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Title: Identification of the Performance Measurement Criteria for Flexible Manufacturing Systems

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IDENTIFICATION OF THE PERFORMANCE MEASUREMENT CRITERIA FOR FLEXIBLE MANUFACTURING SYSTEMS

Tolga Candir, Iffet Iyigun, Mesut Pervizpour

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TOLGA CANDIR

IFFET IYIGUN

MESUT PERVIZPOUR

INSTRUCTOR: Dr. RICHARD F. DECKRO

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ABSTRACT

The purpose of this study is; (1) to identify a list of criteria to be used as measurement tools for flexibility, (2) to determine the degree of importance of the flexibility types based on their contribution to overall flexibility as expressed by a sample of FMS practitioners, (3) to obtain the importance level indicated by the sample group for each criterion (in terms of their relative weights) for measuring the degree of flexibility of the corresponding type.

In the first sections, we reviewed the major manufacturing systems, concept of Flexible Manufacturing Systems (FMS), benefits of FMS, and discuss the need for a performance measurement system in a FMS environment. Definitions of flexibility types at different organization levels, along with related criteria for each type, have been summarized from an in-depth literature search. Linkage between the flexibility types and performance evaluation system has been identified. The importance level of each criteria each flexibility types are presented for our sample. To test the significance of data, gathered from mail-survey, analysis of variance (ANOVA) method and Friedman's two way analysis of variance method were used according to type of questions in the survey. For future studies, the results obtained from this study can be used to aid in the develop of an appropriate measurement technique for each criterion and flexibility types.

1. INTRODUCTION

Since the early seventies, several critical changes have occurred in the manufacturing environment. Recent technological advances have caused changes in both product and production characteristics. Product life cycles have shortened [15,p.30], [31,p.29], [34,p.38], new microprocessor technology has emerged [27,p.289], [1,p.77], market environment have become more unpredictable [11,p.3], and computer technology has been more rapidly applied to manufacturing [36,p.11], [1,p.77]. Technological changes resulted in new customer expectations. Differentiated and low cost products were needed [36,p.13], [31,p.29], [34,p.38], reliable delivery dates were required [15,p.30], and national and international competition increased [3,p.14], [1,p.77].

As a result of these changes, production systems have been drastically altered. New systems must be capable of producing a wide variety of low cost products [34,p.38], [6,p.33], [31,p.29], [29,p.39], [3,p.14], [11,p.3]. Rapidly changing markets demand production equipment capable of small batch sizes [9,p.64] and fast production with increased quality [3,p.14]. Competitive system must use less inventory, have higher machine utilization [3,p.14] and be capable of more customized production [36,p.13]. Adaptability and responsiveness to changing demands have become the major requirements for a competitive manufacturing company [11,p.3].

The simultaneous achievement of these requirements necessitates more flexibility in manufacturing. Flexible Manufacturing Systems (FMS) provide the necessary additional flexibility along with high productivity and high quality [6,p.34].

> "A FMS consists of an integrated assembly of work stations together with means for transferring components automatically through the system, all operating under full computer control for the purpose of carrying out manufacturing of a mixture of parts or products with a minimum of manual attention."[23,p.57]

There has been a number of studies containing critical aspects of Flexible Manufacturing Systems (see, [15][3][9][8][1][32][19][5][25][6][34][30][23][35][28][11][36][14][21][22], among others) The importance and benefits of applying FMS has been cited by previous researchers[27][3][9][8][29][1][10][31][32][19][5][25][35][11]. Although many features of FMS have been studied to a large extent, reported research on the design of measurement systems to identify the performance and efficiency of this new approach is limited.

The performance of an FMS is directly related to the degree of the overall system flexibility. According to Sethi & Sethi [27,p.297], this degree of overall flexibility can be stated in terms of different flexibility types. Furthermore, the degree of flexibility of these types may be characterized by measuring the related criteria under each type. Such measurements can be used to form a basis for the evaluation of the overall system flexibility.

The objective of this study can be divided into three parts;
1) To identify a list of criteria to be used as measurement tools for flexibility types.
2) To determine the degree of importance of the flexibility types based on their contribution to overall flexibility as expressed by a sample of FMS practioners.
3) To obtain the importance level indicated by the sample group for each criterion (in terms of their relative weights) for measuring the degree of flexibility of the corresponding type.

The paper will proceed under the following headings; FMS concept, flexibility types and related criteria and a discussion of our survey development. This will be followed by a review of the statistical analysis methodologies utilized and the findings from the survey. A discussion of the results and the study's limitations are presented. The paper concludes with a discussion of potential future areas of research.

2. FMS CONCEPT

Due to changing market requirements, customer expectations and diversity of needs, the traditional manufacturing techniques have started to lose their effectiveness. The main reason for the increasing importance and application of FMS is its multidimensionality and its ability to provide better solutions for today's manufacturing/market requirements.

2.1 Major Manufacturing Systems

The major manufacturing systems in use can be categorized as; job shop, flow shop, project shop, continuous manufacturing and cellular manufacturing (group technology). These manufacturing systems are reviewed in the following section, based on a study by Black, on cellular manufacturing systems [4,pp:36-40].

A job shop is known by its ability to produce the units for different orders following different paths. Some of the characteristics of this system are; flexibility, variety, highly skilled workers, potentially a great deal of indirect labor, high amounts of material handling, general purpose machines, long in-process times, large in-process inventory, lost orders and poor quality.[4,p.36]

Flow shops are used for the production of larger quantities of the same product or products. The same sequence of operations are undertaken with more specialized equipment. The general characteristics of a flow shop are; large volume-long run production, long set up times, less flexibility and variety, special machines and less skilled workers.[4,p.37]

Another known system is the project shop. The aim of the project shop system is to facilitate the production of a product which is either very large or one-of-a kind. The project shop assumes a set of well defined tasks performed in a known, specified sequence.[4,p.37]

Continuous manufacturing systems are applied generally for products like fluids or some food stuffs. The nature of this system requires a flow through a series of directly connected processes. It is similar to the flow shop, but is distinguished by its continuous lots rather than discrete lots or units.[4,p.38]

Cellular manufacturing (group technology) is one of the more advanced manufacturing techniques in use. This type of system is known to produce specific group of parts in a highly automated nature. It is capable of producing high quality products at low costs by eliminating set-ups between different components and parts. Cellular manufacturing can be considered as a subdivision of FMS [34,p.39]. A FMS builds on cellular manufacturing by connecting the cells with automated material handling and controlling each cell and the material flow with a central computer system.[4,pp:39-40]

Today's competitive pressures and market realities require most production to be done in small to medium batch sizes [9,p.64], [31,p.29], [34,p.38], [30,p.58], [11,p.3]. The manufacturing techniques reviewed above can create problems for small to medium batch size production [9,p.64]. Some of the problems are low machine utilization, production bottlenecks, high labor cost, high work in process (WIP) inventory and high lead times. These type of problems result in a decreased flexibility and efficiency of the production system. FMS provides the required flexibility and efficiency for mid volume/mid variety manufacturing (Figure-1).

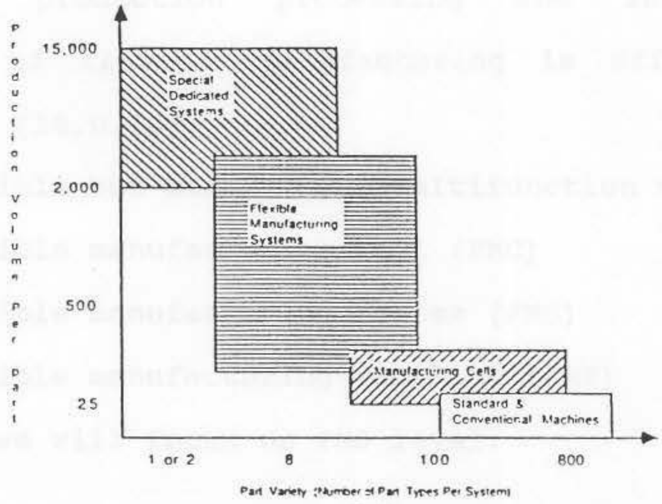

Figure-1

Source: Chen F.F. and Adam E.E.,"The Impact of FMSs on Productivity and Quality",IEEE Transactions on Engineering Management, Vol.38, No.1, February 1991, p.34

FMS provides the efficiency that is lacking in batch manufacturing and the flexibility that is limited in mass production lines [15,p.30].

2.2 Flexibility and FMS

According to Kickert [18,p.7], flexibility can be considered as an increase in variety, speed and amount of responses as a reaction to uncertain future environmental developments. More simply, flexibility is defined as the speed at which a system can react to and accommodate changes [24,p.110]. To be truly flexible, the flexibility must exist during the entire life cycle of the product.

In terms of production processing and facilities, the implementation of flexible manufacturing is effected at four distinct levels [18,p.10]:

- the flexible but stand-alone multifunction machine (FMM)
- the flexible manufacturing cell (FMC)
- the flexible manufacturing system (FMS)
- the flexible manufacturing facility (FMF)

In this study, we will focus on FMS level.

