

## **Copyright Warning & Restrictions**

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be “used for any purpose other than private study, scholarship, or research.” If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of “fair use” that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

**Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation**

Printing note: If you do not wish to print this page, then select “Pages from: first page # to: last page #” on the print dialog screen

The Van Houten library has removed some of the personal information and all signatures from the approval page and biographical sketches of theses and dissertations in order to protect the identity of NJIT graduates and faculty.

## ABSTRACT

### Measures for Estimating the Need for Flexibility in a Manufacturing Facility

by

Raghu Chilukuri

Manufacturing technology is in the midst of on-going developments stemming from rapid improvements in machine tools, computers and robots. These developments present engineers with greater challenges and opportunities in designing more complex and productive systems. The concept of flexibility was defined by authors like Jaikumar, Son & Park, and Buzacott. The various challenges can be partly overcome by building flexibility into the various systems. Various operational or raw measures are described as they help managers to understand the kind and extent of flexibility embedded in their production process and allow them to make informal judgement on new equipment.

Various types of flexibilities such as Product, Process, Machine and Mix are defined and necessity measures are developed. The objective of necessity measures is to determine the flexibility required in a manufacturing facility based on the given set of parameters, such as the number of resources, type of resources, availability of resources, etc. Having derived the necessity measures they have been validated with illustrative examples.

The Mix and Process flexibility measures were found to be very sensitive to the system components and its attributes. With the introduction of new or additional components the necessity measures varies significantly. Product and Machine flexibility are found to be less sensitive. The measures used for the flexibility study are simple and operational. These measures are intended to be used by a decision maker in support of choosing a manufacturing system, set of machines, products to produce, or adding a machine to an existing production system.

MEASURES FOR ESTIMATING THE NEED FOR FLEXIBILITY IN A  
MANUFACTURING FACILITY

by  
Raghu Chilukuri

A Thesis  
Submitted to the Faculty of  
New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
Master of Science

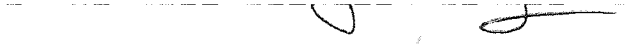
Department of Mechanical and Industrial Engineering

January, 1993


## APPROVAL PAGE

Measures for Estimating the Need for Flexibility in a Manufacturing Facility

by  
Raghu Chilukuri



Dr. Sanchoy K. Das, Thesis Advisor  
Assistant Professor, Department of Mechanical &  
Industrial Engineering  
New Jersey Institute of Technology



Dr. Abdel Malek,  
Director, Department of Industrial Engineering  
New Jersey Institute of Technology

Dr. Xuili Chao,  
Assistant Professor, Department of Mechanical &  
Industrial Engineering  
New Jersey Institute of Technology

## BIOGRAPHICAL SKETCH

**Author:** Raghu Chilukuri

**Degree:** Master of Science in Industrial Engineering

**Date:** January, 1993

### Undergraduate and Graduate Education:

- . Master of Science in Industrial Engineering.  
New Jersey Institute of Technology, Newark, NJ, 1993
  
- . Bachelor of Science in Mechanical Engineering,  
Manipal Institute of Technology, Manipal, India, 1988

**Major:** Industrial Engineering

### Professional Positions:

DJ Plastics Ltd, India, Production Engineer, July 1988 to June 1989.

*This thesis is dedicated with love  
to my Mom & Dad*

## ACKNOWLEDGMENT

The author wishes to thank his thesis advisor, Dr. Sanchoy K. Das for patiently reviewing the progress of the thesis at every stage and helping me to plan it efficiently. This Thesis would not have been successful but for his invaluable guidance and sincere concern.

Special thanks to professors Dr. Abdel Malek, and Dr. Chao for serving as members of the committee.

The author is grateful to the State of New Jersey for funding of the research through the NJIT Research Office.

Thanks also due to the librarians at NJIT for their help in the survey of research papers on the subject of my thesis.

I wish to express my gratitude to my friends Jacqueline & Jeethu for their help and motivation.



## TABLE OF CONTENTS

Chapter	Page
1 INTRODUCTION .....	1
1.1 Introduction to Flexibility .....	1
1.1.1 Evolution of Flexibility .....	2
1.1.2 Problem Areas of Flexibility .....	3
1.2 Problem Description .....	5
1.3 Problem Statement .....	7
1.4 Research Objective .....	9
1.5 Organization of Thesis .....	9
2 LITERATURE REVIEW .....	11
2.1 Aspects of Flexibility .....	11
2.2 Definitions of Flexibility .....	13
2.3 Different Manufacturing Flexibilities .....	15
2.4 Elements of FMS	
2.4.1 Elements of Flexibility .....	21
2.4.2 Operation of FMS .....	21
2.4.3 Changes Affecting Manufacturing System .....	22
2.5 Theory of Flexibility Measurement .....	27
2.5.1 Measuring the Value of Flexibility .....	30
2.6 Need for Flexibility .....	31
2.6.1 Prerequisites for FMS .....	31
2.6.2 Problems Implementing FMS .....	32
2.6.3 Benefits of FMS .....	32
2.7 Summary .....	32
3 SOLUTION CAPABILITIES OF FLEXIBILITY .....	34
3.1 Classification of Changes .....	34
3.1.1 Short Term Changes .....	34
3.1.2 Medium Term Changes .....	35
3.1.3 Long Term Changes .....	35
3.2 Problem Causes .....	36

3.3 Types of Solutions .....	36
3.4 Factors Affecting Manufacturing System .....	36
3.4.1 External Changes .....	37
3.4.2 Internal Changes .....	37
3.5 Definition of Problem Factors .....	37
3.6 Analysis of Problem Factors .....	42
3.6.1 Relation between Flexibilities .....	44
3.7 Arrow Analysis .....	44
3.7.1 Machine Flexibility Analysis .....	44
3.7.2 Routing Flexibility Analysis .....	44
3.7.3 Product Flexibility Analysis .....	48
3.7.4 Process Flexibility Analysis .....	48
3.7.5 Mix Flexibility Analysis .....	48
4 DEVELOPMENT OF NECESSITY MEASURES .....	52
4.1 Importance of Necessity Measures .....	52
4.2 Necessity Measure of Mix Flexibility .....	52
4.3 Necessity Measure of Process Flexibility .....	54
4.4 Necessity Measure of Product Flexibility .....	56
4.5 Necessity Measure of Machine Flexibility .....	56
5 ILLUSTRATIVE EXAMPLES .....	60
5.1 Mix Flexibility .....	60
5.2 Product Flexibility .....	62
5.3 Process Flexibility .....	63
5.4 Machine Flexibility .....	65
6 CONCLUSION AND SUMMARY .....	67
REFERENCES .....	69

## LIST OF TABLES

Table	Page
1 Product and Process Dimensions of Flexibility . . . . .	18
2 Summary of Flexibility Measures . . . . .	25
3 Analysis of Problem Causes . . . . .	44

## LIST OF FIGURES

Figure	Page
1 A Proposed Classification Scheme for Manufacturing Flexibilities. . . . .	6
2 Graphical Representation of the Five Flexibility Measurement Levels. . . .	8
3 Manufacturing Continuum . . . . .	12
4 Relationship Among Flexibility Types (Browne 1985) . . . . .	16
5 FMS Elements . . . . .	20
6 A Scheme for Measuring the Value of Flexibility . . . . .	29
7 The Use of Flexibility to Solve Problems . . . . .	38
8 Causes for the Various Changes . . . . .	45
9 Machine Flexibility Arrow Analysis . . . . .	46
10 Routing Flexibility Arrow Analysis . . . . .	47
11 Product Flexibility Arrow Analysis . . . . .	49
12 Process Flexibility Arrow Analysis . . . . .	50
13 Mix Flexibility Arrow Analysis . . . . .	51

# CHAPTER ONE

## INTRODUCTION

### 1.1 Introduction to Flexibility

The term "Flexible Manufacturing System" was first introduced in 1967. In German literature it refers to processing facilities which are connected with a joint control and material flow system for automatic production of different work pieces. The concept of the Flexible Manufacturing System grew in the 1960's from the need to combine the best features of transfer lines with those of job shops. That is to say the high reliability and productivity of the former with the flexibility of the latter to produce a variety of components.

With the emergence of new microprocessor technologies, the concept of flexibility in manufacturing has currently become a key consideration in the design, operation, and management of manufacturing systems. A substantial amount of literature dealing with manufacturing flexibility has accumulated over the last 10 years. The major part of this literature is devoted to defining various types of flexibilities and identifying systems that exhibit one or more of these. Some papers also deal with the issues of the measurement and/or valuation of the various flexibility. According to Ettl (1988) there are only few rigorous systematic treatments of the topic of flexibility in manufacturing, let alone empirical studies of actual manufacturing plants. Ettl also comments the lack of reports that give a coherent statement of the strategic as well as tactical implications of this important dimension of manufacturing strategy. The literature makes one thing abundantly clear: flexibility is a complex, multidimensional and hard-to-capture concept. At least 50 different terms for various types of flexibility can be found in the manufacturing literature. Usually, there are several terms referring to the same flexibility type. Definitions for these terms that have appeared in the literature are not always precise and are, at times even for identical terms, not in agreement with one another (see also Swamidass 1988). Not much work has been done to develop analytical models that deal with the concepts of flexibility rigorously, and of course, to determine the optimal

levels of flexibility (see also Slack 1987). As a result, the measures proposed in the literature are not always adequate and, at times, somewhat arbitrary.

### **1.1.1 Evolution of Flexibility**

The last two decades have seen fundamental changes in the character of advanced manufacturing system. Developments in numerous enabling technologies have been complemented by the increasingly sophisticated capabilities of manufacturing engineers to understand, analyze and tackle the challenge of efficient manufacturing system design and operation. Over the last decade, evolving technologies in robotic, guided vehicles, sensors, computer control, advanced machine tool design, tooling system and handling technologies have had a profound impact on thinking in advanced manufacturing system design worldwide.

Manufacturing technology is also in the midst of on-going developments stemming from rapid improvements in machine tools, computers and robots. These developments present engineers with greater challenges and opportunities in designing more complex and productive system. Changes occur constantly in the environment thereby forcing the production system to be flexible in order to overcome the changes. The changes may be with respect to product, process, volume, routing, etc. Flexible manufacturing systems incorporate these new technologies to provide manufactures with a competitive tool.

FMS's may be defined as production units capable of producing a wide range of discrete products with a minimum of human intervention. It consists of production equipment workstations ( machine tools or other equipment for fabrication, assembly, or treatment) that are linked by a material-handling system to move parts from one workstation to another, and it operates as an integrated system under full programmable control.

The primary benefit of an FMS is the flexibility it provides to managers. This flexibility permits managers to adapt to changes in the operating environment. For instance, manufacturing systems that are flexible can utilize the flexibility as an adaptive response to unpredictable situations. Needless to say, a variety of different flexibilities are possible. An extensive

review of these flexibilities is provided by Sethi and Sethi (1990) and Gupta Goyal (1989).

