

Performance Evaluation of Flexible Manufacturing Systems

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Abstract—A performance evaluation methodology for selecting flexible manufacturing systems (FMS) is described. Flexible manufacturing systems incorporate numerical control machines with robotic material handling units working automatically under computer control. In the FMS technology increasingly greater benefits are offered as it integrates more elements of the plant operation. Implementation and acquisition decisions leading to the realization of its overall value should take into account complex technical, operational and corporate policy concerns. In doing so, multiple objectives, where some of the factors are difficult to quantify, have to be dealt with. Typical concerns are related to machining capabilities, operational integrity, cost reduction, lead time, vendors' reputation, and so forth. The multitude of issues relevant to these decision problem are addressed by the performance evaluation framework, treating both tangible and intangible decision factors. Their analysis is carried out through the analytic hierarchy process (AHP). A real industrial application of the model presented here is reported in this paper.

I. INTRODUCTION

MANUFACTURING technology is in the midst of on-going developments stemming from rapid improvements in machine tools, computers, and robotics. These developments, on all three fronts, present system engineers with greater challenges and opportunities in designing more complex and productive systems.

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The need to machine complex parts for the aircraft industry in the early 1950's has led to the introduction of the first programmable (flexible) milling machines. They employed numerical control (NC) files to define the fabrication process of each particular job. The production instructions, in the first NC units, were stored on punched paper tapes [22]. Later on the tapes were replaced by direct numerical control systems (DNC) where the part programs were stored in a central digital computer. The appropriate programs for several DNC machines are transmitted from the digital computer in real time during the manufacturing process. The introduction of minicomputers and microcomputers enabled the machine tools designers to interface dedicated computer for each machine [21]. These are the computer numerical control (CNC) systems that appeared commercially in the mid-to-late 1970's.

Recent advances in control theory have also contributed to the general area of manufacturing [1]. Both DNC and CNC units apply adaptive control to optimize machining operations. Robotics research provides industry with a variety of solutions for material handling, welding, assembly, and spray painting tasks [10] [37]. The incorporation of all these late developments into an integrated manufacturing system is still in its infancy. The first attempt in this overall integration effort is offered through the introduc-

tion of the *flexible manufacturing system* (FMS) concept [3]. It incorporates CNC machines with robotic material handling units working automatically under computer control. These systems can machine parts in any sequence and automatically reroute parts to alternate machines when one breaks down [8], [14], [17].

The FMS technology offers increasingly greater benefits as it integrates more elements of the plant operation. Implementation and acquisition decisions leading to the realization of its overall value should take into account complex technical, operational and corporate policy concerns [11], [12], [15], [34]. Doing so, one has to deal with multiple objectives where some of the factors are difficult to quantify. Typical concerns are related to machining capabilities, operational integrity, cost reduction, lead time, vendors' reputation, and so forth.

This paper describes a framework for the determination of an FMS acquisition decision through performance evaluation of competing designs. This framework addresses the multitude of issues relevant to the acquisition problem, treating both tangible and intangible decision factors.

The analytical approach used in treating these multiple criteria decision problems is based on the *analytic hierarchy process* (AHP) introduced by Saaty [25]. The approach decomposes a complex decision problem into one or more levels of detail [27], where value assessment is provided through pairwise (ratio) comparisons [23]. In addition to providing a structuring approach, priority vectors are established along with consistency measures. It differs from the classical multiattribute utility approach [16] in that the deterministic nature of the problem permits direct value assessment, rather than resorting to assessment of risk attitude. The latter approach results in multiattribute utility *curves*, while the AHP results in a single priority point in the attribute space that describes the overall merits of the system. Recent studies by Schoemaker and Waid [30], Sage [28], and by McCord and Neufville [18], have compared a number of approaches for dealing with multiple criteria decisionmaking, indicating the advantage in applying the AHP methodology. This methodology has already been used in a number of applications [20], [24], [26], [36].

The structure of the paper is as follows. Section II describes the FMS concept. Section III develops the performance model, and Section IV develops the cost model. Section V presents the systems selection process for a real industrial application, and Section VI provides a summary and conclusion of the complete methodology.

II. THE FMS CONCEPT

Flexible Manufacturing Systems (FMS) are integrated systems of computers, CNC machine tools, inspection units, and some automated material handling devices such as shuttle pallets, carts (robot carriers), and industrial robots. The raw parts are manually loaded and unloaded at a central load/unload station. Real-time computer control system moves the carts with the fixtures and the parts to the required workstation for processing. Upon completion

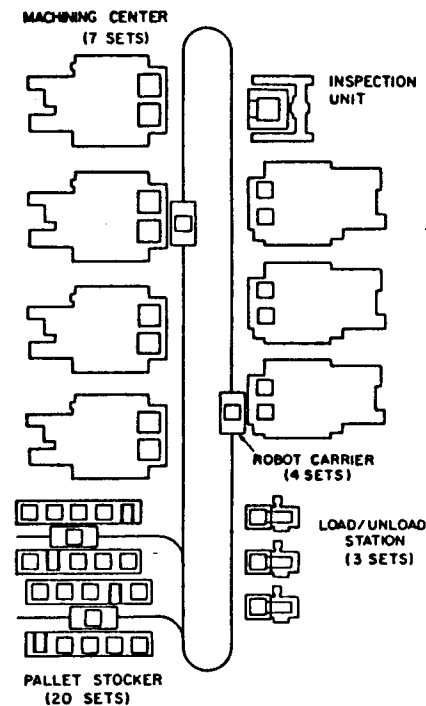


Fig. 1. An FMS layout.

the part is transferred by a cart to its next work station, to the load/unload station, or to the buffer area (pallet stocker) where it queues temporarily [6].