The FMS is usually a major grouping of machines, closely linked by computer and work transfer devices, capable of automatically and completely processing a variety of work with little or no human intervention [24,p.107]. The FMS is a subset of the full-blown automatic factory of the future [36,p.10].

> "A FMS can be defined as a computer controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one part at low to medium volumes" [11,p.3].

The handbook of FMS [11,p.4] states that three essential physical components of an FMS are;

- standard numerically controlled machine tools,
- a conveyance network to move parts and perhaps tools between machines and fixturing stations,
- an overall control system that coordinates the machine tools, the parts-moving elements and the work pieces.

Sharit and Salvendy [28,p.168] summarize all the characteristics of FMS stated above in a single definition;

> "A flexible manufacturing system incorporates automated material handling systems, robots, numerically controlled machine tools, inspection, and group technology into a single production system whose integration is under the control of a hierarchial network of computers."[28,p.168]

The effective functioning of a FMS depends on the efficiency of each component of the system both individually and in conjunction with other components. Due to this condition, each component of a FMS becomes significantly important. Because of this interaction, to obtain a clear understanding of the nature of a FMS, the importance and the function of each component has to be known in detail.

2.3 Key Components of a FMS

The key components of a FMS are briefly explained below, primarily based on the works of Attaran [3,pp:15-16], and Das and Khumawala [9,pp:65-66].

Group Technology (GT): Group technology is a technique and philosophy to increase production efficiency by grouping various parts having similarities in shape, dimension and/or process routes. Classification of parts speeds up the design of similar parts in the company. GT reduces variety in a manufacturing cell. A reduction in variety will lead to a more efficient processing of parts and assemblies, shorter waiting times and lower manufacturing costs. By using GT, a variety of parts can be manufactured in a FMS, with each part having its own, possibly unique, set of operations. A production manager can use GT principles to simplify the planning process. By grouping parts together in families, group technology also achieves both reductions in set-ups and better control. Group technology can also be applied to production machines. Machines can be grouped according to the parts they produce. This process, called cellular manufacturing, involves the physical layout of the factory floor into cells of machines and tools, where each cell is dedicated to the production of a single family of parts. This will lead to a higher production rate and a more efficient use of the machinery.[3,pp:15-16][9,pp:65-66]

Material Handling: Material movement within a FMS is a key factor in its total productivity. Without controlled material movement within the manufacturing shop, wasted utilization occurs in workforce, floor space, and machine tools. Material handling systems must integrate a variety of equipment in the FMS and also be reliable, fast and easy to maintain. They should be capable of providing transportation for raw materials, parts and final products and storage for workpieces. Computer-controlled material handling systems offer a wide range of solutions to the part transportation problem in FMS and can set limits to the flexibility of the system. Six type of materials handling system have been identified for use in FMS. They are listed in an increasing order of flexibility as; belt conveyors, roller conveyors, power conveyors, free conveyors, monorails or monotractors, and automatic guided vehicles.[9,p.66]

Computer Numerical Control Machines: Numerically controlled (NC) machines are the building blocks of FMS. The flexibility of the system, to a great extent, depends on the flexibility of numerically controlled machining centers used. The advances in computer technology and the use of Read Only Memory in numerically controlled machines led to the appearance of computer numerical control machines. The majority of today's machine tools are computer numerically controlled (CNC). A computer control, consists of a central processor, memory and interface, and provides the necessary intelligence to run the machine tools. When computer numerical control machine tools are linked to a host mini or mainframe computer, the system is called direct numerical control (DNC).[3,p.16]

Robots: Robots are programmable, multifunctional machines capable of moving materials, often with many degrees of freedom, and generally performing repetitive tasks. Their important features are: they are flexible, they reduce the need for operators and they provide consistent quality. Within the manufacturing environment, robots perform two distinct functions; value and non-value added work. Although both functions may be present in a FMS, the majority of robot use is for handling relatively small workpieces and tools within and between different modules.[21,pp:113-117]

Hierarchial Computer Network and Control: FMSs are computer integrated systems which are made of a number of modules performing different tasks in harmony. Each modular system requires a modular control system; that is, different components are controlled by individual controller units. These controllers perform their intended tasks under the supervision of a higher controller. This forms a hierarchial control system. In FMS, system integration at all levels is essential. This integration has become possible through the use of different processors and through proper communication between these processors within a FMS hierarchial network. All the disparate computer-controlled operations in the manufacturing organization are directed/coordinated and integrated through the use of data communications, data management, and data processing computers [36,p.9].

Automatic Storage/Retrieval Systems and Automated Inspection: The last area of the factory to be integrated in FMS environment is the warehouse. Automatic storage/retrieval systems provide the integration with the balance of the automated factory that completely automates the material handling task. An automatic storage/retrieval system's major components are the storage structure, storage and retrieval machines, and control system. Additionally, usage of automated inspection techniques sustain higher quality control. [21,pp:120-125]

If other computer or advanced manufacturing applications like computer aided design (CAD), computer aided engineering (CAE), computer aided manufacturing (CAM) and computer aided process planning (CAPP), just in time (JIT), expert systems (ES), materials requirement planning (MRP) and decision support systems (DSS) are used, the capabilities of FMS can be enhanced.

2.4 Benefits of FMS

Enhancing flexibility in manufacturing by applying FMS affects the entire organization. FMS works effectively in coordination with the different components listed above. The improved characteristics of each component and the coordination provided by a FMS setting results in several important benefits. An aggregated list of certain benefits for a properly developed FMS taken from [27][3][9][8][29][27][10][31][32][19][5][25][35][11] is given in Table-I.

Table - I: Benefits of FMS	
Decreases in;	Increases in;
Queue Length	Machine Utilization Rate
WIP Inventory	Product Quality
Lead Time	Rate of Throughput
Machine Downtime	Use of Programmable Equipment
Set-up Time	Response Rate to Market
Product Development Time	Quality of Work Life
Lot Size	Management Control
Inventory Cost	Capital Utilization
Production Cycle Time	Scheduling Efficiency
Indirect/direct Labor Costs	
Plant/Storage Space	
Number of Job Classifications	
Use of Special Purpose Equip.	
Material Cost	
Delivery Times	
Material Handling Cost	
Employee Interface	

These benefits were classified under different categories in the literature. For example, Chen and Adam [6] used operational and strategic grouping, Attaran [3] and Aggarwal [1] classified these benefits under tangible and intangible headings, while Maleki [21], defined short-run and long-run benefits.

2.5 Performance Measurement of FMS

Most of these diversified benefits can be realized in the long term. Since FMS uses advanced technology, the implementation of a system often requires high capital investment. Due to the high initial investment and long term realization of benefits, achieving a desired success level and the continuous improvement of a FMS is essential. Therefore, the company's main task after implementing a FMS should be to check the new system's performance, in terms of its flexibility at the operational and strategic levels.

According to Cox [8,p.68], a performance measurement system should be:

1) straightforward and easy to apply
2) sufficiently comprehensive to be a meaningful indicator of the plant behavioral capabilities which it is expected to represent
3) applicable across plants with different product mixes.

In addition to these objectives, the performance measurement system should be able to represent the characteristics of the system to which it is applied.

In the case of FMS, a major characteristic of the system is its flexibility. It therefore follows that a performance measurement system for a FMS should be based in part on flexibility criteria.

These criteria are obtained from the benefits of FMS, listed previously. For a better understanding of the relation between these criteria and the system performance, the criteria are grouped under different flexibility types. In this study, five flexibility types are used. These are; process, product, routing, volume and expansion flexibilities. Related criteria are also determined under each type. In addition, the extent to which these criteria represent the system flexibility is tested.

3. FLEXIBILITY TYPES and THE RELATED CRITERIA

3.1 Flexibility Types

Flexibility of a system is its adaptability to a wide range of possible environments that it may encounter. A flexible system must be capable of changing in order to deal with a changing environment.

Sethi and Sethi [27,p.297] suggest three levels of flexibility:

1- Component or Basic Flexibilities

- a) Machine Flexibility
- b) Material Handling Flexibility
- c) Operation Flexibility

2- System Flexibilities

- a) Process Flexibility
- b) Product Flexibility
- c) Routing Flexibility
- d) Volume Flexibility
- e) Expansion Flexibility

3- Aggregate Flexibilities

- a) Program Flexibility
- b) Production Flexibility
- c) Market Flexibility

Below a review of the flexibility types , taken primarily from Sethi and Sethi [27,pp:296-313], is presented to give a better understanding of the underlying concepts.