### 1.1.2 Problem Areas of Flexibility

The amount of flexibility necessary to deserve the label "flexible" is arguable. Some FMSs can produce only three or four parts of very similar size and shapes- e.g, three or four engine blocks for different configurations of engines. One FMS expert argues, however, that in the current state of the technology, a system that cannot produce at least 20 to 25 different parts is not flexible. Note that some systems are designed to manufacture up to 500 parts.

Many feel that the "flexibility" of FMSs provide a manufacturer with economic advantages of both a strategic and tactical nature; in particular their ability to :

- 1) Rapidly introduce new parts.
- 2) Introduce new workstations as dictated by technology.
- 3) Re-route work to minimize the impact of breakdowns and overloaded workstations (in the short run).
- 4) Change the production mix rapidly to meet short run fluctuations.
- 5) Introduce new parts.

In the past, a number of research articles have appeared justifying flexible automation, economic and strategic as independent aspect. However, they seem to be unsatisfactory, since the profitability of investment is a function of the firm's strategic position and, otherwise, the only method to evaluate if a production system fits the firms strategy is to analyze its profitability. Therefore, there is a pressing need to develop a new evaluation model that signifies the relations between strategic performances and profitability. Towards this attempt, as a first step, the problem of dividing the general term 'Flexibility' into a number of elementary concepts were discussed by Browne(1985), Buzacott(1982), Grewin(1982). etc

Excellence in manufacturing is increasingly being recognized as an important factor in the success of firms in most of the industries. New technology for manufacturing processes plays a significant role in achieving this excellence. Achieving the full potential of this technology, however,

includes a board range of management, engineering, and systems issues. As a result, the implementation of modern manufacturing methods and technologies represents an opportunity for significant contribution from the fields of Operations Research (OR) or Management Science (MS). The increase in demand for the products, the competition in the market, and the concern about the quality leads the manufacturing industries to implement the new manufacturing concepts such as FMS, JIT and OPT as they are helpful in achieving their objectives on the productivity and quality.

Flexible Manufacturing Systems represent a class of systems for mid-volume production that may provide a competitive edge in certain industries. They include many of the problems and issues that arise in discrete parts fabrication and assembly systems, both automated and manual. There exists different types of FMSs based on the differences in the machine tools and the material handling systems used. Traditionally, production facilities have two conflicting goals; flexibility and productivity. Flexibility means producing a large number of distinct products which is characteristic of a job shop environment. Productivity means high speed production which is characteristic of an assembly line. Many studies have demonstrated that the productivity of a job shop is very low. Therefore, increasing job shop productivity while maintaining its flexibility has been a constant aim of industries. FMS's are a recent development along this line. Moreover, FMSs is an umbrella term that covers a board variety of specific applications. These include: 1) Flexible assembly systems, 2) Flexible fabrication systems, 3) Flexible machining systems, and 4) Flexible welding systems.

In most FMS's, performance evaluation or in general measurement of any alternative for the decision making purposes has become an important part of the system implementation. The lack of insight on flexibility and the inexperience of manufacturing firms in managing flexibly automated systems are among the primary reasons for the disparity between the promised and the actual performance of the FMS's. The growth of flexible automation has been propelled by the advances in computerized manufacturing technology coupled with the need for shorter production runs, greater responsiveness to demand changes, customized production, and superior control of the production processes.



## 1.2 Problem Description

Flexibility in itself is of little value, rather its value comes from being able to provide the means for meeting management objectives. Then, since flexibility is a tool it must be implemented in response to some specific objective. Using Anthony's (1965) decision/objective framework, the various flexibilities may be classified as being either strategic, tactical, or operational in nature. Strategic flexibilities will usually involve a large portion of the company's manufacturing operations, and be initiated by the highest levels of management. The changes countered by this class of flexibility will occur at long intervals, but of considerable magnitude. Tactical flexibility usually occur in relation to a specific performance feature of the production operations, such as machine utilization or work-in-process inventory. The changes encountered at this class will occur at medium intervals, and be less magnitude than those in strategic flexibility. Operational flexibility concern day-to-day changes and individual production functions. This class of flexibility is most closely related to the value adding portion of production. In addition to these three classes a component class is introduced. This class includes flexibilities which concern individual components, and also other features which support flexible manufacturing.

Figure 1 positions several flexibilities in the proposed classes, and identifies possible relationships. This scheme could serve as a guideline for managers interested in flexibility. For instance if managers are interested in product flexibility they could find that it belongs to the tactical class. This indicates the level of effort and resources required to achieve such a flexibility. Three strategic flexibilities are identified in figure 1. These are market, production and expansion. The majority of commonly pursued flexibilities are geared towards achieving market flexibility. This is expected since the market is the source of most changes effecting production operations.

Flexibility of a system is its capability to adapt to a wide range of possible environmental changes that it may encounter. A flexible system must be capable of changing in order to deal with a changing environment. The changes in the environment could be in the form of design changes, demand change, different types of failures in the manufacturing system , etc.

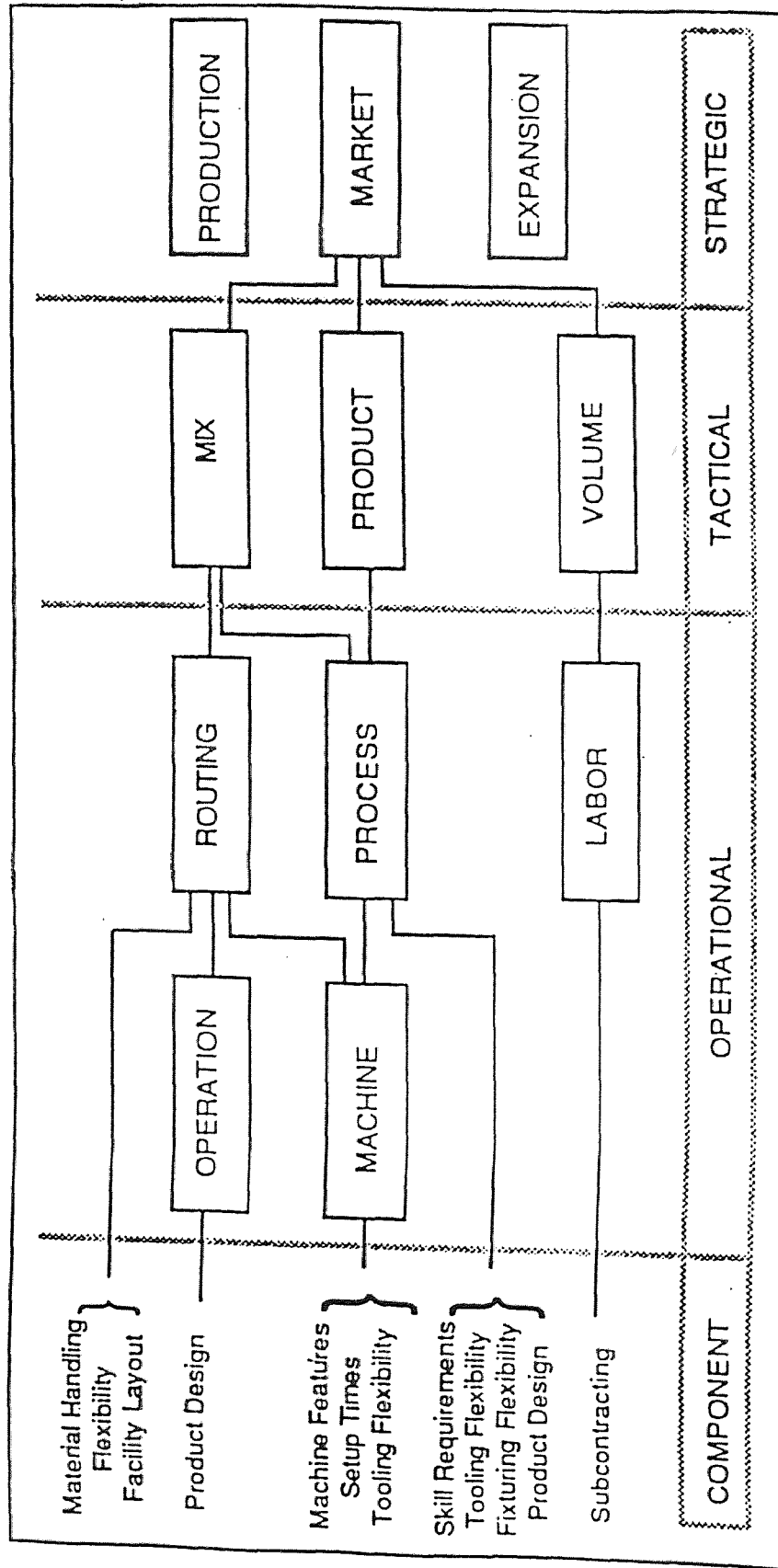


Figure 1. A Proposed Classification Scheme for Manufacturing Flexibilities

The different types of flexibility play an important role in over coming these changes. Clearly, any manufacturing firm facing changes of this type will be interested in acquiring FMS technology. In the acquisition process the firm must answer at least three questions which are discussed later. These are as follows:

- 1) **What flexibilities are to be pursued.**
- 2) **To what extent should the flexibility be shown.**
- 3) **How to execute the flexibility.**

Flexibility measures have been provided by Das (1990) to determine the capability and actuality of a facility. It is of utmost importance to be able to measure the necessity measure of flexibility. This enables the manager in the industry to decide the type of flexibility and the extent of each type appropriate to his manufacturing system in different scenario or time periods. This requires a frame work from which to select the appropriate type. To achieve this, the various factors effecting flexibility need to be identified. Based on the information obtained from the necessity measure, the participating manager must be able to propose the course of action and use to his competitive advantage.

In determining measures for manufacturing flexibility it has been assumed that there will be only one measure for each flexibility type. With reference to the paper published by Das(1990), there are as many as five, levels of measures for each flexibility. Figure 2 illustrates the relationship between these levels, and description of each level is provided in section 2.6. While Das (1990) proposes measures for the capability and actuality levels, no measures for the necessity levels have yet been reported. The objective of this thesis is to develop a set of necessity measures of four types of flexibilities namely mix, product, process, and machine flexibility.