The loading and unloading of all machines, the adaptive route selection, part sequencing, and the determination of various manufacturing variables (e.g., tool changes and spindle feed rate) are conducted under the control of the host computer (Fig. 1). These features, combined with parallel processing capabilities on identical machine tools, result in an enhanced process *flexibility* [38].

The typical FMS can sequence parts randomly and respond quickly to various assembly orders because its setup time is minimal [8], [35]. It can handle a large variety of small and medium size lots with significant savings in direct labor. These systems are therefore designed to fill the gap between high-production *transfer lines* and the low-production stand-alone *job-shop* operations. Transfer lines are efficient only with large volume at high output rates, while job-shop type production tends to be slow and inefficient.

Organizations considering the adoption and implementation of an FMS technology go through the following four stages. The first stage provides the basic *technical data* for the FMS preliminary design. It includes process analysis, production time study, group technology considerations and preliminary definitions of machines, tools, and jigs [2], [5]. The second stage deals with the FMS *concept validation*. It considers both financial analysis of the prospective investment as well as an assessment of specific application problems that the FMS installation is anticipated to solve [4], [31]. The third stage examines the required *capability* (throughput) for various configurations and layouts.

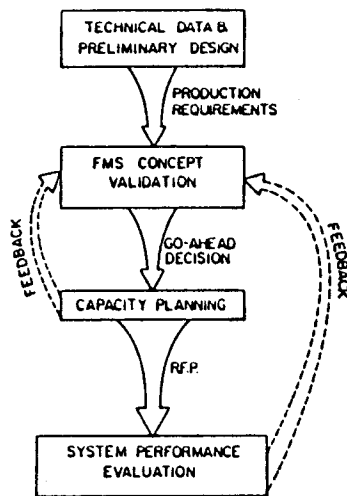


Fig. 2. The FMS decision process.

Recent studies have presented analytical models dealing with capacity planning in FMS designs [7], [32], [33]. The capacity planning stage results in a request-for-proposal (RFP) issued to prospective vendors. The comparative evaluation of the vendors' proposals regarding the overall system performance is conducted at the fourth stage. This *evaluation* addresses the user's requirements, the vendor's product, the operational constraints, and organizational priorities. An overview of the four stages discussed above is depicted at Fig. 2.

The first three stages of the decision process (technical data, FMS concept validation, and capacity planning) have received considerable attention [13]. The fourth stage (evaluation) is an involved issue that forms the focus of our paper.

III. PERFORMANCE MODEL

Flexible manufacturing systems (FMS) are typically procured as an integrated ("total") system from a single source, rather than as an array of subsystems from various vendors. In the latter case, the integration effort rests with the buyer. This may prove to be quite difficult due to incompatibility between machine tools, robots, controllers, software, and computers available from these sources.

The FMS vendors describe their systems by using performance levels—as required by the RFP—of relevant parameters (machining speed, purchase price, etc.). These parameters, important as they may be to the decision problem, describe only part of the picture. These parameters form only a partial list as far as the buyer is concerned. Items such as past experience with a particular vendor, service leadtime, system integration effort, and other important issues can (and should) only be assessed by the buyer. The complete list of parameters should include those (usually tangible) parameters supplied by the prospective vendors, as well as those parameters (usually intangibles) deemed relevant by the buyer. Clearly even a complete list of parameters does not lead to a simple decision. This is because some parameters may be very important for the buyer in some context and unimportant

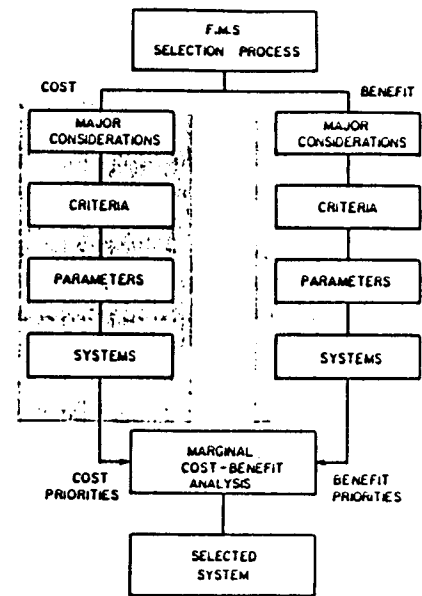


Fig. 3. The FMS evaluation model.