3.1.1. Component Flexibilities

a) Machine Flexibility refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another. Numerical control machines with easily accessible programs, sophisticated part loading and tool changing, automatic chip removal, diagnostic software and integration with CAD/CAM enhance machine flexibility. Major effects of machine flexibility are decreases in batch size, inventory costs, lead time and increases in machine utilization, rate and ability to produce complex parts.[27,pp:298-299]

b) Material Handling Flexibility is the system's ability to move different types of parts efficiently for proper positioning and processing through the manufacturing facility. Transportation devices, an appropriate layout design, more space, better ergonomics, automatic guided vehicles, robots and computer control, general purpose fixtures, automatic tool changers and multiaxis robots positively affect the material handling flexibility. As a result of an increase in material handling flexibility, information processing capabilities of the production system, availability of machines and machine utilization increase. On the other hand, throughput time often decreases.[27,pp:300-301]

c) Operation Flexibility refers to a part's ability to be produced in different ways. Operation flexibility is desirable considering the resulting increase in machine availability, machine utilization and ease of scheduling. CAD/CAM, CAPP and group technology can be utilized to enhance operation flexibility.[27,pp:301-302]

3.1.2 System Flexibilities

a) Process Flexibility is related to the set of part types that the system can produce without major set-ups. Process flexibility derives from machine flexibility, operation flexibility and material handling flexibility. The ability to transfer a variety of fixtures and tooling, and multiskilled workers enhance process flexibility. Basic effects of process flexibility are decreases in lot size, inventory level, the need for duplicate or redundant machines, and increases in the number of machines to be shared. [27,pp:302-303]

b) Product Flexibility is the ease with which new parts can be added or substituted for existing parts. CAD/CAM implementation, group technology organization, use of similar part routings, rapid exchange of tools and dies, and flexible fixtures extend the product flexibility of the system. Product flexibility has a direct effect on increasing the ease of bringing newly designed products quickly to the market.[27,pp:304-305]

c) Routing Flexibility is the system's ability to produce a part by alternate routes through the system. Routing flexibility is different from operation and material handling flexibilities. Operation and material handling flexibilities are related to a part and specific component of a system respectively while routing flexibility is a system property. Different technical characteristics of machines (multipurpose machines, machines with overlapping process envelopes) and different system characteristics (for example, integrated tool management system, software aids for production schedules management, pooling of identical machines into machine groups) enhance the routing flexibility. Efficiency of scheduling (by better balancing of machine loads) increases and production time of a given set of part types (when unanticipated events occur) decreases by an increase in routing flexibility. [27,pp:305-307]

d) Volume Flexibility is the system's ability to be operated profitably at different overall output levels. In addition to considering a just in time approach to inventory flow, providing a subcontracting network and multiskilled workers are key factors in achieving a desirable level of volume flexibility. Volume flexibility enhances the increase of the ability to adjust production upwards or downwards within wide limits, the speed of response and the range of variations.[27,pp:307-309]

e) Expansion Flexibility is the ease with which system's capacity (output rate/unit time) and capability (characteristics as quality, technological state as well as other types of flexibilities) can be increased when needed. Expansion flexibility provides the increase in adaptation of the system for expansion, a decrease in implementation time and cost for new products, variations of existing products and added capacity. With the use of automatic guided vehicles, high level automation, multipurpose machines, and the implementation of modular flexible manufacturing cells, small production units make the system more flexible towards expansion. [27,pp:309-310]

3.1.2 Aggregate Flexibilities

a) Program Flexibility is the ability of the system to run virtually untended for a long period. This flexibility type depends heavily on process and routing flexibilities, and on the availability of sensors and computer controls for detection and handling of unanticipated problems. Application of program flexibility allows simultaneous improvement of productivity and quality. It improves the inspection/gauging and quality of fixtures/tools, reduces the time required for set-up and thereby the throughput time. [27,pp:310-311]

b) Production Flexibility is known as the range of part types that the manufacturing system can produce without adding major capital equipment. This type of flexibility depends on variety/versatility of machines, flexibility of material handling system, factory information and control system, and open communication. The firm can take advantage of this flexibility and diversify risk by increasing the part of families and decreasing development time. [27,pp:311-312]

c) Market Flexibility is the ease with which the manufacturing system can adopt to a changing environment. This flexibility complements the system's production and program flexibilities. Market flexibility is also important for a company's survival in constantly changing environments by allowing the company to respond to these changes (as minor design changes can be done easily). Product, volume and expansion flexibilities contribute to market flexibility. Integration of production planning and inventory control, good customer relations and well developed distribution channels are necessary for achieving a considerable level of market flexibility.[27.pp:312-313]

The linkages between the various flexibility types are shown in Figure-2. As it can be seen from the figure, system flexibilites interact with both component and aggregate flexibilities. System flexibilities represent the overall flexibility of the system. Due to these reasons, in this study systems flexibilities are used as the flexibility types mentioned in the previous section.

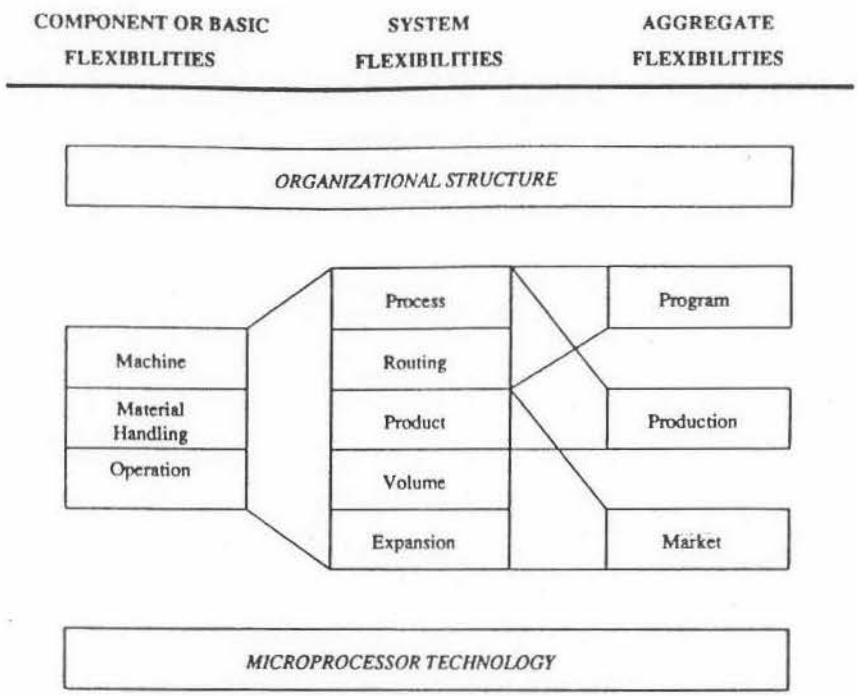

Figure-2
Source: Sethi A.K. and Sethi S.P., "Flexibility in Manufacturing", International Journal of FMS, 2(1990), p.297

3.2 Criteria for the Flexibility Types

The criteria related to these flexibility types are determined from the list of FMS benefits given earlier. The complete list of the criteria used in this study under each flexibility type are shown in Table-II.

The "production costs" criterion mentioned below is the total cost associated with direct and indirect labor, capital equipment, material, tooling, defect, scrap, inspection, rework, service, and material handling costs. Instead of using separate cost components, one measure covering all the production related costs has been used in this study.

Table - II	
Criteria for each flexibility type	
Process Flexibility -lot size -lead time -set-up time -inventory cost -production costs -rate of throughput -machine utiliz. rate	Product Flexibility -lead time -lot size -set-up time -WIP inventory -product development time -production cycle time -no. of job classification -using programmable equip. -using special purpose equip
Routing Flexibility -production cycle time -queue length -WIP inventory -lead time -machine utilization rate -rate of throughput -machine downtime -production costs	Volume Flexibility -queue length -WIP inventory -lead time -machine utilization rate -rate of throughput -production costs -volume range of products -production cycle time
Expansion Flexibility -queue length -product quality -machine downtime -rate of throughput -machine utilization rate -product development time	

4. SURVEY DEVELOPMENT

The survey instrument was designed to accomplish the objective of the study in a systematic way. To meet the objective of the study, the survey was formed in three parts. The first part is designed to obtain industry and company information. Next, the relation of the flexibility types to the overall system flexibility is investigated. Finally, the criteria under each flexibility type are tested for their degree of representation.

The purpose of the first part of the study is to identify the industries that are using FMS, and the level of flexibility they apply. Furthermore, it is aimed to find out whether any performance measurement system is currently used on available FMS in the sample company.

The second part of the survey investigates the importance of each flexibility type considering the element's individual effects on the overall system flexibility. As mentioned in the previous section, five flexibility types are used to represent the overall system flexibility. These are process, product, routing, volume and expansion flexibilities.

The final section of the survey tests the degree of representation of the previously listed criteria under the related flexibility type. Each flexibility type contains a different number of criteria. The respondents are also asked to provide additional criteria, if necessary, to obtain a complete list of the related criteria and suggest other key flexibilities not developed in the literature.

The type of questions in the survey can be divided into two groups; rating and ranking. In the second and third part of the survey, questions are asked in both rating and ranking forms. A six point scale, five levels from most important (representative) to least important (representative) as well as a don't know (not applicable) response, is used to obtain the necessary information in the rating form. Afterwards, respondents are also asked to use a ranking format for the same questions. The aim of using both ranking and rating formats for the same questions is to obtain more consistent and detailed information on the subject. A copy of the survey instrument and cover letter is attached in the appendix.