### **1.3 Problem Statement**

Prior to building or designing an FMS it is required that the types of flexibilities and extent of the flexibility to be exhibited by the facility be known. There is therefore a need to develop necessity measures for each of

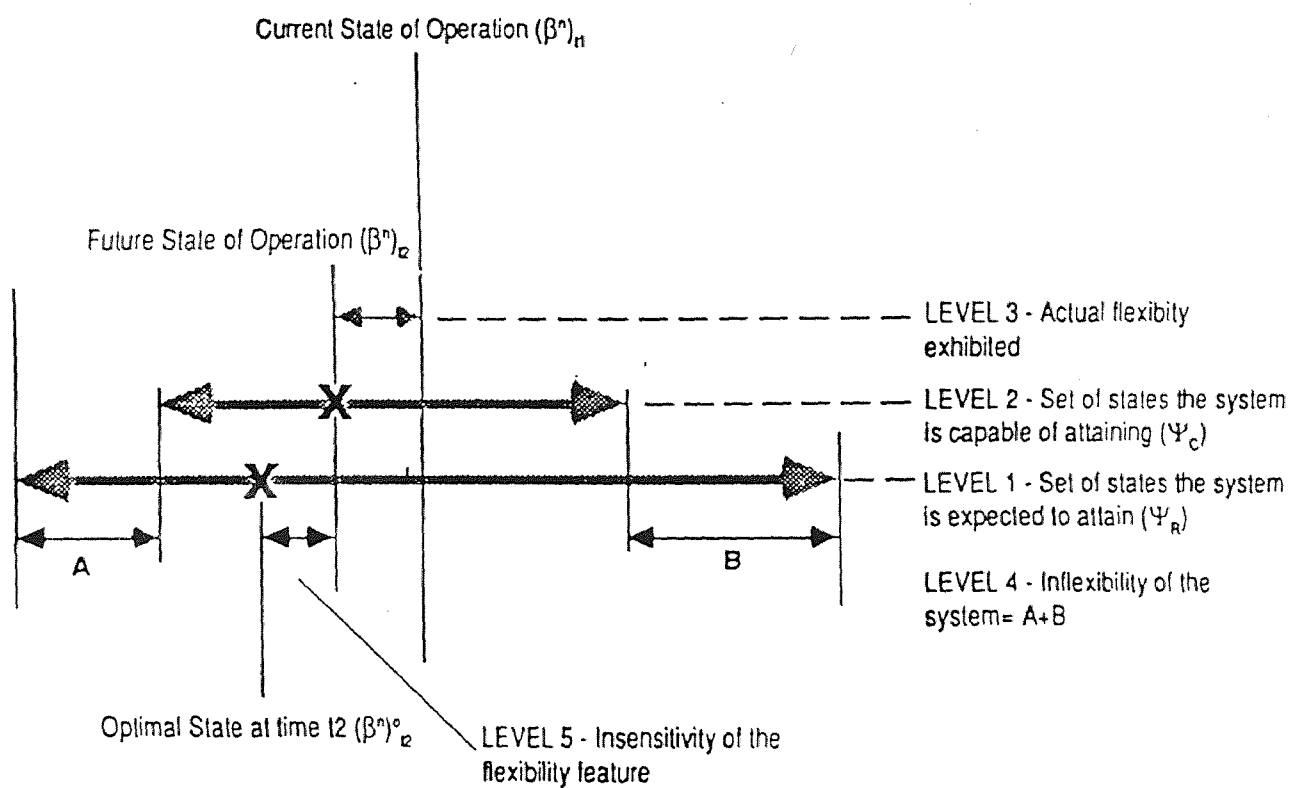


Figure 2. Graphical Representation of the Five Flexibility Measurement Levels

the different types of flexibility. These measures will be indicative of the firms flexibility needs.

#### **1.4 Research Objectives**

The primary objective of this research is to determine the necessity measure for machine, product, process, routing and mix flexibilities. The purpose of these measures is to determine to what extent the each of the above mentioned flexibilities are required in a manufacturing facility. The intermediate objective in meeting the primary objective are:

1. Define mix, product, process and machine flexibilities.
  - . Review the types of flexibilities discussed in the literature.
  - . Define each of the flexibilities individually.
2. Discuss the need for measuring the need for flexibility and the implementation obstacles.
3. Identify the various changing factors that affect a manufacturing facility, and the flexibility that could be used to overcome these changes.
  - . Define each of the factors and determine why they occur.
  - . Identify flexibilities to help overcome the factors.
4. Development of necessity measures for mix, product, process and machine flexibility.
5. Validate each of the measures with case studies.
6. Analyze the test results and provide guidelines for flexibility introduction.

#### **1.5 Organization of Thesis**

The organization of the thesis is as follows. In this section, a historic perspective on flexibility is provided which brings forth reasons for the need for flexibility and flexibility implementation obstacles with definitions of different types of flexibility. Thereby providing a good concept of manufacturing flexibility and its strategic importance in general terms. Also definition of specific flexibilities along with suggested measurements and interrelationship between them are developed. Section 3 brings forth the

Solution capabilities of flexibility. Here the various problems that could come up in a manufacturing facility are listed. Definition and classification of the problems are done. In addition arrow-analysis of the various flexibilities are performed. Section 4, the various necessity measures for the different flexibilities are developed. Section 5, Evaluation of the necessity measures are performed. Section 6, Conclusion and Summary.

## CHAPTER TWO

### LITERATURE REVIEW

A large quantity of literature on issues pertaining to flexibility of manufacturing systems has mushroomed in recent years. Widespread interest in this topic points to the importance of understanding flexibility. Due to the increasing recognition of the importance of flexibility in decision making and planning, there has been a number of attempts to define the term "flexibility". Some researchers have defined flexibility and divided flexibility into different types. Some have provided measures to evaluate flexibility and some have outlined the importance of flexibility in management. Definitions and research related to flexibility are discussed in this chapter.

The evolution of manufacturing can be represented graphically as a continuum as shown in figure 3. As this figure shows, manufacturing processes and systems are in a state of transition from manual operation to the eventual realization of fully integrated manufacturing. The phase preceding computer integrated manufacturing is called flexible manufacturing systems. Flexibility is an important characteristic in the modern manufacturing setting. It means that a manufacturing system is versatile and adaptable, while also capable of handling relatively high production runs. A flexible manufacturing is versatile in that it can produce a variety of parts. It is adaptable because it can be quickly modified to produce a completely different line of parts. This flexibility can be the difference between success and failure in a competitive international marketplace.

#### 2.1 Aspects of Flexibility

The word "*flexible*" is used in the English language to describe objects "capable of responding or conforming to changing or new situations". Flexibility is the property that makes an object "flexible". In the context of manufacturing systems, flexibility is widely accepted to imply the "ability of the system to cope with changes". However, this definition does not explain what "ability" means and is hard to operate.

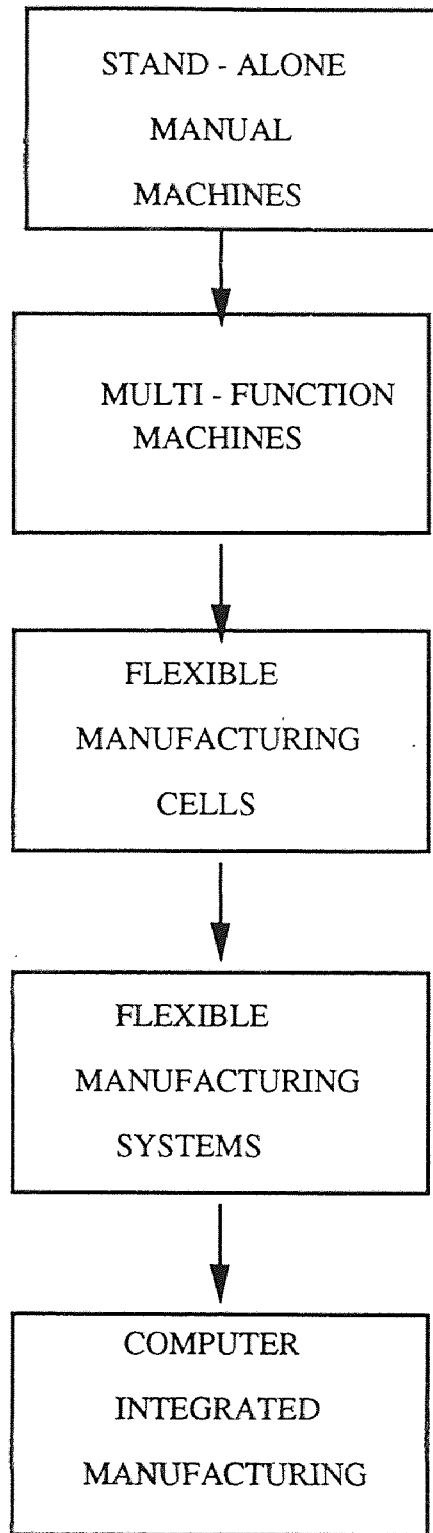


Figure 3. Manufacturing Continuum



An important component of the ability is determined by the manufacturing systems sensitivity and stability. Sensitivity relates to the degree of change tolerated before a deterioration in performance takes place. Reduced sensitivity with respect to a given change implies that the manufacturing system performance is not affected by greater degree of change impacting the system. On the other hand, greater stability implies that the manufacturing system processes the ability to respond to a greater variety of changes and for each such change greater magnitudes could be coped with. For example, a system whose performances is not affected by machine breakdowns (due to excess capacity) is less sensitive than another that is affected by such changes. Similarly, a system capable of making correction for tool wear as well as tool failure is more stable as compared to a system that responds to tool failure only, when the performance of both these systems is affected by tool wear and failure.

## 2.2 Definitions of Flexibility

A flexible manufacturing system (FMS) is an individual machine or group of machines served by an automated material handling system that is computer controlled and has a tool handling capability. Because of its tool handling capability and computer control, such a system can be continually re-configured to manufacture a wide variety of parts. This is why it is called a flexible manufacturing system.

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. According to *Kickert (1985)*, flexibility can be considered as a form of meta-control aimed at increasing control capacity by means of an increase in variety, speed, and amount of responses as a reaction to uncertain future environment development.

Flexibility in manufacturing means being able to re-configure manufacturing resources so as to produce efficiently different products of acceptable quality. An earlier definition goes back to *Ropohl (1967)*; he considers manufacturing flexibility as the property of the system elements that are integrally designed and linked to each other in order to allow the

adaptation of production equipments to various production tasks. The International Institute for Production Engineering Research (CIRP) has defined flexible manufacturing system as an automated manufacturing production system which is capable, with the minimum of manual intervention, of producing any of a range or family of products for which the system was designed.

*The Office of Technological Assessment* defines flexibility as a function of the result of implementing flexibility in a manufacturing system. "Flexibility is the range of products and the range of volume of a specific product which a plant can economically produce."

*Jaikumar (1984)* emphasizes the fact that flexibility in manufacturing is always constrained within a domain. Such a domain should be defined in terms of portfolio of products, process, and procedures and should be well understood by product designers, manufacturing engineers, and software programmers.

