentage of the capital cost. The tax liability is a fixed percentage of the annual sales revenues less production expenses, including depreciation. Because the NPV varies with T_L, T_M and the projected sales volumes, there are eight possible values which represent the maximum and minimum NPV for the four limiting combinations of T_L and T_M. The values of the attributes for each system are summarized in Table 1.

TABLE 1. System Attributes

System	Q	T_L (min.)	T_M (min.)	NPV (millions of dollars)	
				Sales = 60,000	Sales = 28,000
			0.415	3.370	0.8787
	0.996	7.497	90	1.699	−0.2913
1			0.415	3.240	0.8787
	0.936	24.617	90	1.568	−0.2913
			6.683	3.375	0.9187
	0.996	7.497	90	1.821	−0.1695
2			6.683	3.245	0.9187
	0.936	24.617	90	1.690	−0.1695
			65	1.737	−0.393
	0.996	6.868	90	1.270	−0.720
3			65	1.639	−0.393
	0.936	18.967	90	1.172	−0.720

3. COMPARISON OF ALTERNATIVE SYSTEMS

Determination of the effectiveness of each of the proposed systems is made by comparing the mission and system loci in a commensurate attribute space. The possible system and mission attribute ranges are first scaled so that they may be mapped into the commensurate attribute space. Measures of effectiveness are then defined to compare the effectiveness of each proposed system.

3.1 Determination of the System and Mission Loci

Each of the system attribute ranges given in Table 1 and the desired

attributed ranges derived from the mission requirements Eq. (7) and (10), may be scaled as follows. The scaled in-process lead time, T_L^*, which will be mapped in the commensurate attribute space, is given by:

$$T_L^* = 1 - \frac{T_L}{30} \tag{23}$$

so that the system capabilities will increase as the in-process lead time decreases. The multiplicative factor, 1/30, is used so that the system capabilities and mission requirements, when scaled, will fall approximately between zero and one.

The scaled market response time may be calculated as follows:

$$T_M^* = 1 - \frac{T_M}{90} \tag{24}$$

The market response time is subtracted in order to show increasing system capabilities with decreasing market response times. The multiplicative factor, 1/90, is used to scale the value between zero and one.

The scaled product quality, Q^*, is given by:

$$Q^* = (10 * Q) - 9.0 \tag{25}$$

Equation (30) is appropriate for mapping the quality of systems with a rating of at least 0.9 (as in the case of the example systems). The upper bound on the mission requirement then becomes 1.0 (100% correct).

It is necessary to pick an NPV scaling factor which is large enough to map all possible NPV values in the 0 to 1 range:

$$NPV^* = \frac{NPV}{3.5*10^6} \tag{26}$$

The scaling factor is 3.5 million dollars.

Scaling of the mission requirements given in Eq. (2) through (5) results in a mission locus which is defined by the following inqualities.

$$0.733 \geq T_L^* \geq 0.267 \quad ; \quad 0.933 \geq T_M^* \geq 0$$

$$1.0 \geq Q \geq 0.4 \quad ; \quad NPV^* \geq 0$$

(27)

The resulting mission locus is defined in the four dimensional space $(NPV^*, T_M^*, T_L^*, Q^*)$. The projections of this locus in two three-dimensional subspaces are shown in Figures 5 and 6.
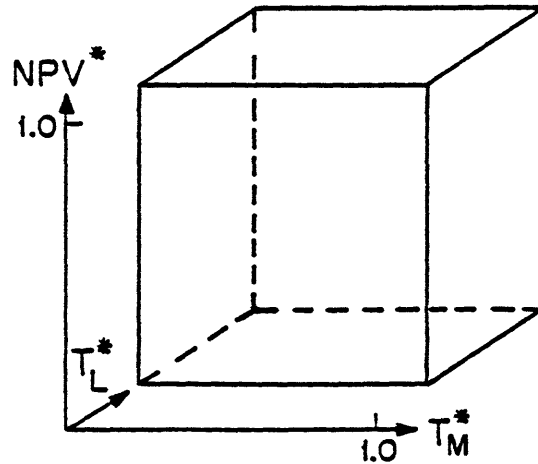

Figure 5. Projection of the Mission Locus in the Space (NPV^*, T_M^*, T_L^*)
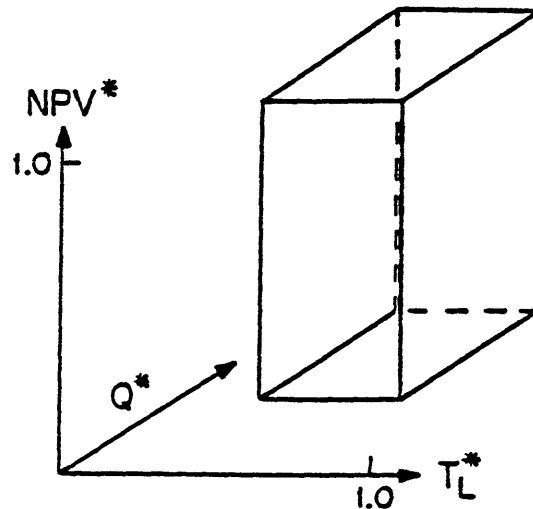
Figure 6. Projection of the Mission Locus in the Space (NPV^*, T_L^*, Q^*)