A preliminary pilot study was performed in two stages. The first stage was in the methods of design and analysis of the survey while the second was on the clarity and sufficiency of the content. A draft of initial design of the survey was used to gather the necessary feedback from the practioners and academicians who have been recently working on FMS. The draft of our survey was sent to four individuals who are currently dealing with FMS. They were asked to provide information on the survey design, and the clarity of the questions and the concepts. This feedback was used to make the final adjustments in the survey instrument.

Obtaining an effective mailing list was the major difficulty faced throughout the entire study period. The mailing list used in this study was formed by using the indepth literature search conducted at the early stages of the study. The names of the individuals and the companies involved in FMS were selected from the written materials on FMS and these names formed the mailing list.

The survey was sent to 13 individuals and 57 companies. The surveys that were sent to the companies were directed to the vice president of manufacturing or to a similar level. Two additional copies of the survey were included in the same package and the correspondents were asked to forward these copies to the individuals whom they felt were most familiar with the topic in their firm. To increase the response rate, a follow-up was prepared and sent to the individual correspondents after a period of one month from the first mailing date.

By April 25, twenty-one responses were received. This is a total response rate of 30%. While our sample size is not extremely large, the response rate is good for an unsolicited survey.

5. STATISTICAL ANALYSIS METHODOLOGIES

The rate of importance of each flexibility type on the overall system flexibility and the degree of representation of the related criteria of the flexibility types, will be determined by using arithmetic means and standard deviations.

The significance of the results obtained through the rating questions will be tested using the analysis of variance (ANOVA) method [16],[20]. On the other hand, Friedman's two way analysis of variance method will be used to test the significance of the results to the ranking questions.[20]

The purpose of Analysis of Variance (ANOVA) is to determine if one or more factors have significant effect on the variable being measured [31,p.568]. ANOVA looks at two sources of variation. (1) being the variation within the samples and (2) the variation between the samples. The sources of variations are calculated by using various sums of squares (SS).[20,p.569]

SS (factor) measures between sample variation.

SS (error) measures within sample variation.

SS (total) = SS (factor) + SS (error)

In general, one factor ANOVA techniques can be used to study the effect of any single factor on questionnaire scores, exam performance and the like. This factor can consist of any number of levels. To determine whether the levels of this factor affect our measured observations we examine the hypothesis:

Ho : all means are equal

Ha : not all means are equal

For a specified confidence interval, the hypothesis is accepted when the calculated F-value is smaller than the table F-value and otherwise it is rejected.[20,p.570]

The aim of the testing the survey questions is to investigate whether there is any statistical relationships between the results obtained from survey and the questions which had been asked. For rating type of questions, the significance level of the flexibility types with respect to system flexibility and, the flexibility criteria for each flexibility types need to be tested. At each examinatination, different factors should be tested with respect to one dependent variable. As explained above, ANOVA tests these significance levels.

The analysis technique used to analyze the ranking questions is called Friedman's two way analysis of variance. The purpose of Friedman's test is similar to the ANOVA's in that it is also designed to check the significance of the factors affecting the variable in question [7,p.266]. But it is some what different as it is dealing with ranks. The hypothesis used is the same with ANOVA case but the tool used in hypothesis testing is different. Friedman's test uses a t-test instead of an F-test. For this reason, the accept-reject decision depends on the comparison of the calculated t-values and the t-values taken from the related tables for a specific confidence interval.

In order to reach the necessary response rate for a statistical analysis, a sample size of 70 was chosen.

Up to the date when analysis was performed, 21 returned surveys were received, providing a 30 % return rate. Considering the methods used for data analysis, the number of responses and the return rate satisfy the necessary conditions for their utilization. We therefore can assume that sample size will not be a limitation for our analysis. The only problem with our survey analysis might be a non-respondent bias. Since no information is available on the nature of non-respondents and their possible answers to the questions of the survey, no inference can be made on their possible effect over the distribution obtained from the returned surveys. To overcome this difficulty and recover a portion of non-respondents, a follow-up was prepared including a second cover letter along with the previous information and a survey. The follow-ups with additional surveys to be given to other individuals related to FMS were sent to the individuals on our mailing list as they are known to be directly related to the FMSs. Since the survey does not ask for an identity from the respondent, it is not possible to gauge the effect of the follow-ups to the response rate.

6. FINDINGS FROM THE SURVEY

The first part of survey generated the qualitative information on the nature of the respondents. The distribution of the industries within the respondents are shown in Figure-3. The application of flexibility was observed to be mostly at the FMS level (71%). Approximately 50% of the respondents have already been using some means of performance measurement system for evaluation purposes. All the statistical analysis on the survey results are performed by using a 95 % confidence interval and two tails test.

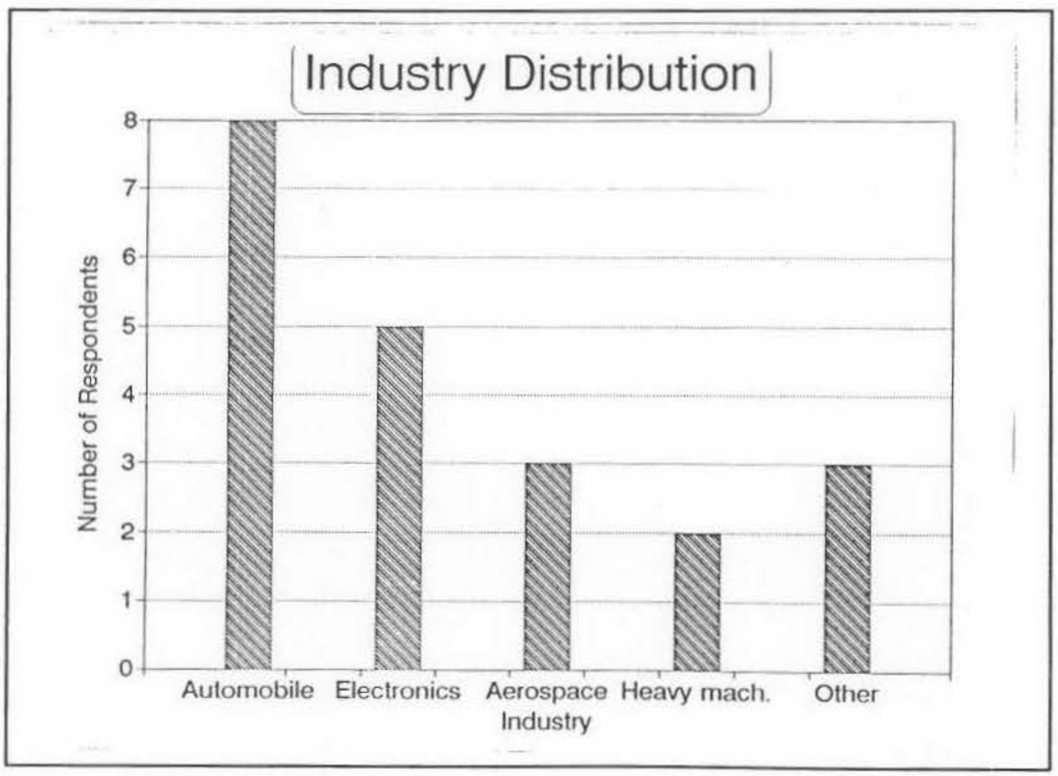

Figure - 3

The findings from the rating questions and the results of the ANOVA tests performed on these findings are presented in tables III-VIII.

Table - III		
Type of Question : Rating		
Overall System Flexibility	Mean	Variance
1- Volume flexibility	4.0	0.9
2- Product flexibility	3.81	1.56
3- Process flexibility	3.52	2.06
4- Routing flexibility	3.04	1.25
5- Expansion flexibility	2.76	1.79
Calculated F-value : 3.72 Table F-value : 2.93		
Hypothesis : Rejected		

As observed from Table-III, the different flexibility types can be ordered under the overall flexibility. The rejected hypothesis indicates that the means for each flexibility type is different. One can use the mean values to make a reasonable list of the flexibility types. The numbers at the left indicate the order of each flexibility type.

Table - IV		
Type Of Question : Rating		
Process Flexibility	Mean	Variance
Rate of Throughput	3.52	1.56
Set-up Time	3.52	2.26
Lot size	3.48	1.06
Machine Utilization	3.48	2.46
Production Costs	3.33	1.23
Lead Time	3.00	2.20
Inventory Costs	2.71	1.41
Calculated F-value : 1.2 Table F-value : 2.15		
Hypothesis : Accepted		

Table-IV lists the criteria under process flexibility, where the hypothesis has been accepted. This indicates that the mean values for the criteria are somewhat equal and no reasonable sequence can be stated. Therefore no numbers are used by the criteria.

Whereas in Table-V,VI,VII the hypotheses are rejected, indicating that criteria listed here can be ordered, and this is shown by the numbers at the left.