*Mandelbaum (1978)* defines flexibility as "the ability to respond effectively to changing circumstances" and observes that it can be characterized into two different forms: action flexibility, "the capacity to take new actions to meet new circumstances," and state flexibility, "the capacity to continue functioning effectively despite changes in the environment."

*Zelenovic (1982)* provides a physical definition of flexibility as applied to a complete system. "Flexibility of a production system is a measure of its capacity to adapt to changing environment until condition and process requirements."

*Son & Park (1987)* have defined flexibility into different types and provided definitions for each type. "Flexibility is a measure of manufacturing performance which indicates the manufacturing system's adaptability to change in manufacturing environments."

Different authors have identified different types of flexibility and provided different measures for them. Flexibility is defined in different ways

because the nature and scope of the disturbances or changes in a manufacturing system alter over time, thereby increasing or decreasing the importance of some type of flexibility. The nature and scope of these changes are difficult to identify and understand. This shows that flexibility is a relative term measure and the system is to be constantly modified to maintain the flexibility.

### 2.3 Different Manufacturing Flexibilities

Researchers have defined different types of Manufacturing flexibilities and have also provided measures for estimating them. This section identifies the various flexibilities. Browne et.al.(1984) defined eight flexibilities and provided the relationship and defined among them which is shown in figure 4, these are:

1. Machine Flexibility is the ability to make changes to produce a given set of part types.
2. Product Flexibility is the ability to produce different products of varied mixes.
3. Process flexibility is the ability to produce a given set of parts in more than one way.
4. Operation Flexibility is the ability of a machine to perform more than one type of production operation.
5. Routing Flexibility is the ability to select and follow a set of production routes.
6. Capacity Flexibility is the ability to operate economically different production volumes.
7. Expansion Flexibility is the ability to expand the system as needed and modularly.
8. Production Flexibility is the ability to produce more than one part type.

*Gerwin (1982)* has defined five types of flexibilities, these are:

1. Mixed Flexibility - The processing at any one time of different parts loosely related to each other.
2. Parts Flexibility - The addition of parts to the mix and the removal of parts from the mix over time.

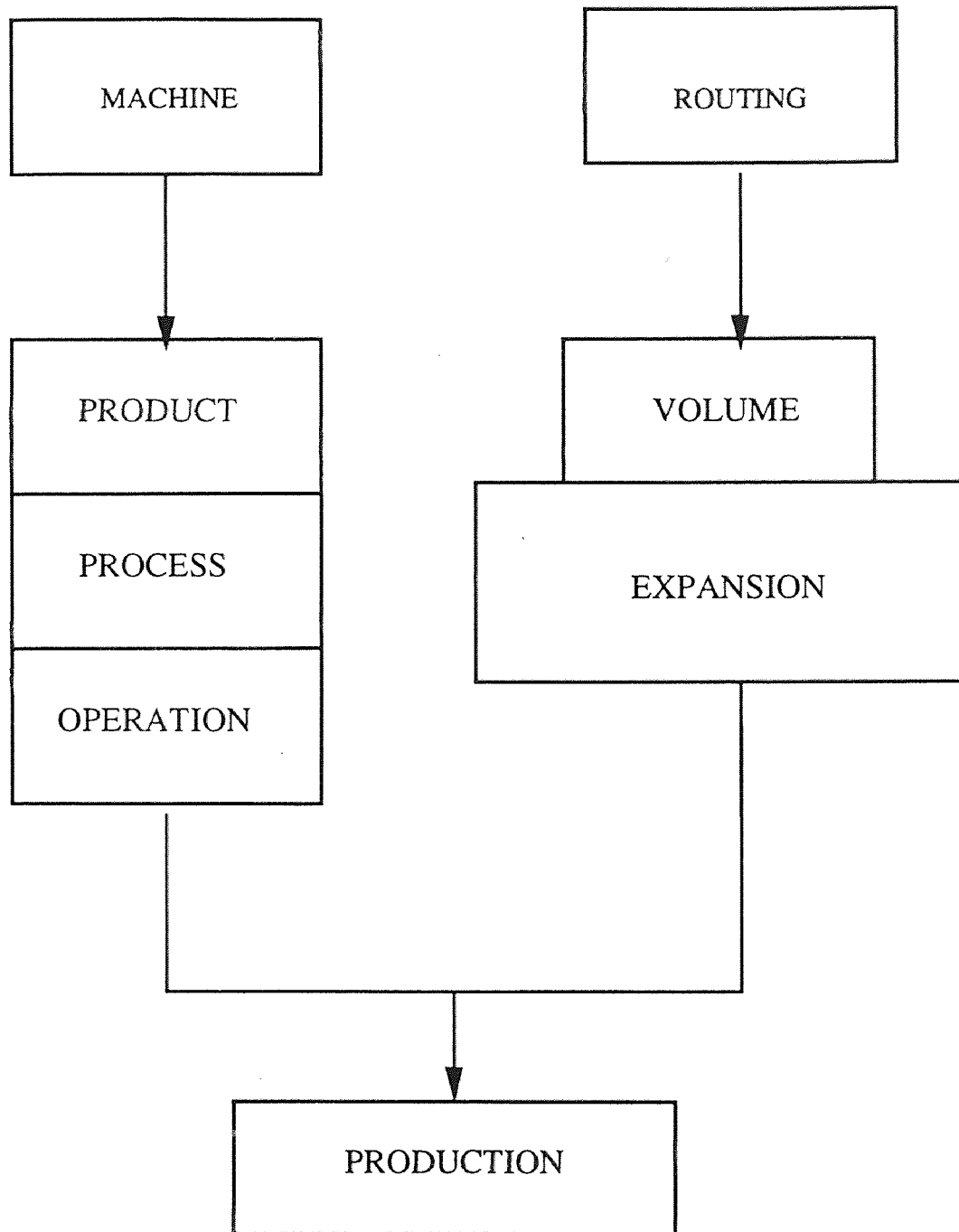


Figure 4 Relationship Among Flexibility Types  
(Browne, 1985)

3. Routing Flexibility - The dynamic assignment of part to machine
4. Design-Change Flexibility - The fast implementation of engineering changes for a particular type of product.
5. Volume Flexibility - The accommodation of shifts in volume for a given part.

*Buzacott (1982)* identifies three types. State Flexibility, Machine Flexibility and Job Flexibility. *Mandelbaum (1988)* identifies two types. State Flexibility and Action Flexibility.

*Jaikumar (1986)* has identified three types of flexibilities.

1. Product Flexibility.
2. Process Flexibility.
3. Program Flexibility.

*Son & Park (1987)* recognize the following four types of flexibilities.

1. Equipment Flexibility - It is the equipment's capacity to accommodate new products and some variance of existing products.
2. Production Flexibility - It is the adaptability of a manufacturing system to changes in product-mix.
3. Process Flexibility - It is the adaptability to various changes in part processing.
4. Demand Flexibility - It is the adaptability to changes in the demand rate.

*Swamidas (1986)* has identified three types of flexibilities.

- Type 1 - High - volume / Low - variety Flexibility.  
 Type 2 - Mid - volume / Mid - variety Flexibility  
 Type 3 - Low - volume / High - variety Flexibility

Clearly a variety of different flexibilities have been proposed in the literature. *Adler (1988)* attributes these differences to the difficulty in linking the two key dimensions of flexibility production and process. Table 1 shows the different types identified by *Gerwin, Mandelbaum, Buzacott, Browne and Jaikumar*.

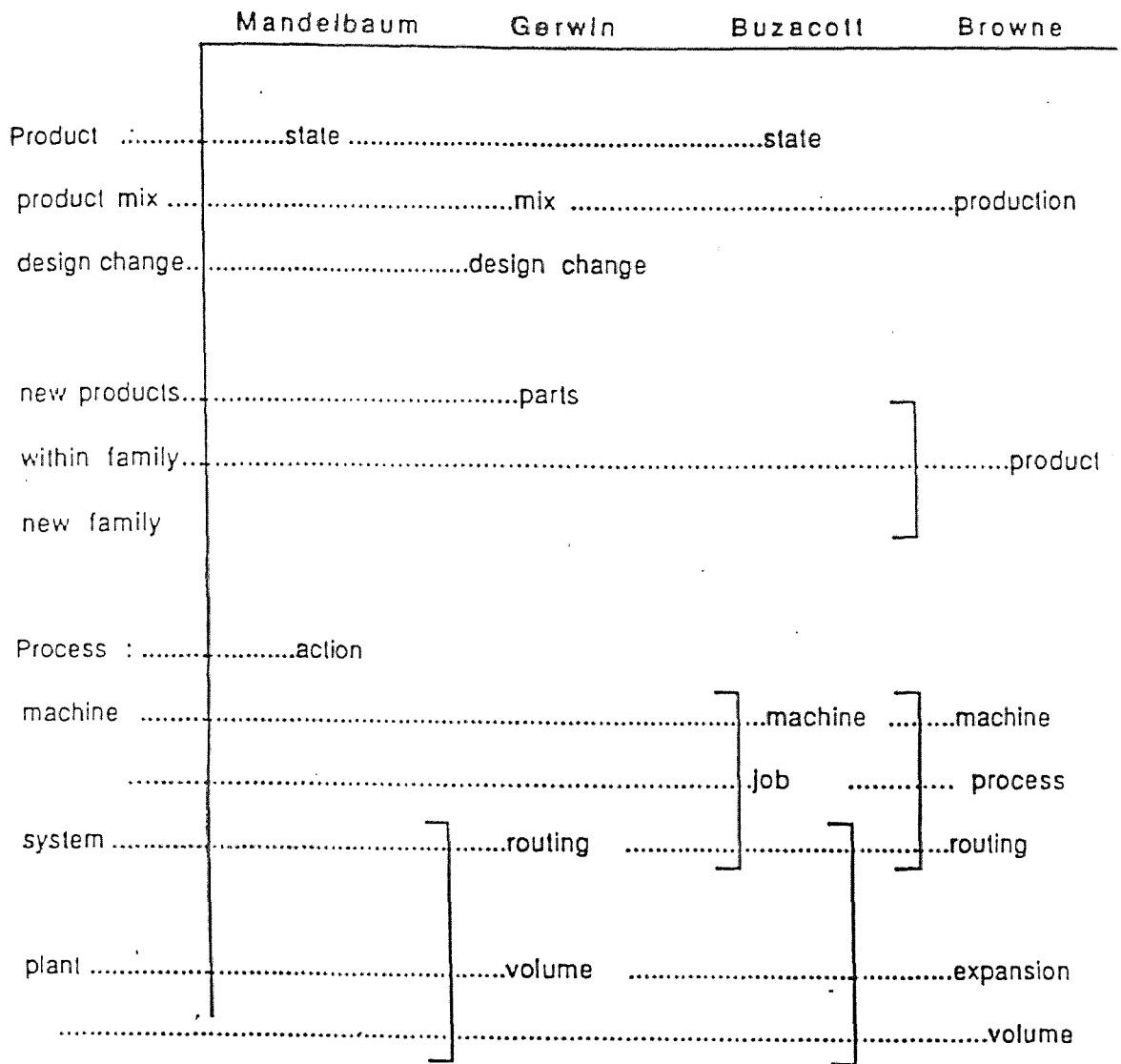


Table 1 Product and Process Dimensions of flexibility (Adler, 1988)

Given this classification, we propose the following five primary flexibility types - Machine, Routing, Process, Product and Mix flexibilities, which represent the most important components of the system. While the remaining flexibilities apply to the manufacturing system as a whole.