The descriptions of the system loci differ slightly because all attributes are not independent. In the system loci, the net present value attribute is dependent on the market response time and the in-process lead time. Because all of the components of the NPV vary linearly, all of the system volumes have planar boundaries. For System 1, the locus of points is defined by:

$$0.96 \geq Q^* \geq 0.36 \quad ; \quad 0.75 \geq T_L^* \geq 0.18$$

$$0.986 \geq T_M^* \geq 0 \quad ; \quad a_1 \geq NPV^* \geq b_1 \qquad (28)$$

$$a_1 = 0.499 \; T_M^* + 0.065 \; T_L^* + 0.45 \quad ; \quad b_1 = 0.35 \; T_M^* - 0.086$$

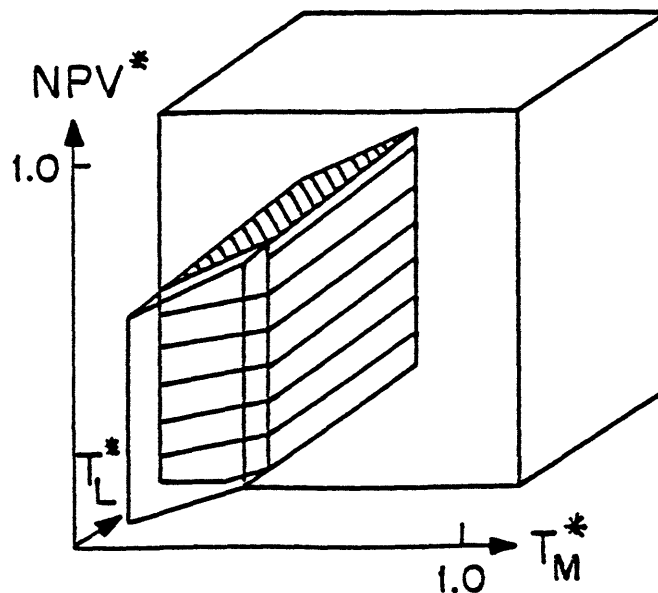The System 1 locus, the mission locus, and their intersection are depicted in Figures 7 and 8.

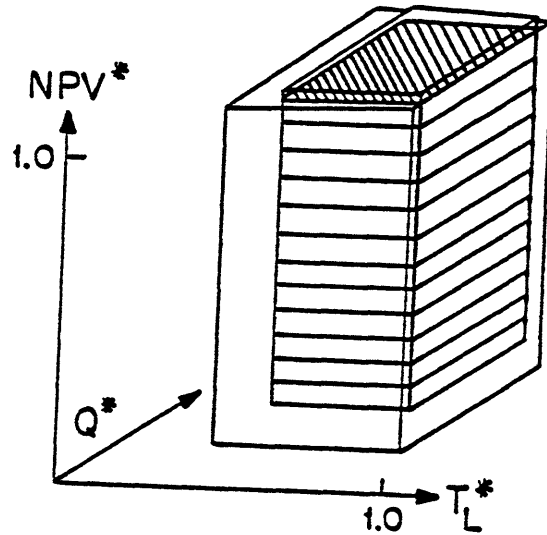Figure 7. Projection of the System 1 Locus in the Space $(NPV^*, \; T_M^*, \; T_L^*)$

23

Figure 8. Projection of the System 1 Locus in the Space (NPV^*, T_L^*, Q^*)

The inequalities that define the system locus for System 2 are:

$$0.96 \geq Q^* \geq 0.36 \quad ; \quad 0.75 \geq T_L^* \geq 0.18$$

$$0.926 \geq T_M^* \geq 0 \quad ; \quad a_2 \geq NPV^* \geq b_2 \quad \quad (29)$$

$$a_2 = 0.49 \, T_M^* + 0.068 \, T_L^* + 0.485 \quad ; \quad b_2 = 0.345 \, T_M^* - 0.05$$

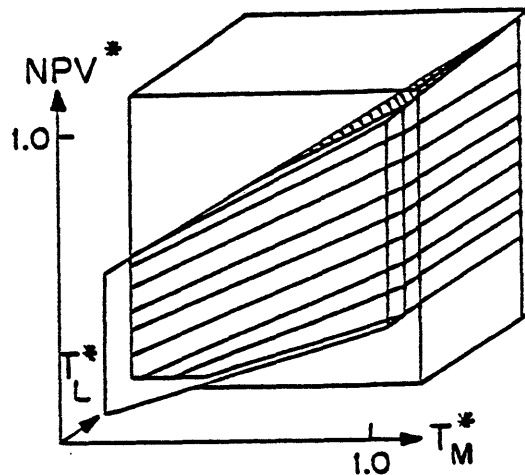System 2 intersects the mission locus as shown in Figures 9 and 10.