As observed from Table-V, under the Product Flexibility the most important criteria are found to be Product development time, Product cycle time, and set-up time. This simply shows the direct relationship of criteria and the flexibility type. As indicated before product flexibility is the ease with which new parts can be added or substituted for existing parts. Consequently, the product development time should be in the first row, since it is the major factor in introducing new parts.

Table - V		
Type of Question : Rating		
Product Flexibility	Mean	Variance
1- Product development time	3.76	1.39
2- Production cycle time	3.52	0.76
3- Set-up time	3.52	2.46
4- Lot size	3.14	1.23
5- Lead time	3.05	1.54
6- WIP inventory	2.71	1.41
7- No.of job classification	2.43	1.96
8- Using Prog. Equipment	2.29	2.01
9- Using special Purp.equip.	2.14	2.43
Calculated F-value : 4.33 Table F-value : 1.99		
Hypothesis : Rejected		

Table - VI		
Type of Question : Rating		
Routing flexibility	Mean	Variance
Queue length	3.62	2.24
Production cycle time	3.43	1.66
Production costs	3.33	1.53
Rate of throughput	3.29	1.01
WIP inventory	3.24	1.39
Lead time	3.14	1.53
Machine utilization rate	2.90	1.79
Machine downtime	2.90	2.39
Calculated F-value : 0.75 Table F-value : 2.06		
Hypothesis : Accepted		

The hypothesis (Ho : all means for the routing flexibility type criteria are equal) is accepted. This indicates that there is no possible order for these criteria. Anyone of the criteria is not more important yhan the other ones.

Table - VII		
Type of Question : Rating		
Volume flexibility	Mean	Variance
1- Production costs	4.00	1.30
2- Rate of Throughput	3.81	0.76
3- Volume range of products	3.52	3.06
4- Production cycle time	3.38	1.44
5- WIP inventory	3.09	1.39
6- Lead time	3.09	1.89
7- Machine utilization rate	2.90	1.49
8- Queue length	2.81	1.56
Calculated F-value : 2.36 Table F-value : 2.06		
Hypothesis : Rejected		

For the volume flexibility the hypothesis is; Ho: All means for the criteria of the volume flexibility type are equal. Table VII summarizes these results.

Since the hypothesis is rejected, the representation level of the criteria for the volume flexibility measurement can be distinguished. In other words, the means for the criteria are not equal, and we can give an order for each one of them.

Table - VIII		
Type of Question : Rating		
Expansion Flexibility	Mean	Variance
1- Product development time	4.19	1.26
2- Rate of throughput	3.95	0.64
3- Machine utilization rate	3.52	1.36
4- Product quality	3.33	1.93
5- Machine downtime	3.24	1.19
6- Queue length	2.57	2.06
Calculated F-value : 4.87 Table F-value : 2.29		
Hypothesis : Rejected		

As observed from the tables, the ANOVA tests indicates that each flexibility type has a different importance level for the overall system flexibility. Therefore, the flexibility types can be arranged in an order by making use of their mean values as in Table-III. The ANOVA test performed on flexibility types showed that the criteria given under process and routing flexibilities have equal degrees of representation of the related flexibility type. While the criteria related to product, volume and expansion flexibilities can be expressed in a specific order based on their mean values.

The findings from the ranking questions and the results of Friedman analysis are presented in Tables IX-XIV.

The results obtained from Friedman's test are presented in the same manner as for rating, where rejected hypothesis indicates that the means are different and a reasonable ordering can be performed. On the other hand, an accepted hypothesis indicates the fact that the means are somewhat equal and no ordering can be specified.

The results from the rating and ranking are generally in agreement.

Table - IX		
Type of Question : Ranking		
Overall System Flexibility	Mean	Variance
1- Process flexibility	2.09	1.89
2- Product flexibility	2.28	2.01
3- Volume flexibility	3.00	1.80
4- Routing flexibility	3.23	1.09
5- Expansion flexibility	3.95	1.45
Calculated t-value : 19.56 Table t-value : 9.49		
Hypothesis : Rejected		

Table - X		
Type of Question : Ranking		
Process Flexibility	Mean	Variance
Production costs	3.14	3.13
Set-up time	3.24	4.59
Rate of throughput	3.76	2.59
Machine utilization	4.09	2.79
Lead time	4.14	3.13
Inventory cost	4.24	3.39
Lot size	4.33	2.89
Calculated t-value : 7.29 Table t-value : 12.59		
Hypothesis : Accepted		

The hypothesis is that all means for the process flexibility type criteria are same. There is no order for the process flexibility measurement criteria, because the hypothesis is accepted. It means that any one of the criteria has same degree of representation for the measurement of the process flexibility.

Table - XI		
Type of Question : Ranking		
Product Flexibility	Mean	Variance
1- Production cycle time	3.24	2.59
2- Product development time	3.24	3.09
3- Set-up time	3.43	4.46
4- Lot size	4.14	3.53
5- Lead time	4.33	2.93
6- WIP inventory	4.52	1.86
7- Using prog. equipment	5.29	2.11
8- No. of job classifications	5.38	2.13
9- Using special Purp.equip.	5.67	0.73
Calculated t-value : 30.77 Table t-value : 15.51		
Hypothesis : Rejected		

Since the calculated t-value is greater than the Table t-value, the hypothesis is rejected. It can be concluded that the first three criteria have more importance than the the rest of the criteria.

Table - XII		
Type of Question : Ranking		
Routing flexibility	Mean	Variance
Queue length	2.90	3.60
Rate of throughput	3.90	1.89
WIP inventory	3.90	2.89
Production cycle time	4.14	3.63
Machine downtime	4.43	3.86
Production costs	4.52	3.46
Machine utilization rate	4.67	2.83
Lead time	4.76	2.99
Calculated t-value : 13.03		
Table t-value : 14.07		
Hypothesis : Accepted		

For both routing flexibility and volume flexibility the hypothesis (Ho: All means for the flexibility type criteria are equal) are accepted. In other words, for measurement of these types of flexibilities any criteria has no statistical greater degree of representation.

Table - XIII		
Type of Question : Ranking		
Volume flexibility	Mean	Variance
Production costs	3.48	4.26
Production cycle time	3.76	4.19
Volume range of products	3.76	5.09
Lead time	4.05	2.25
Rate of throughput	4.29	2.51
WIP inventory	4.29	2.71
Machine utilization rate	4.62	2.65
Queue length	4.76	3.09
Calculated t-value : 8.80 Table t-value : 14.07		
Hypothesis : Accepted		

Table - XIV		
Type of Question : Ranking		
Expansion Flexibility	Mean	Variance
1- Rate of throughput	2.81	1.56
2- Production development time	3.00	3.70
3- Product quality	3.29	3.21
4- Machine utilization	3.52	2.46
5- Machine downtime	4.24	2.19
6- Queue length	4.38	3.05
Calculated F-value : 12.56 Table F-value : 11.07		
Hypothesis : Rejected		

As in the case of the rating test, the hypothesis (Ho: all means for the expansion flexibility criteria have equal degree of representation) is rejected. According to the results of the two tests, the first two criteria (the rate of throughput and the production development time) have priority to measure the expansion flexibility.

The Friedman test performed on overall system flexibility, indicates that the flexibility types can be listed in a specific order according to their mean values. The Friedman analysis is also performed on the flexibility types. These tests indicated that the criteria under process, volume and routing flexibilities are at the same significance level for the related type. Criteria under product and expansion flexibilities have different significance levels and can be arranged in an order using their mean values.

7. DISCUSSION and CONCLUSION

The objective of this research was to identify the components of flexibility in FMS, to provide a better understanding of the system. The components that are tested in this study, can be used to begin to build a performance measurement system for a FMS that is already in application. However, the construction of such a measurement system is beyond the scope of this study. This paper presents the criteria affecting the flexibility applied and their relative importance at each case.

The survey, used in identifying these criteria, utilized two type of scales (rating and ranking) for the same questions. The basic idea behind this approach was to observe the consistency of the answers. The trade-off between a higher response rate and a more detailed information, was known in advance. A reduction in the expected return rate was also observed due to presenting the same question in two different forms. The results of the ranking questions are mostly in agreement with the answers to the rating questions. The only major discrepancy occurred in the tests of the criteria under volume flexibility. The null hypothesis was accepted by Friedman's analysis while the ANOVA test results rejected.

The rest of the findings from the analysis of both question scales were the same. The answers to the rating questions were considered to be predominantly representative of the results. This approach is superior to the ranking approach in the sense that the rating is done for all the criteria under each flexibility type where the ranking is used only to put the first five most important criteria in an order. Also, during the evaluation of the ranking, the values which are not provided, were considered to have a value of 6 in our scale. This assumption is necessary to calculate the mean and standard deviation values. As a result of this, ranking results are not as reliable as the rating results where all the values are provided by the respondents.