#### 1. Machine Flexibility

Machine flexibility refers to the various types of operations that the machine can perform efficiently without regarding a prohibitive effort in switching from one operation to another

#### 2. Routing Flexibility

Routing flexibility refers to the ability of the scheduler to manufacture a product by alternate routes through the system.

#### 3. Process Flexibility

Process flexibility refers to the ability of a machine or work-center to perform more than one type of processing operation efficiently.

#### 4. Product Flexibility

Product flexibility refers to the ability to economically produce a variety of products with varying product structures.

#### 5. Mix Flexibility

Mix flexibility refers to the ability of the system to vary the product mix as per the demand requirements and operate profitably at all output levels.

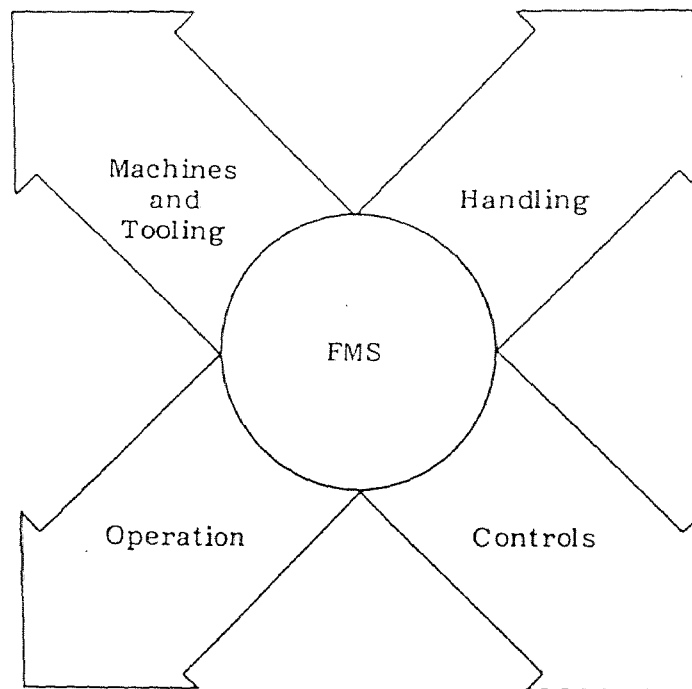
### 2.4 Elements of FMS

Flexible manufacturing systems usually focus on the machining of large standard parts in moderate volume. The principle elements of FMS are shown in figure 5 and they are as follows:

- . Machine tools
- . DNC (distributed numerical control)
- . Automated material Handling
- . Supervisory computer control

Methods  
 Cutting operations  
 Part qualification  
 Orientation and fixturing  
 Machine types, sizes, H.P.  
 Standards  
 Operation balance  
 Gauging  
 Changeover  
 Reliability features  
 Tool life  
 Swarf ejection  
 Coolant  
 Layout

Pallet/cart  
 Clamping/fixturing  
 Identification  
 Interstation movement  
 On/off machine  
 Load/unload station  
 Tool distribution and return  
 Swarf system



Manning and skills  
 Maintenance skills and spares  
 Programming  
 Scheduling  
 Targets  
 Training  
 - operators  
 - supervision  
 - support  
 Communication

Machine CNC and PLC  
 Co-ordinating computer  
 Cart/pallet  
 - feedback  
 - direction  
 Programme distribution  
 Condition monitoring  
 - machine functions (diagnostics)  
 - tool  
 Adaptive control  
 Management reports  
 - performance  
 - production etc.

Figure 5. FMS ELEMENTS



Machine tools used in a FMS depend on the processing requirements to be accomplished by the system. These processing needs have tended to divide FMS into two distinct types: 1. *Dedicated FMS*: designed to meet known specific machining applications and to meet a limited variety of processing needs. 2. *Random FMS*: designed to handle a greater variety of parts in random sequence. In practice, a given flexible manufacturing system often tends to be a hybrid of the two types, incorporating both special machines and standard NC machines.

Within the manufacturing cells and FMSs, work-in-process must be transported quickly and reliably from one work station to the next. Stored work pieces must be easily accessible and recovered rapidly when required. Automated material transport system perform all of these functions, and should be viewed as the key to integrating manufacturing cells into the FMSs that make up the automated factory.

#### 2.4.1 Elements of Flexibility

The computer control system is the linkage needed to transform a group of machines and stand-alone systems into an effective FMS. The functions performed by the computer control system can be categorized into either machine support or planning support. The computer system may be programmed to perform many different functions namely:

- . Sequencing and tracking different loads to selected work stations, based on variable routing instructions.
- . Providing added control to machines and robots at work stations.
- . Collecting real-time data regarding operation of the work station equipment and production.
- . Communicating with a host computer system.
- . Performing other process monitoring functions as required.

#### 2.4.2 Operation of FMS

The structure of an FMS represents the static aspect of the system while the operation of an FMS describes its dynamic aspect. Basically these are two major functions in the operation of an FMS 1) System control, and 2) System monitoring.

### 1. System control:

System control is the most important operation in an FMS. It includes the control of machine tools, material handling equipment, work transportation devices, and auxiliary equipment. In an FMS, re-route control tasks can be handled by a computer quickly and accurately.

### 2. System monitoring:

The operation of an FMS requires a hierarchy of computers which perform various monitoring and control tasks. In general, system state information shows whether equipment or a machine is busy, idle, or down. It also shows how long a tool has been used and whether there is excessive wear on the tool. The progress of the work piece and its associated quality are also monitored. The information collected by the monitoring equipment is used either for control decision-making or for performance measurement.

#### 2.4.3 Changes Affecting Manufacturing System

Any attempt to evaluate the flexibility of a manufacturing system must begin with consideration of the nature of the changes and disturbances with which the system should be able to cope.

Having defined the system and its boundaries, i.e., the manufacturing system consists of a variety of work stations, machines, material handling facilities, tools, fixtures etc., then a useful distinction is between

*External changes:* e.g., changes such as non availability of raw materials as a result of shortage or other factors, increase and decrease in demand, product obsolete, price variations as a result of external competition, etc.

*Internal changes or disturbances:* e.g., machine and material handling system breakdowns, variability in processing time, operator absences, quality problems.

Most of the emphasis on achieving flexibility in manufacturing system is related to job flexibility

## 2.5 Theory of Flexibility Measurement

Different authors have provided varying operational measures for flexibility. Some of them have provided measures for the different types of flexibilities

and some have developed measures for the entire flexibility space of a system. Some measures are either deterministic or probabilistic.

*Brill and Mandelbaum (1988)* have provided probable measures of flexibility of a group of machines relative to a task set. A task set is a group of tasks. They have provided both optimistic and pessimistic measure for flexibility.

*Hutchinson and Sinha (1989)* have determined that flexibility has an economic value. They concentrated on two aspects of flexibility - the ability to change manufacturing mission and capacity. They examined the value of flexibility of scope as a function of the uncertainty faced by the investor as measured by standard deviation. They concluded that increased uncertainty favors flexibility.

*Gupta and Buzacott (1989)* are of the opinion that flexibility can not have an unique measure. They have developed a surrogate measure of flexibility which is called 'the value of flexibility'. The flexibility objectives have to be well defined initially and they have to be classified as long-term, medium-term and short-term. Suitable measures for flexibility objectives are given according to the time categories in which they fall.

*Abdel - Malek and Wolf (1989)* have provided a Ranking Method for flexibility evaluation by identifying the attributes of the different system components. Their methods is helpful for management in preliminary decision making.

*Son & Park (1987)* have provided measures for four different types of flexibility that have been identified namely equipment, product, process, demand.

They provide measures in terms of output (OT) which is the sum of all units of production (not units sold) times the market price.

Equipment flexibility for a given period

$$FE = OT / CI$$

Production Flexibility is given by

$$FP = OT / A$$

Process flexibility for a given period

$$FS = OT / CW$$

Demand flexibility for a given period

$$FD = OT / H$$

where,

CI = Idling cost of equipment.

A = Set - up cost.

CW = Waiting cost of parts processed

H = Inventory cost of products & raw material.

$$TF = OT / (CI + A + CW + H)$$

TF is the total flexibility for a given period defined as the sum of these partial flexibilities and can be used as a global measure of the opportunity of a manufacturing system to add value to products.

Das (1990) has provided measures for the four primary flexibility types. He provided both capability measure which represents the level of flexibility possible as well as dynamic actuality measure which represents the actual levels achieved. This is shown in Table 2. Let the state of the facility at any time, with regard to a particular flexibility type, be given by the vector  $\beta^n$  consisting of 'n' elements. The elements represent different attributes of the production facility such as, product routing, work force levels, or tool location. The value of these elements indicate their current configuration. Let  $\Psi_R$  be the set of different  $\beta^n$  that the facility is required to attain, if it is successfully counter all the anticipated changes.  $\Psi_R$  does not necessarily have to be equal to the euclidean n-spaces of  $\beta^n$ , since the anticipated changes may not require all possible states. Similarly,  $\Psi_C$  denotes the set of states that the facility is requires to attain. As an illustration consider a machine that is required to perform ten different process operations,  $i=1,..,10$ , but has the