or completely irrelevant in another. This potential shift of priorities requires a structural approach for deriving them. A parameters list should support certain *major acquisition considerations*. Therefore these considerations should be articulated first. Second, one should formulate or state a set of *criteria* used in satisfying these needs or considerations. Then the *parameters* are used in the context of relevant criteria, and finally, after all these groups have been considered and *prioritized*, one can compare the respective systems (vendors) relative to their performance. This approach results in a *hierarchy* of factors, where the major acquisition considerations form the first level, the criteria the second, the parameters the third, and the systems will enter on the fourth level. Complex acquisition problems should consider not only the positive (benefit) aspects, but also the negative (cost) aspects. Therefore a second hierarchy depicting these "cost" (in a broad sense) elements is constructed. The priorities of the systems from the benefit and cost perspective are then used to arrive at a decision. This overall schematic approach is depicted in Fig. 3. The elements of the benefit hierarchy will be described next.

The acquisition of an FMS is motivated by three major considerations. The *economic* consideration is concerned with cost reduction in the manufacturing process. The *production* consideration is concerned with enhancing the operational flexibility. Lastly the *organizational* consideration is concerned with the ability of the organization to respond quickly to changing market demands without loss of opportunities due to slow tooling changes and other manufacturing problems.

Next, one considers the *criteria* used in judging how well these considerations are addressed. The *line efficiency* criteria include three major subsets: the first subset is the expected machine utilization; the second subset is the required-direct and indirect-labor to operate the FMS; and the third subset considers setup times between subsequent

TABLE I
SYSTEM PARAMETERS

1. Precision Parameters
Table indexing accuracy; Indexing angle;
Positioning accuracy; Pallet positioning accuracy;
Positioning repeatability.
2. Table and Pallet Parameters
Table size; Number of pallet changers;
Pallet change time; Table load capacity; X-Y-Z stroke.
3. Machining and Spindle
Speed range; Maximal feed-rate;
Spindle torque; Rapid traverse;
Cooling system.
4. Automatic Tool Changer (ATC)
Magazine capacity; Tool selection system;
Tool-life monitoring; Adaptive feedrate control;
Machine failure detection; Machine time monitoring.
5. Monitoring System (Manufacturing Control)
Tool breakage detection, Spare tool selection;
Tool life monitoring; Adaptive feedrate control;
Machine failure detection; Machine time monitoring.
6. Dimensions Control
In-post process work gauging; Automatic centering;
Tool length measuring.
7. CNC Software
CAM language; Automatic programming;
Self diagnostic/alarm; data logging;
Background programming.
8. Transport Software
Tool room communication; Robot control;
Pallet control; Fixture control;
Pallet sequencing.
9. System Control
Production scheduling; Machine loading;
Material control; Data base management;
Management interface; Production planning;
System upgrade.
10. Robot Loader
Number of robots; Maximal load;

Speed; Pallet size.
Number of pallets; Computer routing.

11. Loading/Stocking Features

Computer control; Display panel;
Number of load/unload stations; Data entry.

12. Computability

Machine tools; Transport system;
Computer control; Data communication.

jobs. The anticipated production lead time, from order to delivery, and the in-process inventory form the *performance* criteria. Major *process* elements include the ability to handle a large part-mix simultaneously, design changes accommodation, ease of operation, scheduling and control functions, along with routing flexibility. The *volume* criteria considers both the installed production capacity and the potential for capacity growth in the future. The *configuration control* criteria regard the delivered accuracy (percent defectives), the manufacturing precision (machinery tolerances), and the capability to machine parts designed with complex geometry.

Finally, the relevant benefit parameters are considered. These include twelve major groups of relevant parameters that are summarized in Table I. The parameters listed are self explanatory and their respective values are supplied by the vendors in their systems specifications. Detailed descriptions of these parameters can be found in modern manufacturing systems literature [3], [10], [13], [19], [21], [22].

All these decision elements (major considerations, criteria, and parameters) form together the performance model depicted in the *hierarchy* shown in Fig. 4. In order to arrive at the *benefit priorities* associated with the systems under consideration, one has to prioritize all the elements of the hierarchy. This prioritization is carried out by the *analytic hierarchy process* (AHP) developed by Saaty [25]. The AHP methodology performs pairwise comparisons of elements in one level relative to a single element in a level immediately above it to derive *local priorities* of these elements that reflect their relative contribution to the subject of comparison. Thus in comparing the three major considerations the following *comparison matrix* (Table II) was arrived at.