As a result of the statistical analysis, a list of criteria under each flexibility type has been generated. It is essential to remember that the usage of different flexibility types simplifies the analysis and provides a grouping of the related criteria. Each group of criteria under the corresponding flexibility type is arranged in an order with respect to their mean values and variances after checking their significance level. In the same manner, the five flexibility types are also put in an order for their importance to the overall system flexibility.

Consequently, future researchers can make use of the orders stated in this study. By measuring each criteria quantitatively, it would become possible to obtain the degree of flexibility of the system.

The measurement system and the scales for the criteria given in this paper are not in the scope of this study. The future researchers should study the appropriate measurement technique for each criterion and develop a scaling to combine the values with the level of importance provided in this paper. This approach will enable the researchers to obtain a comparable performance measurement value in a FMS.

The paper is concluded by stating the important comments of the respondents.

"Long term success of FMS is very dependent on migrating lower volume products with higher levels of variety into FMS."

"Concurrent engineering is critical in FMS."

"MIS and database management are critical for a FMS performance measurement system."

"Performance should be based on the entire company being oriented to (1) employee satisfaction and contribution (2) customer satisfaction (3) profits. If (1) and (2) are achieved (3) occurs automatically."

"Process complexity between product types can impact productivity. That is an important factor when developing a long term manufacturing plant which is capital intensive and product cycle is 3 years. So, there is tremendous need to develop a flexible manufacturing process and tools."

In the responses we received, respondents did not add any new criteria for the measurement of five flexibility types. In one of the returned survey, the tooling cost was added. However, in the questions "Production Costs" include the tooling costs. As a result, for the calculation originial criteria list was used.

8. APPENDIX A:

Survey Materials

Portland State University
Engineering Management Program
P.O. Box 751 Portland, OR 97207-0751

March 9, 1992

Dear Respondent;

As part of our final project in the Engineering Management Program at Portland State University, we are investigating critical performance elements of Flexible Manufacturing Systems (FMS). The purpose of this study is to identify and rank critical elements currently in use with flexible manufacturing systems. This will provide a basis for future studies to develop a performance measurement system to evaluate the degree of flexibility present in an FMS.

The necessary definitions that will help you to understand the content of our study and the objective of the survey are stated in the next page.

The questionnaire has been designed so that you can complete it very quickly and easily. It should only take a few minutes; you need only check off your answers or write down a number. A postage paid return envelope has been included for your convenience.

You can be absolutely sure that all of the information you provide is strictly confidential. Your answers will be combined with others and used only for statistical analysis.

We will be pleased to learn about your interests and ideas related to our study. We would like to thank you in advance for your effort and time in sharing your experience and knowledge by filling out our survey. If you wish a copy of our results, please indicate to whom it should be forwarded in the space provided at the end of the survey or, if you wish, send the information separately.

If possible, please, complete and return the survey as soon as you are able. Again, thank you for your help.

Cordially,

Tolga Candir
Iffet Iyigun
Mesut Pervizpour

Phone: (503) 725-4660 FAX: (503) 725-4667 BITNET: d6emp@psuorvm INTERNET: d6emp@psuorvm.cc.pdx.edu

Flexibility can be considered as an increase in the variety, speed, and amount of available responses as a reaction to uncertain future environmental developments. FMS are used among today's progressive manufacturers to enhance their competitive edge. The increased usage and the critical insight that FMS provides to the manufacturers necessitates a complete and effective monitoring and/or measurement system to evaluate the performance of an implemented flexible manufacturing system.

The effectiveness of the performance of a FMS is directly related to the degree of the overall system flexibility. This degree of overall system flexibility can be stated in terms of the five different flexibility types:

-<u>Process Flexibility</u>; is related to the set of part types that the system can produce without major set-up changes.

-<u>Product Flexibility</u>; is the ease with which new parts can be added or substituted to existing parts.

-<u>Routing Flexibility</u>; is the system's ability to produce a part by alternate routes through the system.

-<u>Volume Flexibility</u>; is the system's ability to be operated profitability at different overall throughput levels.

-<u>Expansion Flexibility</u>; is the ease with which the system's capacity and capability (quality, technological state, and so forth) can be increased.

The degree of flexibility found in these five categories can be characterized by measuring the criteria and factors corresponding to each type. Related criteria are mentioned under each type of flexibility in the survey below.

The objective of the survey is to identify a complete list of the criteria and their importance in maintaining the desired flexibility type and level (in an ideal case).

1) Please indicate the industry in which your firm is involved:

Automobile Industry	( )
Electronic Industry	( )
Aerospace Industry	( )
Heavy Machinery	( )

Other: ____________________

2) What is the level of flexibility applied in your company?

Stand-Alone Multifunction Machines	( )
Manufacturing Cells	( )
Manufacturing System	( )
Manufacturing Facility	( )

3) Is your company applying any systematic performance measurement to the evaluation for flexibility?

Yes ( ) No ( )

4) Given the following five flexibility types defined above, use the rating scale below to rate the importance of each flexibility type, considering their individual effects on the overall system flexibility to the best of your knowledge and experience.

	Don't Know 0	Least Important 1	Less Important 2	Important 3	Highly Important 4	Most Important 5
Process Flexibility	( )	( )	( )	( )	( )	( )
Product Flexibility	( )	( )	( )	( )	( )	( )
Routing Flexibility	( )	( )	( )	( )	( )	( )
Volume Flexibility	( )	( )	( )	( )	( )	( )
Expansion Flexibility	( )	( )	( )	( )	( )	( )

5) Given the same flexibility types, rank each type from most important[1] to the least important[5] to your operation.

Process Flexibility	[ ]
Product Flexibility	[ ]
Routing Flexibility	[ ]
Volume Flexibility	[ ]
Expansion Flexibility	[ ]

6) Rank the five most representative criteria under each type of flexibility by giving a [1] to most representative and a [5] to least representative. If necessary, add and rank other relevant/applicable criteria.

A) Process Flexibility

Lot size	[ ]
Lead Time	[ ]
Set-Up Time	[ ]
Inventory Costs	[ ]
Production Costs	[ ]
Rate of Throughput	[ ]
Machine Utilization Rate	[ ]

Other:

____________________	[ ]
____________________	[ ]
____________________	[ ]

B) Product Flexibility

- Lead Time [ ]
- Set-Up Time [ ]
- Lot Size [ ]
- Product Development Time [ ]
- WIP Inventory [ ]
- No. of Job Classification [ ]
- Production Cycle Time [ ]
- Using Programmable Equip. [ ]
- Using Special Purpose Equip. [ ]

Other:

- ____________________ [ ]
- ____________________ [ ]
- ____________________ [ ]

C) Routing Flexibility

- Production Cycle Time [ ]
- Lead Time [ ]
- Queue Length [ ]
- WIP Inventory [ ]
- Production Costs [ ]
- Rate of Throughput [ ]
- Machine Utilization Rate [ ]
- Machine Downtime [ ]

Other:

- ____________________ [ ]
- ____________________ [ ]
- ____________________ [ ]

D) Volume Flexibility

- Lead Time [ ]
- Queue Length [ ]
- Production Costs [ ]
- Machine Utilization Rate [ ]
- WIP Inventory [ ]
- Rate of Throughput [ ]
- Production Cycle Time [ ]
- Volume Range of Production [ ]

Other:

- ____________________ [ ]
- ____________________ [ ]
- ____________________ [ ]

E) Expansion Flexibility

- Queue Length [ ]
- Product Quality [ ]
- Product Development Time [ ]
- Rate of Throughput [ ]
- Machine Utilization Rate [ ]
- Machine Downtime [ ]

Other:

- ____________________ [ ]
- ____________________ [ ]
- ____________________ [ ]

7) Given the criteria under each flexibility type please rate each for its degree of representation of the related type. If necessary, add and rate other relevant/applicable criteria.

Not Applicable	N/A
Least Representative	1
Less Representative	2
Representative	3
Highly Representative	4
Most Representative	5

A) Process Flexibility

	N/A	1	2	3	4	5
Lot size	( )	( )	( )	( )	( )	( )
Lead Time	( )	( )	( )	( )	( )	( )
Set-Up Time	( )	( )	( )	( )	( )	( )
Inventory Costs	( )	( )	( )	( )	( )	( )
Production Costs	( )	( )	( )	( )	( )	( )
Rate of Throughput	( )	( )	( )	( )	( )	( )
Machine Utilization Rate	( )	( )	( )	( )	( )	( )
Other:						
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )

B) Product Flexibility

	N/A	1	2	3	4	5
Lead Time	( )	( )	( )	( )	( )	( )
Set-Up Time	( )	( )	( )	( )	( )	( )
Lot Size	( )	( )	( )	( )	( )	( )
Product Development Time	( )	( )	( )	( )	( )	( )
WIP Inventory	( )	( )	( )	( )	( )	( )
No. of Job Classification	( )	( )	( )	( )	( )	( )
Production Cycle Time	( )	( )	( )	( )	( )	( )
Using Programmable Equip.	( )	( )	( )	( )	( )	( )
Using Special Purpose Equip.	( )	( )	( )	( )	( )	( )
Other:						
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )

C) Routing Flexibility

	N/A	1	2	3	4	5
Production Cycle Time	( )	( )	( )	( )	( )	( )
Lead Time	( )	( )	( )	( )	( )	( )
Queue Length	( )	( )	( )	( )	( )	( )
WIP Inventory	( )	( )	( )	( )	( )	( )
Production Costs	( )	( )	( )	( )	( )	( )
Rate of Throughput	( )	( )	( )	( )	( )	( )
Machine Utilization Rate	( )	( )	( )	( )	( )	( )
Machine Downtime	( )	( )	( )	( )	( )	( )
Other:						
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )

Please continue rating using the same scale.