Table 2 Summary of Flexibility Measures

Capability Measure	Activity Measure	Variable Definitions
$PFLX = \frac{\sum_{i=1}^N \sum_{j=1}^M (e_{ij}   e_{ij} \geq k)}{\sum_i \bar{M}_i}$ <p>Processing Flexibility</p>	$PFLX = \frac{1}{N} \sum_{i=1}^N \frac{\sum_{t=1}^T \sum_{j=1}^M (x_{ijt} e_{ij} d_{it})}{\bar{M}_i^2 T}$	<p>N = Number of machines  M = Set of processes  M<sub>i</sub> = Number of processes in set M that are relevant to machine i  e<sub>ij</sub> = Efficiency at which machine i does process j  x<sub>ijt</sub> = Is '1' if process j is done on machine i in period t, and '0' otherwise  d<sub>it</sub> = Number of different processes done by machine i in T periods  k = Lowest acceptable efficiency</p>
$RFLX = \frac{1}{N} \sum_{g=1}^N \sum_{k=1}^P \sum_{j=1}^P (\text{Max } d_{gjk})$ <p>where,</p> $d_{gjk} = \frac{\sum_i  t_{gik} - t_{gij} }{\sum_i t_{gik} + \sum_i t_{gij}}$ <p>Routing Flexibility</p>	$RFLX = \frac{1}{NT} \sum_{g=1}^N \sum_{t=1}^{T-1} d_{g,z_{gt},z_{g,t+1}}$	<p>N = Number of products  P = Number of routes/product  T = Number of periods  t<sub>gik</sub> = Processing time of product g on machine i, via route k  z<sub>gt</sub> = Route number selected by product g in period t</p>
$CFLX = \frac{1}{N} \sum_j \left[ 1 - \frac{q_j + S_j}{H_j} \right]$ <p>Capacity Flexibility</p>	<p>where,</p> $B_{j,t} = \frac{ A_{j,t} - A_{j,t+1} }{H_j}$ $CFLX = \frac{1}{N(T-1)} \sum_{j=1}^N \sum_{t=1}^{T-1} B_{j,t}$	<p>N = Number of workcenters  T = Number of periods  H<sub>j</sub> = Resource operating cost at full center utilization. This includes only costs directly incurred by workcenters  Q<sub>j</sub> = Resource operating cost at lower bound of center utilization range  S<sub>j</sub> = Setup cost in moving from lower to full utilization for center j  A<sub>j,t</sub> = Actual cost incurred by center j in period t</p>
$DFLX = \frac{1}{N^2} \sum_{i=1}^N \sum_{j=1}^N [1 - D_{ij}]$ <p>where,</p> $D_{ij} = w_1 \frac{T_{ij}}{T_{bw}} + w_2 \frac{S_{ij}}{\text{Min}(C_i, C_j)}$ <p>Product Flexibility</p>	$DFLX = \frac{\text{\# of product changes}}{T}$	<p>N = Number of products  T<sub>ij</sub> = Setup time in moving from product i to j  T<sub>bw</sub> = Average time between two product changes, i.e. length of a run  S<sub>ij</sub> = Setup cost in moving from product i to j  C<sub>i</sub> = Production cost for product i, per T<sub>bw</sub>  w<sub>1</sub> + w<sub>2</sub> = 1 or weighted importance of setup time and cost</p>

capability to perform only eight of these,  $i=3,4,5, 10$ . Then  $Kr =\{1,..10\}$ , and  $\Psi_C=\{3,..10\}$ . Logically we would expect that  $\Psi_R > \Psi_C$ , when this is not the case it implies a redundancy in the facility's flexibility range. Figure 2 presents a graphical representation of this quantification. Both  $\Psi_C$  and  $\Psi_R$  are represented linearly for convenience.

The actual flexibility exhibited is determined by the rate at which the state of the facility changes. Let  $(\beta^n)_t$  be the state at time 't', and  $\phi(\beta_1^n, \beta_2^n)$  be some function which defines the difference between any two states. Then, the measure of actuality in the period  $t_1$  to  $t_2$  is

$$\text{ACTUAL FLEXIBILITY} = \frac{\phi\left[(\beta)_{\tau_1}^n, (\beta)_{\tau_2}^n\right]}{\tau_2 - \tau_1} \quad (1)$$

Similarly the measure for capability and necessity are,

$$\begin{aligned} \text{FLEXIBILITY CAPABILITY} = \quad & \text{Max} \quad \Phi\left[\beta_1^n, \beta_2^n\right] \\ & \text{s.t. } \beta_1^n, \beta_2^n \in \Psi_C \end{aligned} \quad (2)$$

$$\begin{aligned} \text{FLEXIBILITY NEEDED} = \quad & \text{Max} \quad \Phi\left[\beta_1^n, \beta_2^n\right] \\ & \text{s.t. } \beta_1^n, \beta_2^n \in \Psi_r \end{aligned} \quad (3)$$

In addition to the above three levels of measures, two other measures characterize a FMS. The first of these estimates the inflexibility of the system, and is the difference between necessity and capability. This is expressed in set form as,

$$\text{FMS Inflexibility} = \Psi_R - [\Psi_C \cap \Psi_R] \quad (4)$$

In Figure 2 of chapter 1, the graphical representation of the five flexibility measurement levels are shown. Inflexibility is indicated by the A and B zones. Expression (4) could also be divided by  $\Psi_R$  to get the proportionate inflexibility.

The final level of flexibility measurement, estimates the insensitivity of the flexibility feature. Typically, when an environmental change occurs, some controlling mechanism will interpret this change and then instruct the FMS to attain a new state.

Let  $(\beta^n)_t^o$  be the optimal or best performing state of the FMS, in response to the environmental conditions at time 't'. Due to a variety of reasons the FMS may not actually attain this optimal state, even though  $(\beta^n)_t^o \in \Psi_C$ . Then at a given instance,

$$\text{Flexibility Insensitivity} = \zeta \left[ (\beta^n)_t^o, (\beta^n)_t \right] \quad (5)$$

if  $(\beta^n)_t^o \in \Psi_C$

If  $(\beta^n)_t^o \in \Psi_C$  then it represents the Inflexibility of the system.

Where  $\zeta$  is a function that estimates the deterioration in performance as a result of attaining  $(\beta^n)_t$  and not  $(\beta^n)_t^o$ . Flexibility insensitivity is more a measure of the ineffectiveness of the FMS control function than flexibility itself.

### 2.5 1 Measuring The Value of Flexibility

The objective of measuring the value of flexibility is to determine the following:

- . *How flexible the system is at present?*
- . *Whether additional flexibility is required?*
- . *Can we achieve better control?*

The above questions are not as simple as they sound. They have to be analysed in great depth in order to be able to provide a justified solution. For example in order to find out how flexible the system at any given time? there are a number of questions that need to be asked and information to be collected, such as, Is the system capable of overcoming a given set of changes due to the various factors both internal and external to the system? If the answer is yes then we can say that the system is flexible enough to overcome the given set of changes which may be defined. If the system is not capable of overcoming the changes, then we need to determine what additional resources are required to overcome these changes. As a result of which we can achieve better control of the system.

Another question often asked when determining measure for flexibility is to find out what to measure? i.e. change in operation, change in performance, or change in environment. It has been seen that the change in environment results in change in performance and operation, and hence there is no control over the environment. Therefore the ultimate component to measure is the change in performance.

A complete approach to help evaluate the value of flexibility has been outlined in figure 6. A list of all the anticipated changes and the objective are obtained then for each change, the value of flexibility is the expected utility of having the ability to respond to the changes. The next step involves identification of FMS components being affected with respect to each change. This is fairly straight forward after the changes have been classified. First, short-term changes is considered, we assume that the FMS is stable with respect to the change being considered because performance is all that matters in the short-time frame. In the medium-term changes sensitivity and stability must be considered. The situation is entirely different for long-term changes because the ability to respond to these changes might depend on factors such as the objective of the management, etc. A major bottle-neck in the rapid implementation of this approach is the dearth of performance



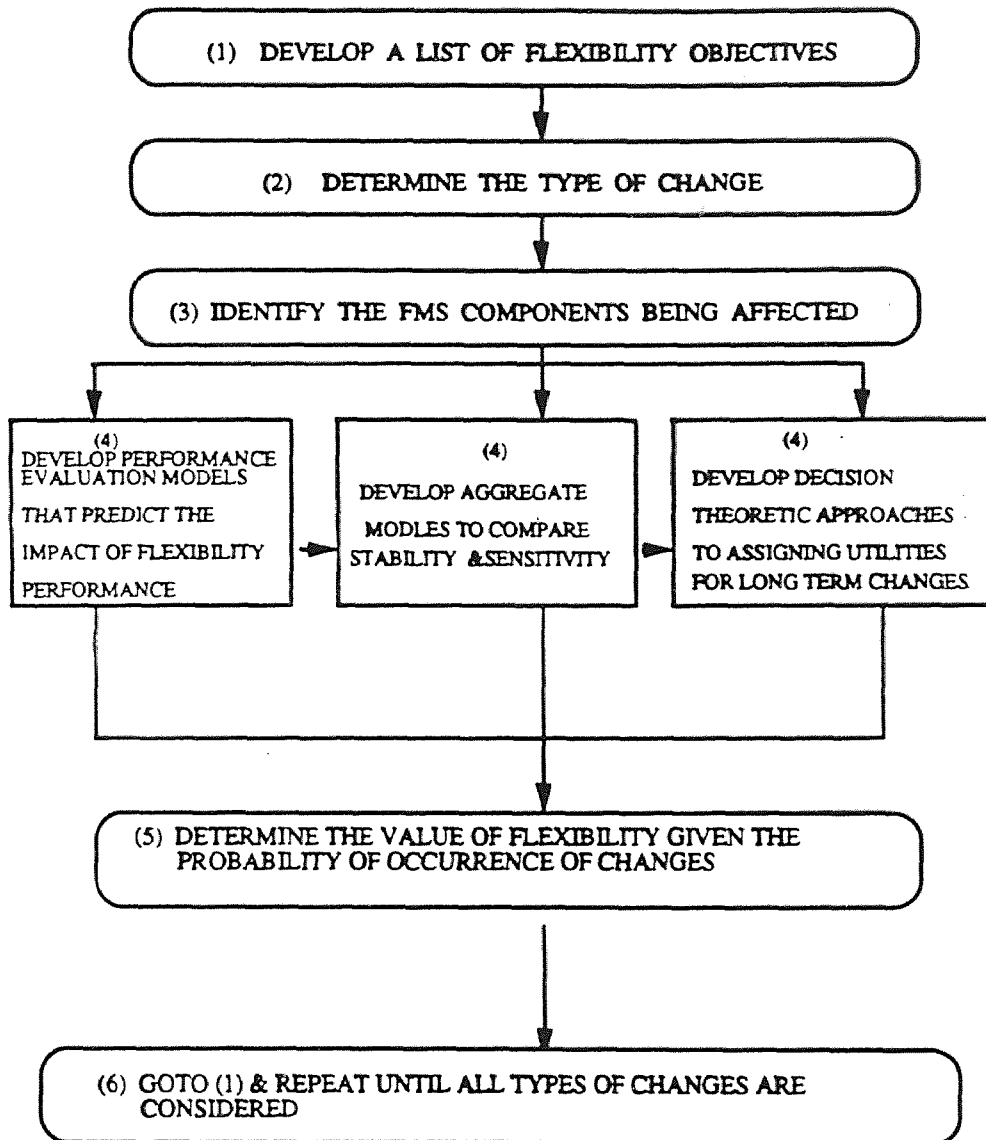


FIGURE 6 A Scheme for Measuring the Value of Flexibility

evaluation and aggregate models of step 4 in the figure. This approach is a means of presenting performance related benefits of flexibility to the managers and thus explicitly include considerations of flexibility in the decision criteria.