The entries of the matrix are the answers to the three pairwise comparison questions asked. These entries are taken from the comparison table shown in Table III. For example, in comparing the "economic" consideration to the "production" consideration (element $a(1,2)$ of the matrix) it was judged that the first "strongly" (scale value of five) dominates the second. Only the upper triangular

TABLE II
PRIORITIZATION OF MAJOR CONSIDERATIONS

Considerations	1	2	3	Priorities
1) Economic	1	5	2	0.58
2) Production		1	1/3	0.11
3) Organization			1	0.31
C. R.=0.0003185				1.00

part of this matrix is shown since it is a reciprocal matrix, i.e., $a(i, j) = 1/a(j, i)$. Therefore, the element $a(2, 3) = 1/3$ means that element 3 ("organization") has a "moderate" (scale value of three) dominance over "production." Once all the entries of this matrix are available (these are supplied by the decisionmaker rather than the analyst (more on this point later on in Section VI), one solves for the priority vector from

$$Aw = \lambda_{\max} w \quad (1)$$

where w , the priority vector, is the eigenvector associated with the largest eigenvalue of the comparison matrix A . Consistency is checked by ascertaining whether

$$a(i, j) = a(i, k)a(k, j), \quad \text{for all } i, j, k. \quad (2)$$

The situation depicted in (2) represents the perfectly consistent case. In practice, the elements of the matrix A in Table III are estimated through the use of the scale whose values are given in Table III.

In general the elements of the matrix A in Table II satisfy $a_{ij} = w_i/w_j + \epsilon_{ij}$ where ϵ_{ij} is some error that represents inconsistencies in judgment and then $a_{ij} \neq a_{ik}a_{kj}$. It can be shown that the largest eigenvalue of the matrix A , λ_{\max} , satisfies $\lambda_{\max} \geq n$, where equality holds for the perfectly consistent case only. A consistency index is now defined as

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

which is zero in the perfectly consistent case. To assess the consistency derived in (3) we compare it to the worst case that will be the case of a pairwise comparison matrix whose entries are filled at random. Doing it for many samples and for various matrices, Saaty [25] has obtained the following:

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

where n represents the dimension of the matrix and RI is the random index evaluated through (3) for these random matrices. Now one defines the consistency ratio (CR) as

$$CR = CI/RI \quad (5)$$

which is required to be less than 0.1 for acceptable results (more on this is found in [25]).

Returning to Table II one observes that the derived priorities of the major considerations, as assessed by the corporate management in this case, were 58 percent for economic considerations, 11 percent for production, and 31

TABLE III
COMPARISON SCALE

1	Equal importance.
3	Moderate importance of one over another.
5	Essential or strong importance.
7	Very strong or demonstrated importance.
9	Absolute importance.
2, 4, 6, 8	Intermediate values between adjacent scale values.

percent for organizational considerations. This agrees rather well with the general reasons stated in the literature for the introduction of FMS technologies [17].

The second level of the hierarchy, the criteria level, is next prioritized with respect to each of the three major considerations. The prioritization is done by using comparison matrices describing the relative contribution of the criteria to each of the major considerations. This is summarized in Table IV.

Each of the first three columns describes the local priorities of the criteria with respect to the relevant consideration of that column. A zero entry means that the particular criteria is not relevant for that consideration. Next, using the priorities of the major consideration, the global priorities of the criteria are derived. Line efficiency, performance, and volume emerged as the high priority criteria for this particular FMS selection. Each of the criteria is subdivided (see Fig. 4) and the priorities of these subdivisions are again computed through a pairwise comparison matrix describing the relative importance of the subdivisions of the "host" criteria. This step is omitted for brevity. The priorities of the major subcriteria are shown in Fig. 5.

The third level deals with the specific FMS parameters. Following the same prioritization scheme as done in the criteria level one derives first the local priorities of the parameters with respect to each subcriteria (for example, automatic tool change with respect to machine utilization) and then, using the priorities of the subcriteria, one derives the global priorities for the parameters. These are summarized in Table V, and depicted in Figs. 6 and 7.

The ATC, Compatability, and System Control were found to be the most significant parameter sets. This group

and its derived ordinal ranking agreed with the prior expectations of the participants. The AHP model, however, has provided them with the relative priority of all the FMS parameters that contribute to the major benefit considerations (rather than simple ordinal ranking).

IV. COST MODEL

As outlined in Fig. 3, the FMS evaluation model is composed of two parts: the benefit model, discussed in Section II, and the cost model to be discussed here. The

TABLE IV
PRIORITIZATION OF CRITERIA

Criterion	Economic	Production	Organization	Global
Line Efficiency	.52	.10	.0	.312
Performance	.14	.19	.46	.247
Process	.0	.38	.19	.100
Volume	.27	.29	.29	.280
Configuration	.07	.04	.06	.061
	1.00	1.00	1.00	1.000

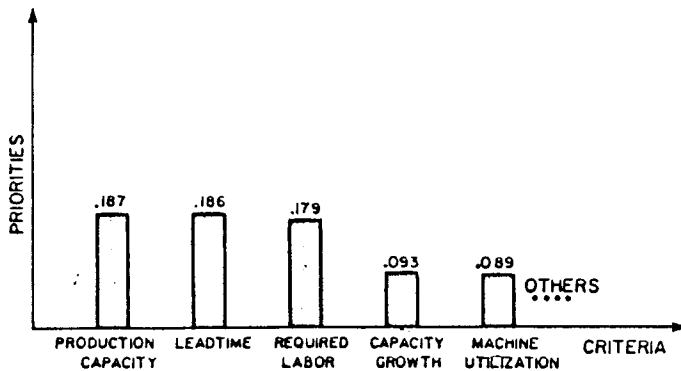


Fig. 5. Priorities of major subcriteria.

difference between the two parts is that while one wishes to *maximize* the benefits derived by the proposed system the cost model deals with those issues and parameters whose influence one wishes to *minimize*.