Not Applicable	N/A
Least Representative	1
Less Representative	2
Representative	3
Highly Representative	4
Most Representative	5

D) Volume Flexibility

	N/A	1	2	3	4	5
Lead Time	( )	( )	( )	( )	( )	( )
Queue Length	( )	( )	( )	( )	( )	( )
Production Costs	( )	( )	( )	( )	( )	( )
Machine Utilization Rate	( )	( )	( )	( )	( )	( )
WIP Inventory	( )	( )	( )	( )	( )	( )
Rate of Throughput	( )	( )	( )	( )	( )	( )
Production Cycle Time	( )	( )	( )	( )	( )	( )
Volume Range of Production	( )	( )	( )	( )	( )	( )
Other:						
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )

E) Expansion Flexibility

	N/A	1	2	3	4	5
Queue Length	( )	( )	( )	( )	( )	( )
Product Quality	( )	( )	( )	( )	( )	( )
Product Development Time	( )	( )	( )	( )	( )	( )
Rate of Throughput	( )	( )	( )	( )	( )	( )
Machine Utilization Rate	( )	( )	( )	( )	( )	( )
Machine Downtime	( )	( )	( )	( )	( )	( )
Other:						
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )
____________________	( )	( )	( )	( )	( )	( )

8) Please give any comments you might have on the development of a performance measurement system based on the flexibility types and the underlying measurement criteria. Please use the space below and/or additional paper as required.

Thank you for your time and assistance.

8.APPENDIX B:

Actual Responses

Overall System Flexibility-Rating

	Process Flexib.	Product Flexib.	Routing Flexib.	Volume Flexib.	Expansion Flexib.
Automobile					
1	4	5	4	3	2
2	4	4	3	5	2
3	3	4	4	5	3
4	3	4	2	5	1
5	3	5	5	4	5
6	5	4	1	2	1
7	4	4	3	4	2
8	2	3	2	3	3
Heavy Mach.					
9	4	3	1	5	1
10	0	5	3	5	4
Electronic					
11	4	3	3	4	3
12	3	5	4	5	4
13	5	4	2	3	1
14	5	3	4	4	3
15	4	2	4	3	4
Aerospace					
16	0	3	2	4	5
17	4	5	2	3	1
18	3	5	4	5	3
Other Ind.					
19	4	5	4	3	4
20	5	0	4	5	4
21	5	4	3	4	2
Total	74	80	64	84	58
Mean	3.52	3.81	3.04	4.00	2.76
Variance	2.06	1.56	1.25	0.90	1.79

Overall System Flexibility-Ranking

	Process Flexib.	Product Flexib.	Routing Flexib.	Volume Flexib.	Expansion Flexib.
Automobile					
1	2	1	5	3	4
2	1	3	4	2	5
3	4	2	3	1	5
4	3	2	4	1	5
5	5	1	3	4	2
6	1	2	5	3	4
7	2	1	3	4	5
8	2	1	4	3	5
Heavy Mach.					
9	1	3	2	4	5
10	5	1	3	1	2
Electronic					
11	1	5	2	4	3
12	1	2	4	5	3
13	3	1	2	1	2
14	1	2	4	3	5
15	1	3	2	4	5
Aerospace					
16	1	4	3	5	2
17	2	1	4	3	5
18	4	5	1	2	3
Other Ind.					
19	2	1	3	5	4
20	1	5	3	2	4
21	1	2	4	3	5
Total	44	48	68	67	83
Mean	2.09	2.28	3.23	3.00	3.95
Variance	1.89	2.01	1.09	1.80	1.45

Process Flexibility- Rating

Auto	Lot Size	Lead Time	Setup Time	Inven-tory Cost	Produc-tion Costs	Rate of Throughput	Mach. Util.rate
1	4	3	4	1	3	4	5
2	3	2	5	4	3	2	3
3	3	4	5	4	3	2	3
4	3	5	4	2	3	5	4
5	4	3	5	3	5	3	4
6	3	0	0	3	4	4	5
7	3	3	1	2	2	4	5
8	1	0	1	2	3	4	5
H.Mc							
9	4	3	2	0	5	1	0
10	2	4	4	2	3	3	5
Elc.							
11	4	3	2	4	3	4	3
12	2	1	4	3	2	5	1
13	3	3	4	2	5	5	4
14	3	4	5	2	2	1	4
15	4	5	3	2	3	3	4
Aero spce							
16	4	5	3	5	2	4	3
17	5	2	4	2	3	4	1
18	5	3	4	4	5	3	5
Oth.							
19	5	3	4	3	5	5	5
20	4	4	5	3	2	3	1
21	4	4	5	4	4	5	3
Tot.	73	63	74	57	70	74	73
Mean	3.48	3.00	3.52	2.71	3.33	3.5	3.48
Var.	1.06	2.20	2.26	1.41	1.23	1.56	2.46

Process Flexibility- Ranking

	Lot Size	Lead Time	Set-up Time	Inven- tory Costs	Produc- tion Costs	Rate of Throghput	Machine Utiliz. Rate
Automobile							
1	6	5	6	4	1	2	3
2	6	3	1	6	2	4	5
3	6	6	5	4	2	3	1
4	3	5	1	6	2	6	4
5	5	6	1	2	6	3	4
6	5	1	6	2	6	3	4
7	3	6	1	6	2	5	4
8	5	4	1	6	2	3	6
Heavy Mac.							
9	6	3	6	2	5	4	1
10	2	3	4	6	1	5	6
Electronic							
11	4	1	5	6	3	6	2
12	3	4	1	6	5	6	2
13	5	6	3	6	1	2	4
14	6	5	2	3	4	1	6
15	6	4	5	2	3	1	6
Aerospace							
16	6	1	6	2	3	4	5
17	1	6	2	3	5	4	6
18	2	6	4	5	1	6	3
Other							
19	6	3	1	5	4	2	6
20	4	6	6	1	2	2	3
21	2	3	1	6	6	4	5
Total	92	87	68	89	66	78	85
Mean	4.33	4.14	3.24	4.24	3.14	3.76	4.09
Variance	2.83	3.13	4.59	3.39	3.13	2.59	2.79

Product Flexibility-Rating

	Lot Size	Lead Time	Set-up Time	WIP Inv.	Product Develop. Time	No.of job Clas.	Production Cycle Time	Using Prog. Equip.	Using Spec. Equip.
Auto.									
1	4	3	5	2	5	2	4	2	1
2	4	5	2	4	3	3	3	0	0
3	5	2	4	4	3	0	2	4	1
4	4	3	5	3	5	2	4	1	0
5	3	3	5	3	5	5	4	3	3
6	2	3	3	3	4	0	2	5	1
7	3	1	1	2	2	3	3	5	5
8	1	0	1	1	2	5	3	2	4
Heavy Mach.									
9	2	5	1	0	4	1	3	1	1
10	5	4	4	3	5	4	4	2	2
Electr.									
11	3	2	4	4	5	3	4	1	3
12	1	3	2	2	3	2	4	1	1
13	3	3	4	4	5	3	5	2	2
14	3	3	4	2	3	2	5	2	3
15	3	5	5	2	4	4	3	3	0
Aeros.									
16	4	3	5	3	3	2	4	2	1
17	2	3	5	2	4	1	2	0	2
18	3	4	5	4	4	3	3	3	5
Oth.									
19	4	3	3	4	3	0	4	3	3
20	4	2	1	1	1	2	4	2	3
21	3	4	4	4	4	3	4	4	4
Tot.	61	64	74	57	79	51	74	48	45
Mean	3.1	3.0	3.5	2.7	3.8	2.4	3.5	2.3	2.1
Var.	1.2	1.5	2.5	1.41	1.39	1.9	0.76	2.01	2.43