## 2.6 Need for Flexibility

A large group of manufacturing companies have requirements that make flexible manufacturing system desirable. Today's competitive world markets have caused several new challenges for manufactures. For many of these firms, the market's needs for product differentiation have resulted in widely diversified production requirements.

Flexible Manufacturing System (FMS) have been proposed as a means of gaining several advantages for production of diversified intermediate volume products. In order for a company deciding to implement flexibility there are a number of questions that should be answered accurately. They are as follows.

1. What Flexibility is appropriate?
2. How to obtain that Flexibility and to what extent?
3. What technology should be used?

In order to provide a satisfactory answer for the first question the management should be able to find out exactly what type of flexibility is required for the production system. This can be obtained by actually studying the system to see where exactly and what type of flexibility is required. For example, let us consider that the company has a poor routing flexibility. Questions such as if the number of routes are increased would it increase the machine utilization? If it does to what extent. What would be the additional cost to provide this flexibility? etc. The second question asks what is the method you are going to use to implement the required flexibility. Whether additional equipment is to be added to existing facility or to provide a new system, and to what extent. Though the later part of the question seems simple, it is the most difficult question to provide satisfactory answer. The main reason is because the management is not very sure of their capability and actuality of their systems.

### 2.6.1 Prerequisites for FMS

Up till now the production structure has been able to exist through development of relatively small incremental methods improvements within definable limits. However, recent advancements in product and production technologies and heightened worldwide competitive pressure have made it necessary for companies to fully automate production facilities as rapidly and completely as possible. Therefore, to become a low-cost producer by introducing FMS into the work place, a company must be able to satisfy these market-driven requirements:

- . Produce more different products.
- . Produce more variations of products.
- . Anticipate products will have longer life cycle
- . Reduce design time thus responsive to market.
- . Produce small Quantity with faster delivery turnaround.
- . Continually improve productivity.
- . Develop plans that will help long-term stability.
- . To meet these requirements, installation of a flexible manufacturing system must effect the following changes in the production facility:
  - . Automate production process
  - . Achieve flexibility of machine tools
  - . Integrate control of work-in-process materials
  - . Integrate computerized information system
  - . Integrate preventive maintenance

### 2.6.2 Problems Implementing FMS

While technological advances have been facilitating the development of successful FMS many of the more strategic problems still remain. Issues such as:

- . How does the FMS fit into the company's long-term manufacturing marketing strategy?
- . How should the FMS investment be justified?
- . How should the design and operation of the system be optimized?
- . How should the risks and costs associated with the development of control software be minimized?

- . How should multiple vendor's devices be interfaced into one integrated system?
- . How should components and processes be selected?

The answers to some of these questions lies in technologies such as computer simulation, group technology, broad based long-term planning and common sense. However, the issues of device integration and control software development are particularly interested since they are areas in which significant progress is likely to be seen during the next couple of years.

Installed FMS are growing in number and range of sophistication. FMS today is the focus of much attention in the engineering manufacturing world. One reason for this is that it offers a path to the unmanned system of the future.

### 2.6.3 Benefits of FMS

Flexible manufacturing systems are designed to fill the gap between high-production transfer lines and low-production NC machines.

**There are six major benefits of a flexible manufacturing system and they are as follows**

- . Increased labor productivity
- . Increased quality
- . Less scrap, rework
- . Increased production flexibility either by product design or production volume
- . Reduce operating costs
- . Higher machinery utilization

In addition to the above advantages the FMS provide better management control.

## 2.7 Summary

The literature makes one thing abundantly clear: Flexibility is a complex, multidimensional and hard to capture concept. At least 50 different terms of various types of flexibility can be found in the manufacturing literature. Manufacturing flexibility is generically defined as the system's ability to

respond to a dynamic situation quickly and inexpensively. Thus manufacturing flexibility clearly has major implications for a firm's competitive strength. This significant role of manufacturing flexibility makes it a part of the firm's strategy. By strategy here we mean " Set of plans and policies by which a company tries to gain advantage over its competitors.

## CHAPTER THREE

### SOLUTION CAPABILITIES OF FLEXIBILITY

#### 3.1 Classification of Changes

The motivation for our methodology by which flexibility necessarily measure are developed, is based on figure 1 of chapter 1. Clearly, as a consequence of the changes the facility experiences, certain undesirable effect or problems arise. Assuming these changes cannot be removed, then the purpose of flexibility is to enable the company to avoid the problems. Thus, the flexibility needs of a company are a function of the changes it experiences, the nature of its operations and the type of problems it anticipates. Our methodology is to first study the determinants of flexibility needs, and then to develop measures. To evaluate the value of flexibility of an FMS, it is first necessary to develop lists of all anticipated changes and the flexibility objectives. Changes should then be grouped into the three categories of short, medium, and long-term changes, depending on how frequently they occur, as mentioned by D Gupta and J.A. Buzacott.

##### 3.1.1 Short Term Changes

Short term changes may be effective for a period of few minutes to a few hours. Individually, each short-term changes affect the FMS less significantly than medium or long-term changes. Nonetheless, short-term changes occur very frequently and their collective action might cause significant production losses if the system does not respond effectively. The need for quick responses makes the mechanism of coping with short-term changes particularly suitable for automation.

Note that the term "short-term" could imply different time scale for different industries, depending on other parameters like the processing times. For example, short-term may mean a few hours for a machine shop, but only a few seconds for an electronic assembly operation. In other words, time scales are not absolute and have to be recognized as short, medium, or long with

respect to the other parameters of the system, that is, keeping in mind the relationships.

Examples of short-term changes are:

**1. *Changes in Demand:***

- a). Changes in the type of part being produced at a machine that requires no new set-up of the tool magazine, jigs, and fixtures.
- b). Change in Part mix at a machine.

**2. *Changes in Resource Availability***

- a). Machine or handling equipment failure
- b). Tool wear or failure.
- c). Variability of machining times.
- d). Contention among common users of a resource (bottlenecks), of raw materials, pallets, machines, materials handling equipment, and tools.

**3.1.2 Medium Term Changes**

Changes belonging to this category may have a time scale ranging from few days to few months. Examples of such changes are:

**1. *Changes in Demand***

Change in the demand for certain products where the production capacity and the long-term average demand do not change. Such changes may be caused by forecast errors or by market fluctuations.

**2. *Changes in Resource Availability***

Major machine or material handling equipment breakdowns.

**3.1.3 Long Term Changes**

As the name suggest, long term changes occur quite infrequently and may be effective over a period ranging from a few months to a few years. Examples of Long-term changes are:

**1. *Change in Demand***

- a). Introduction for new products.
- b). Discontinuation of product(s) currently being produced (obsolescence).

## 2. *Change in Resource Availability*

- a). Development of new raw materials.
- b). New developments in types of machine tools and production processes.

### 3.2 Problem Causes

Problem causes are factors that affect the manufacturing environment there by resulting in the disruption of the normal proceedings of the manufacturing system. These factors that affect the system could be both external or internal to the manufacturing system.

*Internal to the system* relates to factors such as machine failure, tool failure, etc. *External to the system* relates to factors such as changing customer requirements, availability of raw material, etc.

### 3.3 Types of Solutions

In order to rectify the problem causing factors there are two types of solutions. Namely:

- 1) *Normal solutions*
- 2) *Flexibility solutions*

#### 1) Normal Solutions:

Normal solutions tackles the problem on a day to day basis, that is as the problem arises. For example if a tool failure occurs, the process is stopped and the tool is changed before the process continues.

#### 2) Flexibility Solutions:

The objective of flexibility solutions is to benefit on a long term basis. For example if a tool failure occurs, the process is not stopped but the product is routed to a different machine while the tool is changed on the previous machine.

### 3.4 Factors Affecting Manufacturing System.

The factors can be classified based on whether they affect the system internal or external to the system. Figure 7 shows the use of flexibility to solve problems.



### 3.4.1 External Changes

- . Design changes.
- . Product obsolete
- . Increased demand.
- . Decreased demand
- . Availability of resources.
- . Non-availability of raw-materials.

External factors are factors that occur external to the system. These factors cannot be controlled as they are due to environmental changes.

### 3.4.2 Internal Changes

Internal changes are changes that occur within a manufacturing facility. These changes occur due to a number of reasons. Many of these changes can be solved and hence such changes can be controlled so that their occurrence can be minimized. The number of changes are very large and some of these changes are inter-related. Here we have list a few of the major changes that occur in a manufacturing facility.

- |                        |                         |
|------------------------|-------------------------|
| . M/C failure.         | . Tool failure.         |
| . Lead time.           | . Delivery time.        |
| . Tool change.         | . Product orientation.  |
| . Product quality.     | . Product fixture.      |
| . Flow time.           | . Maintenance.          |
| . Power failure.       | . Inspection & Gauging. |
| . Set-up time.         | . Queueing delay.       |
| . Work-in-process.     | . Station break downs   |
| . Rejects.             | . Reworks.              |
| . Improper scheduling. | . Product mix.          |
| . Line unbalance.      | . Material handling.    |
| . Worker error.        | . Processing delay.     |
| . Inventory.           | . Worker skill...       |

## 3.5 Definition of Problem Factor

Definition of the various problems that occur in a manufacturing environment.

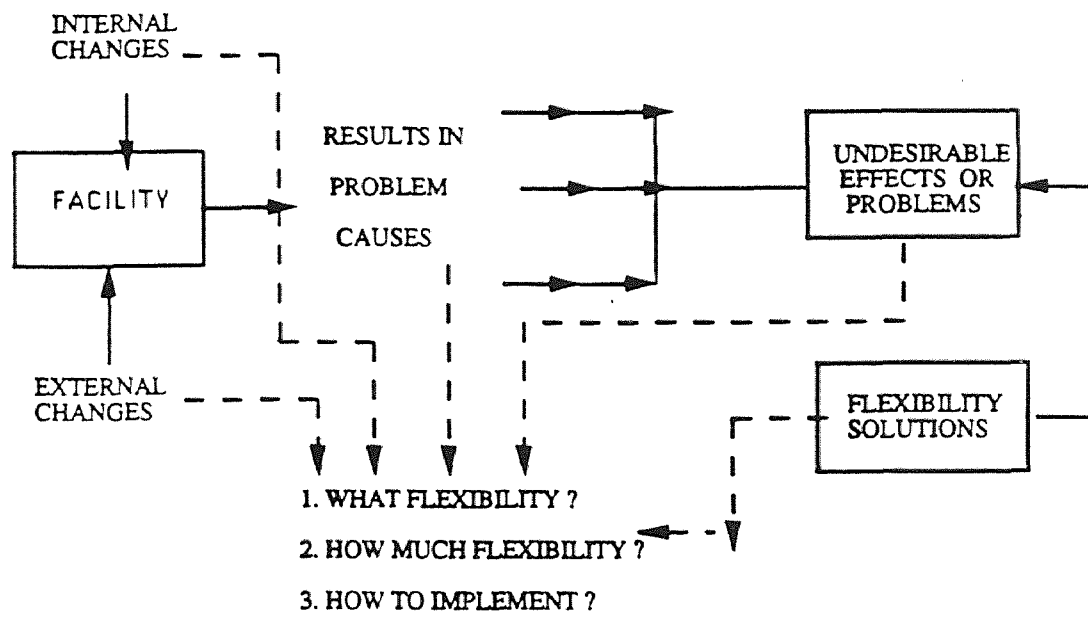


FIGURE 7 The Use of Flexibility to Solve Problems

**Failure:**

When an element of a system does not perform its intended function, then the element is said to have failed.