The cost model follows the general outline of the benefit model (cf. Fig. 4). Major considerations in the cost model consist of *system expenditures* and *system dependability*. The criteria level includes *installation, service, vendor, and operational integrity*. The parameters level includes eight major groups: *procurement cost, contractual clauses, operating cost, manufacturer, local distributor, required costomizing, vulnerability, and maintainability*. These parameters and their subdivision are shown in the cost hierarchy of Fig. 8, (for a detailed list of the parameters please refer to Table VI).

The prioritization process of the cost hierarchy follows the same steps described in Section III for the benefit hierarchy. The first step prioritizes the major cost considerations in the acquisition of the FMS. In this particular application this has resulted in 60 percent being given to system acquisition and 40 percent to the system dependability issues (the comparison matrix is not shown). Next the criteria were prioritized with respect to the relevant consid-

TABLE V
GLOBAL PRIORITIES OF FMS PARAMETERS

Parameters Group	Priority
Precision	.047
Table and Pallet	.059
Spindle	.008
A.T.C.	.226
Monitoring System	.045
Dimension Control	.122
CNC Software	.006
Transport Software	.031
System Control	.194
Robot Loader	.026
Loader/Stocker	.034
Compatibility	.202
	1.000

erations and using the priorities of the major considerations these local priorities were weighted to yield the criteria's global priorities. At the third step, the parameters group were prioritized with respect to their contribution to the relevant criteria. Using the global weights of the criteria the same weighting process lead to the derivation of the global priorities of the parameter sets. The global priorities of the parameters are summarized in Table VI. A sample derivation of local priorities for one parameter set ("local distributor") is shown in Table VIII, depicting the comparison matrix between the relevant parameters.

Examining Table VI one observes that out of the eight major groups of parameters, three parameters sets, namely: "procurement cost" (24 percent), "local distributor" (19.3 percent) and "required: stomizing" (17.5 percent) account for more than half of the overall weights assigned. This can

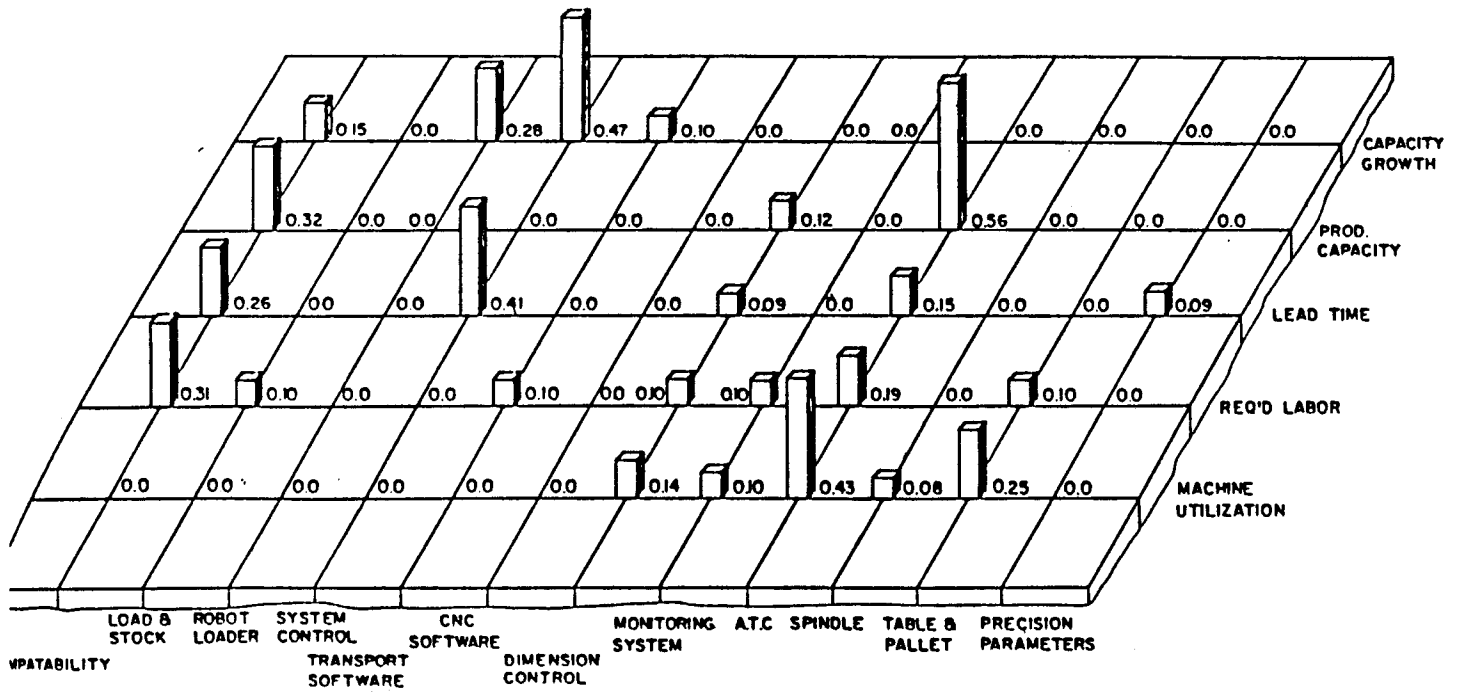


Fig. 6. Local priorities of parameters.