Figure 9. Projection of the System 2 Locus in the Space (NPV^*, T_M^*, T_L^*)
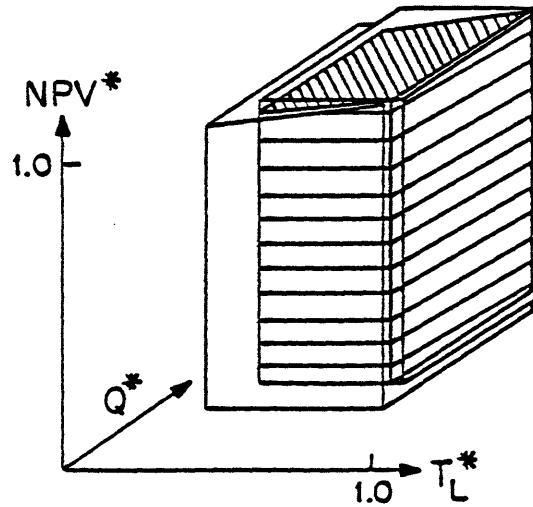
Figure 10. Projection of the System 2 Locus in the Space (NPV^*, T_L^*, Q^*)

The final system to be considered, System 3, is characterized by:

$$0.96 \geq Q^* \geq 0.36 \quad ; \quad 0.77 \geq T_L^* \geq 0.368$$

$$0.28 \geq T_M^* \geq 0 \quad ; \quad a_3 \geq NPV^* \geq b_3 \tag{30}$$

$$a_3 = 0.5 \, T_M^* + 0.0746 \, T_L^* + 0.3165 \quad ; \quad b_3 = 0.343 \, T_M^* - 0.212$$

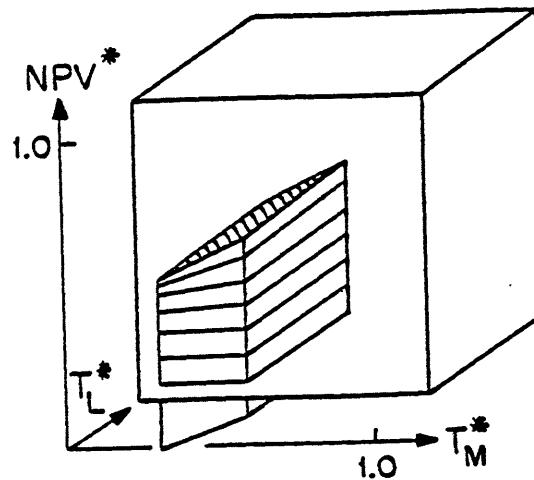The system and mission loci intersect as shown in Figures 11 and 12.

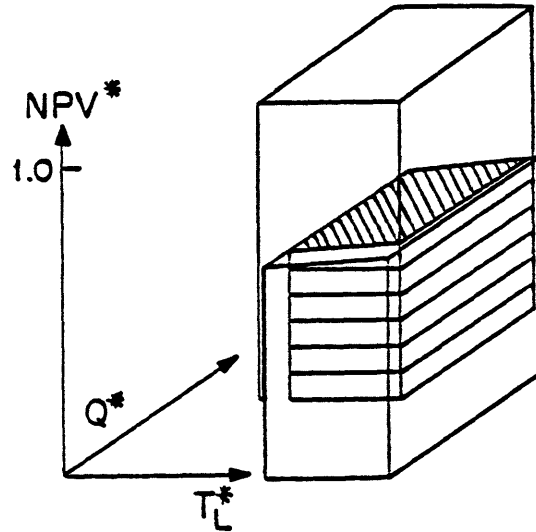Figure 11. Projection of the System 3 Locus in the Space (NPV^*, T_M^*, T_L^*)

Figure 12. Projection of the System 3 Locus in the Space (NPV*, T_L^*, Q*)

3.2 Effectiveness Analysis

The effectiveness of each of the systems may be determined by comparing the intersection of the system loci with the mission locus in the commensurate attribute space (Step 5). Effectiveness analysis requires calculation of the mission volume, the system volume, and the volume of the intersection. The volume of each system, V_s, is calculated by integrating over the admissible ranges of each of the attributes.

$$V_s = \int_{Q^*} \int_{T_L^*} \int_{T_M^*} \int_{NPV^*} d(NPV^*) \, dT_M^* \, dT_L^* \, dQ^* \qquad (31)$$

Similarly, the mission volume, V_m, is calculated by integrating over the desirable attribute ranges. The volume of the intersection is calculated by integrating over the attribute ranges which are found in both the mission and system loci.