Product Flexibility - Ranking

	Lot Size	Lead Time	Set-up TIme	WIP Inv.	Product Develop. Time	No.of Job Clas.	Production Cycle Time	Using Prog. Equip.	Using Spec. Equip.
Auto.									
1	5	6	1	3	2	6	4	6	6
2	2	1	6	4	6	3	5	6	6
3	2	6	1	5	3	6	4	6	6
4	5	6	1	3	2	6	4	6	6
5	6	5	3	6	2	1	4	6	6
6	5	6	4	3	6	6	1	2	6
7	3	1	6	6	2	6	6	5	4
8	6	6	6	6	4	2	1	5	3
Heavy Mach.									
9	4	1	5	6	2	6	3	6	6
10	1	4	3	6	2	6	5	6	6
Elec.									
11	6	5	4	2	1	6	3	6	6
12	6	3	6	4	1	6	2	5	6
13	6	5	3	4	2	6	1	6	6
14	4	2	5	6	3	6	1	6	6
15	1	2	6	4	5	6	3	6	6
Aero space									
16	6	3	2	4	5	6	6	1	6
17	6	4	1	5	2	6	3	6	6
18	2	5	1	6	3	6	4	1	6
Other									
19	2	6	1	2	6	5	4	6	6
20	6	6	6	5	6	6	1	3	4
21	3	4	1	5	2	6	3	6	6
Total	87	91	72	109	67	112	68	111	119
Mean	4.14	4.33	3.43	4.52	3.24	5.38	3.24	5.29	5.67
Var.	3.53	2.93	4.46	1.86	3.09	2.15	2.59	2.11	0.73

Routing Flexibility-Rating

	Lead Time	WIP Inv.	Production Costs	Rate of Throug.	Production Cycle Time	Queue Length	Mach. Util. Rate	Machine Down-time
Auto.								
1	1	2	5	2	2	1	4	3
2	4	1	2	2	1	3	3	3
3	3	1	2	3	4	3	3	5
4	3	3	3	4	3	5	5	4
5	3	4	2	3	5	5	1	1
6	2	3	3	4	2	4	2	2
7	4	5	2	4	2	4	1	1
8	3	5	2	3	4	5	2	4
H.M.								
9	3	4	3	3	5	4	5	5
10	3	1	5	1	4	0	1	1
Elc.								
11	5	4	5	4	2	5	4	2
12	1	3	5	4	2	2	2	1
13	2	4	3	3	2	5	3	5
14	4	3	2	2	5	4	1	1
15	5	3	2	4	4	2	3	2
A.s.								
16	4	3	3	4	5	5	4	5
17	3	4	4	2	3	5	2	1
18	3	4	3	4	4	5	5	3
Oth.								
19	5	4	5	4	5	4	4	4
20	1	3	5	4	4	2	3	4
21	4	4	4	5	4	3	3	4
Tot.	66	68	70	69	72	76	61	61
Mean	3.14	3.24	3.33	3.29	3.43	3.62	2.90	2.90
Var.	1.53	1.39	1.53	1.01	1.66	2.24	1.79	2.39

Routing Flexibility-Ranking

	Lead Time	WIP Inv.	Production Costs	Rate of Througput	Production Cycle Time	Queue Length	Mach. Util. Rate	Mach. Down-time
Auto.								
1	6	6	4	3	5	6	2	1
2	4	1	2	6	6	3	6	5
3	3	6	6	4	2	6	5	1
4	6	6	6	3	5	1	2	4
5	6	2	4	3	5	1	6	6
6	6	3	6	4	1	2	5	6
7	2	3	6	5	4	1	6	6
8	5	6	6	2	4	1	3	6
H.M.								
9	6	5	6	6	1	4	2	3
10	3	6	1	4	2	6	6	5
Elec.								
11	1	2	6	5	3	6	4	6
12	6	3	6	4	2	1	6	5
13	6	3	4	6	6	2	5	1
14	5	3	1	2	6	4	6	6
15	6	3	5	4	1	2	6	6
Ae.s.								
16	1	2	6	5	6	4	6	3
17	5	3	6	1	6	4	2	6
18	6	3	6	4	5	1	2	6
Other								
19	6	6	2	3	5	1	6	4
20	6	4	2	5	6	3	1	6
21	5	6	4	3	6	2	6	1
Total	100	82	95	82	87	61	98	93
Mean	4.76	3.9	4.52	3.90	4.14	2.90	4.67	4.43
Var.	2.99	2.9	3.46	1.89	3.63	3.60	2.83	3.86

Volume Flexibility - Rating

	Lead Time	WIP Inven.	Production cost	Rate of Througput	Production Cycle Time	Queue Length	Machine Util. Rate	Volume Range of Production
Auto.								
1	3	2	4	5	4	2	3	5
2	3	3	4	5	2	2	1	5
3	3	4	5	3	2	5	2	3
4	2	3	5	4	4	3	2	5
5	3	2	5	3	3	3	2	5
6	1	4	4	4	4	1	3	5
7	2	3	5	3	1	2	4	1
8	0	2	5	4	3	4	4	2
Heavy Mach.								
9	4	0	5	1	3	0	0	2
10	5	3	4	4	5	5	3	4
Elec.								
11	5	3	2	3	5	4	4	4
12	1	3	5	4	2	2	3	1
13	4	5	3	4	3	4	3	5
14	4	5	2	4	4	3	5	5
15	4	3	5	4	2	2	3	2
Aero Space								
16	4	3	4	4	5	4	4	5
17	2	3	4	4	2	2	4	1
18	3	5	4	4	4	3	3	5
Other								
19	5	3	4	4	4	3	4	0
20	3	2	1	4	3	2	1	5
21	4	4	4	5	4	3	3	4
Total	65	65	84	80	71	59	61	74
Mean	3.09	3.09	4.00	3.81	3.38	2.81	2.90	3.52
Var.	1.89	1.39	1.30	0.76	1.44	1.56	1.49	3.06

Volume Flexibility - Ranking

	Lead Time	WIP Inven.	Production Costs	Rate of Througput	Production Cycle Time	Queue Length	Machine Util. Rate	Volume Range of Production
Auto.								
1	6	5	4	6	1	6	3	2
2	4	5	3	2	6	6	6	1
3	5	3	2	4	6	1	6	6
4	6	2	5	4	3	6	6	1
5	4	6	3	6	1	5	6	2
6	6	6	1	3	5	6	3	4
7	4	2	1	6	6	5	2	6
8	6	5	1	3	4	6	2	6
Heavy Mach.								
9	2	6	1	5	3	6	6	4
10	3	6	6	4	1	2	6	5
Elec.								
11	2	6	3	4	5	1	6	6
12	4	3	6	2	1	5	6	6
13	3	2	6	5	6	4	6	1
14	4	3	6	6	2	5	6	1
15	1	3	2	5	6	6	4	6
Aero space								
16	3	6	6	6	1	4	5	2
17	5	2	1	6	4	6	3	6
18	3	6	4	5	6	6	2	1
Other								
19	6	3	1	5	6	2	4	6
20	5	6	6	2	4	6	3	1
21	3	4	5	1	2	3	6	6
Total	85	90	73	90	79	100	97	79
Mean	4.05	4.29	3.48	4.29	3.76	4.76	4.62	3.76
Var.	2.25	2.71	4.26	2.51	4.19	3.09	2.65	5.09

Expansion Flexibility - Rating

	Queue Length	Product Quality	Product Development Time	Rate of Throughput	Machine Utilization Rate	Machine Downtime
Automobile						
1	2	4	5	3	4	3
2	2	4	5	3	4	4
3	5	3	4	4	3	2
4	1	3	5	4	4	3
5	0	3	5	3	5	3
6	1	3	5	4	4	3
7	4	1	5	5	3	2
8	0	5	2	3	4	4
Heavy Machinery						
9	2	4	3	5	0	1
10	3	1	5	5	3	5
Elec.						
11	3	4	5	4	2	2
12	1	2	2	3	5	4
13	3	0	5	4	5	3
14	2	4	5	4	3	4
15	4	5	4	3	3	3
Aerospace						
16	4	3	5	5	4	5
17	3	4	5	4	3	2
18	4	3	4	5	3	2
Other						
19	3	5	3	4	4	4
20	3	4	4	5	3	4
21	3	5	2	3	5	4
Total	54	70	88	83	74	68
Mean	2.57	3.33	4.19	3.95	3.52	3.24
Variance	2.06	1.93	1.26	0.64	1.36	1.19

Expansion Flexibility - Ranking

	Queue Length	Product Quality	Product Development Time	Rate of Throughput	Machine Utilization Rate	Machine Downtime
Auto.						
1	6	1	5	4	2	3
2	1	5	6	4	2	3
3	5	3	1	6	2	4
4	6	5	1	3	2	4
5	6	3	1	2	4	5
6	1	5	4	2	3	6
7	6	2	1	5	3	4
8	1	5	3	2	4	6
Heavy Mach.						
9	4	2	3	1	6	5
10	5	6	3	2	5	4
Electronics						
11	5	3	1	2	4	6
12	5	4	6	3	1	2
13	5	6	2	3	1	4
14	6	3	1	2	4	5
15	2	1	6	3	5	4
Aerospace						
16	4	3	1	2	6	5
17	3	1	4	2	5	6
18	5	6	2	3	4	1
Other						
19	6	1	2	3	4	5
20	5	1	6	4	2	3
21	5	3	4	1	6	2
Total	92	69	63	59	74	89
Mean	4.38	3.29	3.00	2.81	3.52	4.24
Variance	3.05	3.21	3.70	1.56	2.46	2.19

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