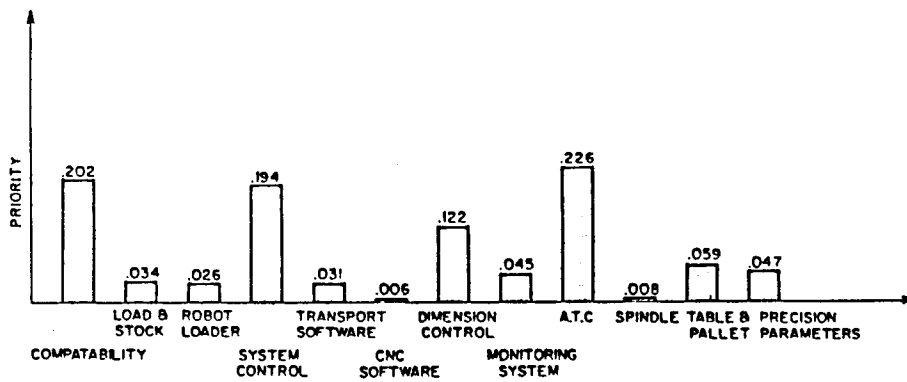


Fig. 7. Global priorities of parameters.

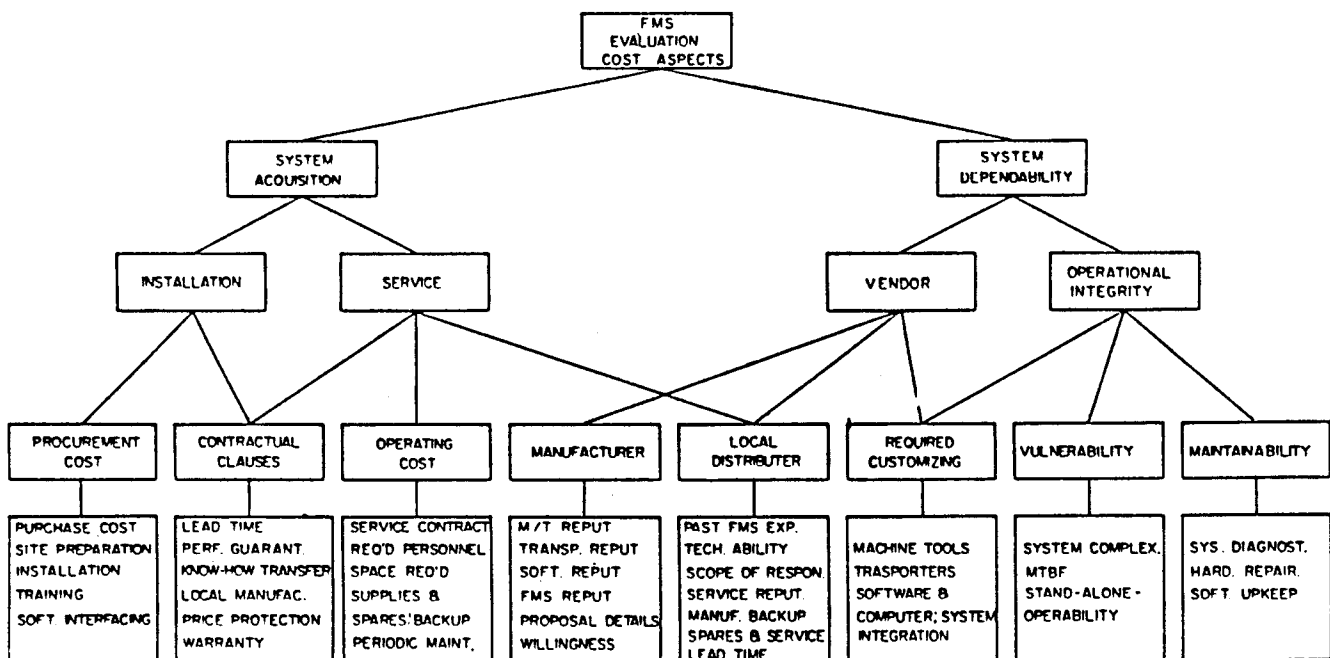


Fig. 8. FMS cost hierarchy.