Two partial measures of effectiveness (MOEs) are appropriate to compare the system. The first partial MOE, E_1, is defined as:

26

$$E_1 = \frac{V_s \cap V_m}{V_s} \tag{32}$$

This measure indicates how effectively the system capabilities will be used. It shows how much of the system's operating range will be used to accomplish the mission. Systems with lower or higher technological capabilities than required will be penalized by this partial measure since such systems might be better used elsewhere.

The second partial measure of effectiveness, E_2, is defined as:

$$E_2 = \frac{V_s \cap V_m}{V_m} \tag{33}$$

This MOE indicates how well the system covers the desired operating range. This is particularly important for FMS analysis, since the stated mission will often reflect both current and future needs.

Consider a case where the system capabilities are entirely encompassed by the mission. The first partial measure of effectiveness will then yield the maximum effectiveness rating of 1.0 since all of the system capabilities will be used. However, if the system only covers a small portion of the mission locus, the second partial measure of effectiveness would be low.

The two partial measures of effectiveness may then be combined to form a global measure of effectiveness, $\widetilde{E}$. An admissible utility function that balances both points of view is:

$$\widetilde{E}_i = E_1^\alpha \; E_2^\beta \quad ; \quad \text{i: system number} \tag{34}$$

For the example systems, both partial measures of effectiveness will be weighted equally.

27

$$\alpha = \beta = 0.5 \tag{35}$$

The results are sumarized in Table 2.

TABLE 2. <u>Effectiveness Analysis Results</u>

System #	V_s	$V_s \cap V_{\tilde{m}}$	E_1	E_2	$\tilde{E}$
1	0.21566	0.15258	0.71	0.586	0.64
2	0.20103	0.15284	0.76	0.585	0.67
3	0.04004	0.01826	0.46	0.07	0.18

$$V_m = 0.26087$$

As a reminder, the descriptive labels of the systems are listed.

System 1 - Computerized Automated Line (Part Mix Flexibility)

System 2 - Automated Line/Potential Routing Flexibility

System 3 - Automated Line/Actual Routing Flexibility

System 1, which exhibited a high degree of part-mix flexibility (rapid changeover,) does not receive the highest E_1 because such flexibility is not required to achieve the mission. The first partial measure of effectiveness indicates that this system has greater technological capabilities than will be utilized. System 3 receives the lowest E_1 largely because it exhibits poor volume flexibility. Although this system provides high reliability, in the form of routing flexibility, it does so at prohibitive cost. System 2 receives the higher partial measure of effectiveness, E_1, because the capabilities it provides will be more fully utilized in achieving the mission. The second martial measure of effectiveness clearly indicates that System 3 is unsuitable for the given mission and context even though it is the more "flexible" system. The extremely low rating, E_2, is again a function of the poor volume flexibility. For the given sales projections, System 3 simply is not able

28

to meet the mission requirement of a positive NPV. Systems 1 and 2 are equally effective with respect to the given mission. The relative close global effectiveness measures of System 1 and 2 might be expected since the systems have similar structures. However, it is clear that of the three systems, System 2 is the most appropriate choice for the given context and mission.

4. CONCLUSION

This paper presents a new technique for assessing Flexible Manufacturing Systems (FMSs). Unlike coventional methods of assessment, the methodology weighs not only a system's financial performance, but also other system attributes which are key indicators of overall system performance. For an FMS, these attributes are: In-Process Lead Time, Market Response Time, Strategic Response Time, Product Quality, and Net Present Value. Therefore, in defining the mission, attributes which influence subjective measures, such as customer satisfication, are included. Because assessment is carried out in the N-dimensional attribute space, trade-offs between attributes may be shown.

Some of the flexibility of the methodology is demonstrated in the selection of the partial measures of effectiveness. Two appropriate partial measures were applied to the FMSs in this paper. The first measure shows what portion of the system's capabilities are required by the mission. When using this measure, a technologically advanced system may not achieve a high measure of effectiveness, if the system capabilities will not be utilized. This measure penalizes the use of complex technology when a simple solution is more appropriate. The second measure shows what portion of the mission can be reached by the system. This measure is important for an FMS since, due to longer life expectancy, the mission will often cover current requirements and anticipated future requirements over some planning horizon. In a sense, this measure indicates the portion of the planning horizon during which the FMS may be used effectively.

The flexibility of the general methodology is demonstrated by the fact

that it may be applied to many types of systems; including C^3 systems (Bouthonnier and Levis, 1984), automotive systems (Levis, Houpt, and Andreadakis, 1984), large-scale power systems (Dersin and Levis, 1981), and, in this paper, manufacturing systems.

5. REFERENCES

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