TABLE VI
GLOBAL PRIORITIES OF "PARAMETERS"

<u>1. Procurement Cost</u>	<u>.240</u>
Purchase cost	.102
Site preparation	.040
Installation	.056
Training	.016
Software interfacing	.026
<u>2. Contractual Clauses</u>	<u>.120</u>
Leadtime	.018
Performance guarantees	.047
Know-how transfer	.010
Local Manufacturing	.010
Price Protection	.018
Warranty	.018
<u>3. Operating Cost</u>	<u>.120</u>
Service contract	.015
Required personnel	.042
Space required	.006
Supplies and spares	.025
Backup	.025
Periodic maintenance	.009
<u>4. Manufacturer</u>	<u>.073</u>
Machine tool reputation	.030
Transporters	.004
Software reputation	.011
Proposal details	.007
Willingness	.003
FMS reputation	.018
<u>5. Local Distributer</u>	<u>.193</u>
Past FMS experience	.014
Technical ability	.050
Scope of responsibility	.026
Service requirement	.026
Manufacturer's backup	.026
Service Leadtime	.050
<u>6. Required customizing</u>	<u>.175</u>
Machine tools	.040
Transporters	.021
Software	.040
System integration	.074
<u>7. Vulnerability</u>	<u>.040</u>
System complexity	.007
MTBF	.022
Stand-alone-operability	.012
<u>8. Maintainability</u>	<u>.040</u>
System diagnostics	.022
Hardware repairability	.007
Software upkeep	.012
Total	1.00

be explained through the observation that a system whose only advantage is a low purchase cost may have a detrimental impact on the overall performance of the organization due to ineffective customizing and service. These results have been derived through a long chain of pairwise comparisons of different elements in all the three levels of the costs hierarchy. The hierarchical structure and analysis of this problem has preserved the primitive (unprocessed) preferences expressed in favor of the three sets of parameters as being the most important cost factors. The formal study of the interplay between the various decision elements allows the decisionmakers preferences and perceptions to be refined and defined.

V. SYSTEM SELECTION PROCESS

Following the analysis performed in the previous two sections one is in a position to compare the candidate FMS proposals. This direct comparison is done with respect to

both the benefit and the cost parameters whose global priorities has been established in Sections III and IV, respectively. In this particular application a few candidate systems have been considered, but only two have passed the prescreening test where system parameters (e.g., X-Y-Z stroke, spares lead time, spindle torque, etc.) are contrasted with minimal RFP requirements. Given the sensitive nature of this real application these two competing vendors are not identified but will be referred to as system A and system B.

Starting with the benefit model, the two candidate systems are compared with respect to each of the 61 parameters of the benefit model. The comparison process is illustrated with respect to a number of parameters. For example, considering the table and pallet group, there are a number of specific parameters with varying priorities describing them (cf. Table VIII).

Comparing the two systems with respect to each of the parameters of Table VIII the local priorities of the two systems are derived. These local priorities are summarized in Table IX. Note, for example, that system A has received a higher (0.75) priority than system B (0.25) with respect to the table size parameter. This priority was derived, through a pairwise comparison matrix (not shown here) whose entries, taken from the scale of Table III were supplied, in the case discussed here, by a team member of the decision group who is an expert in production systems.

Using the priorities for the parameters, the local priorities for each system are converted to the global priorities shown in the last column of Table IX. The sum of the global priorities of the two systems yield the global priority of the table and pallet parameter set (0.059).

In some cases, performance data is supplied through a nonnumeric presentation; e.g., response surfaces, diagrams, and by qualitative statements. The processing of this type of data is done by a decisionmaker who is an expert on the particular topic under discussion. For example, the spindle performance data is provided through a torque versus speed diagram supplied by the vendor. Such diagrams for the two candidate systems are shown in Fig. 9.

In comparing the two systems with respect to their spindle torque, system A was ranked slightly higher than system B (0.55 versus 0.45). System B, however, is ranked higher than system A with respect to spindle speed range (0.75 versus 0.25). These assessments were provided by the plant expert examining these diagrams and taking into account the machining requires (e.g., tapping at slow speeds with high torque), and the type of raw materials (e.g., cast iron versus alloys) used in the plant.

These direct comparisons of systems with respect to parameters is done for all parameters in the benefit model, and using the priorities of the parameters one derives a global measure for each system. In this particular application the process has resulted in an advantage for system B over system A (0.56 for B versus 0.44 for A). This shows that system B provides greater benefit than system A. One cannot conclude, however, that system B should be acquired before considering the cost aspects of the problem. Follow-

TABLE VII
PRIORITIES OF LOCAL DISTRIBUTOR

1) Past FMS Experience	1	1/3	1/2	1/2	1/2	1/3	.07
2) Technical Ability		1	2	2	2	1	.25
3) Scope of Responsibility			1	1	1	1/2	.14
4) Service Reputation				1	1	1/2	.14
5) Manufacturer Backup					1	1/2	.14
6) Service Leadtime						1	.26
							1.00
CR = 0.0002230							

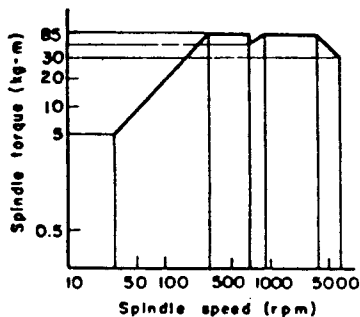
TABLE VIII
TABLE AND PALLET DATA

Parameter	System A	System B
1. Table size ⁽¹⁾	500x500	400x410
2. No. of pallet changers	2	2
3. Pallet change ⁽²⁾ time	18	9
4. Table load capacity ⁽³⁾	410	260
5. X-Y-Z stroke ⁽¹⁾	610-450-450	460-400-460

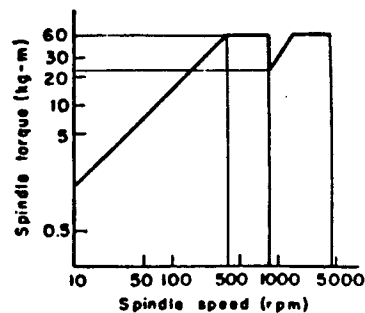
(1) millimeters, (2) seconds, (3) kilograms

TABLE IX
SYSTEMS COMPARISON

Parameter System	Table Size	# Of Pallets	Change Time	Load Capacity	X-Y-Z Stroke	Global Priority
System A	.75	.50	.33	.75	.67	.038
System B	.25	.50	.67	.25	.33	.021
	1.00	1.00	1.00	1.00	1.00	.059



(a)



(b)

Fig. 9. Spindle performance curves: (a) System A; (b) System B.

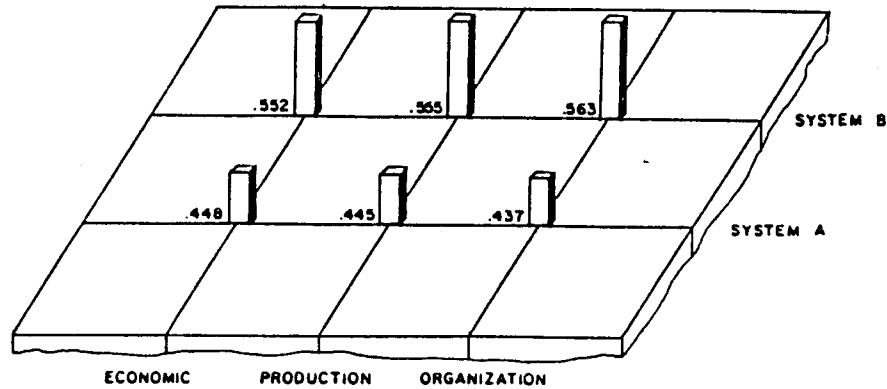


Fig. 10. Systems versus major performance considerations.

ing the same prioritization scheme for the cost model has resulted with the global cost priorities for the two systems.

This time, in the cost model, the analysis have shown a significant advantage (i.e., *lower* cost priority) for system B. The exact results were 0.41 for system B and 0.59 for system A. Normally, a marginal cost-benefit-analysis will be performed to determine the overall superior system [9], [29]. In this particular application, the choice is clear since system B dominates system A (has a *higher* priority) in the benefit model and also dominates system A (has a *lower* cost priority) in the cost model.

At this point the system to be procured has been determined. However, before the final adoption of the decision, sensitivity analysis should be conducted. This was done by varying the priorities assigned to the major cost and benefit considerations (level one in the respective models) and observing the change in the global merit evaluation. This has resulted in no significant shift in priorities form which one can conclude that the choice made is robust. Fig. 10 shows, for instance, the priorities of the two systems with respect to each one of the major performance considerations.

VI. SUMMARY

The model developed and presented in this paper dealt with performance evaluation and selection of a flexible manufacturing system in a real application. The model has considered both the benefit and the cost aspects of the problem where the vehicle for analysis was provided by the analytic hierarchy process. The methodology has proved to be quite useful for a number of reasons. First it allowed the incorporation of various levels of expertise into an integrated framework. Thus, upper level management and engineering experts could contribute in their respective areas of knowledge and responsibility. This assured that all important concerns were properly addressed in the process.

Second, the approach is based on combining different modules into an assessment hierarchy. This modularity property permits a great amount of flexibility in addressing different decision issues to reflect the idiosyncrasy of the particular organization. For example, if enough robot trailers are already available in the plant, one can strike out

that module from the hierarchy and perform the analysis without the need to restructure the whole model. Similarly, modules can be added when necessary. Also, a host of management questions can be answered. These include sensitivity issues and the relative performance of systems with respect to distinct elements of the hierarchy. For example, in the current application a question of interest was the relative production capacity of the two candidate systems. This and similar questions can be answered by tracing the respective subhierarchy whose apex is the respective element (e.g., capacity) under consideration. The effort involved in providing, and processing the pairwise comparison questions was not excessive; particularly since different teams of experts are involved in the various stages of the analysis, which were supported by an interactive computer program. When the "team" of experts is made of more than one member, differing views were settled through debate and presentation of arguments that led to a consensus opinion. In rare cases when this is not reached immediately, the use of the interactive program can show the result of the differing views and aid in arriving at a consensus after a few iterations.

Finally the complete process proved to be very useful in communicating ideas between the participating decision-makers who identified with the focus and details of the study and could contribute to the analysis rather than simply depend on the analyst. This last point provides a consistent and comprehensive "audit trail", traceable by corporate management who therefore adopted the recommendations resulting from this model with greater confidence.

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