**1. Machine failure:**

Machine failure is said to have occurred when the machine sizes to perform the necessary function it is required to perform.

*Machine failure may occur due to the following reasons :*

1. Mechanical failure and breakdown.
2. Drive failure.
3. Control failure.

Intended function to provide an output.

**2. Tool failure:**

Tool failure is said to have occurred when the tool seizes to perform the necessary cutting operation which it is intended to perform.

*Tool failure may occur due to the following reasons:*

1. Poor tool material and design.
2. Due to improper feed and depth of cut specifications.
3. Machining a defective product (poor material).

**3. Power failure:**

The intended function of a power source is to drive a machine. If this is not so power failure is said to have occurred.

*Power failure is due to the following reasons:*

1. External supply fault.
2. Failure in the internal generating of power.

**4. Queueing delay:**

Queueing delay is said to have occurred when there is bottle neck at the machine center and also refers to the time lost due to the component waiting in the queue.

*Queueing delay can occur due to the following reasons:*

1. Randomness in process lines.
2. Unexpected failure of resources. (tool, of machine, due to inherent shortage in capacity).

#### 5. Material handling failure:

Material handling system is said to have failed when the system does not perform its function of moving the material between one point to the other.

*Material handling failure is said to occur because of the following reasons:*

1. Mechanical failure or breakdown.
2. Drive failure.
3. Control failure.

#### 6. Material failure:

When the material does not meet the intended purpose in terms of quality and composition the material is said to have failed.

*Material failure occurs because of the following :*

1. Direct and indirect.
2. Non-availability of right material

#### 7. Worker error:

Worker is said to have made an error if he performs a function either poorly or by accident.

*Worker error is caused due to the following reasons:*

1. Inadequate skill.
2. Monotony or fatigue.
3. Non-availability of skilled labor.

#### 8. Set-up and Fixture delay:

The above delay refers to the time lost due to the delayed setting up and fixture of either the component or tool or booth.

*Set up and Fixture delay occurs due to the following*

1. Worker is not skilled enough to perform in a specified time.
2. Tool may be complex or have design error.
3. Product is complex.

**9. Scheduling error:**

Scheduling error is said to have occurred when the product or the resources does not arrive at the predetermined place or at the scheduled time.

*The scheduling error may occur due to the following reasons.*

1. Ineffective scheduling technique.
2. Insufficient data to obtain efficient scheduling.

**10. Processing delay:**

Processing delay is said to have occurred when the time for performing a particular process has taken longer than the specified time for that particular process.

*Process delay occurs due to the following reason.*

1. Machine and tool failure, product failure or non-availability of resources.

**11. Design changes:**

Design changes can be defined as the change in attributes, characteristics or property of the products.

- a. Dimensions.
- b. Functions.
- c. Finish.

**12. Demand mix changes:**

Demand mix changes can be defined as the change in the ratio of products.

*Demand mix changes occurs because of the following reason:*

1. Change in customer needs.

**13. Volume changes:**

Refers to the change in quantity. Volume changes may be either that a product is in demand or in excess.

*Volume changes occur due to the following reasons.*

1. Increase or decrease in demand.
2. Product obsolete.

### 3.6 Analysis of Problem Factors

After having listed and defined the internal and external factors that affect a manufacturing facility, the next step is to narrow the list of all the factors that was provided so that a more concised list is obtained. The new list gives all the factors that frequently affect the manufacturing facility. Based on the new list a chart has been developed to relate the type of flexibility that could be a possible solution for each of the problem. This is shown in Table 3. This helps in determining whether a particular factor can be overcome by either machine, routing, product, process or volume flexibility. Let us consider one factor say machine failure, now this factor can be overcome if the machine was more flexible, ie. if the machine can perform the required task by another operation, as a result of which the process is not stopped completely and thereby loose production time.

The procedure followed to obtain this chart is as mentioned above. If a particular problem factor can be solved by any of the flexibilities it is marked as 'yes' denoted by (✓) or 'no' denoted by (X). In this case machine flexibility can overcome machine failure. Next consider routing flexibility, if a machine failure occurs and if we have routing flexibility than we can route the product to a different machine that can perform the same operation. On the other hand if we do not have routing flexibility and a machine failure occurs, we have to stop the operation and wait until the machine is repaired, during which period production time is lost. Hence we can conclude that machine failure can be solved if we have routing flexibility.

Next consider process flexibility, if machine failure occurs and if we have process flexibility, the product can be produced by a different process and hence we can say that machine failure can be overcome by process flexibility. This is represented by a (✓) mark in the chart.

Considering product flexibility and machine failure it can be said that machine failure cannot be overcome by product flexibility. Having product flexibility we can only introduce new products into the manufacturing system without major changes in the existing system. Similarly mix or volume flexibility cannot overcome the problem factor machine failure. Using the logic mentioned the Table 3 has been developed.

Problem causes	Machine	Routing	Process	Product	Volume
M/C failures	√	√	√	X	X
Tool failures	√	X	√	√	√
Lead time	√	√	√	X	X
Delivery time	√	X	√	X	X
Tool change	√	X	X	X	X
Product orientation	X	X	√	√	X
Product quality	√	X	√	X	X
Product fixturing	X	X	√	X	X
Flow time	√	X	√	X	X
Maintenance	√	X	√	X	√
Power failure	√	X	√	X	√
Inspection & gauging	X	X	√	X	X
Set up time	X	X	√		
Queueing delay	√	√	√	X	√
Work in process	√	√	√	X	√
Station break downs	√	√	X	X	√
Rejects	√	X	X	√	√
Reworks	√	X	X	√	√
Improper scheduling	X	√	X	X	X
Product mix	√	√	√	√	X
Line unbalance	√	√	X		
Material handling					
Worker error	√	X	X	√	X
Processing delays	√	X	√	X	√
Inventory	√	X	X	X	√
Worker skill	X	X	√	√	X

Table 3. Analysis of Problem Causes

### 3.6.1 Relationship between Flexibilities

Many of the problem causing factors cannot be directly overcome or solved by the various types of flexibilities. In order to overcome a few of the problem factors, two or more of different types of flexibilities must be combined together. Some of the problem factors that require more than one type of flexibility to overcome that factor is shown in figure 8.

For example, consider the factor machine failure. Machine failure can be overcome by having both machine flexibility and routing flexibility. If a product A is manufactured in machine M and if machine M. The product A can be manufactured by machine N since this machine is flexible. But this is possible only if there is routing flexibility so that the product can be sent to the machine N.

On a similar basis we have developed different relationship between the various flexibilities that are required to overcome the problem factors.

## 3.7 Arrow Analysis

Arrow analysis is a methodology which helps in trying to obtain a solution for a given problem by breaking down the problem into a number of factors thus simplifying the process to analyze the problem. It can be said that any problem is a result of a number of smaller problems. They occur in sequence of events.

### 3.7.1 M/C Flexibility Analysis

Arrow analysis for machine flexibility is shown in figure 8. This figure gives us some of the factors that can be overcome by machine flexibility and from where they originated. For example processing mix arises as a result of demand change and design change. Machine failure can be overcome by machine flexibility, this is only possible if there is routing flexibility. Similarly other factors that can be solved by machine flexibility is shown in the figure.

### 3.7.2 Routing Flexibility Analysis

Arrow analysis for routing flexibility is shown in figure 9. This figure gives us some of the factors that can be solved by routing flexibility. From the figure we see that if a machine failure occurs this results in queueing delays



## RELATIONSHIP

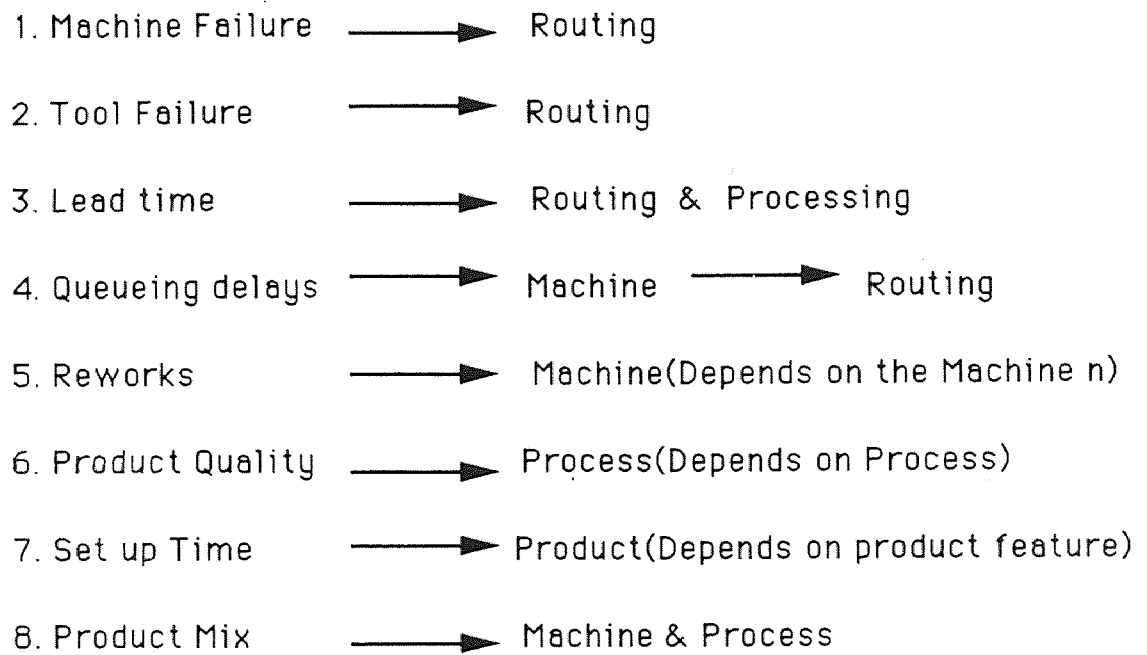


Figure 8. Causes For The Various Changes

## ARROW ANALYSIS

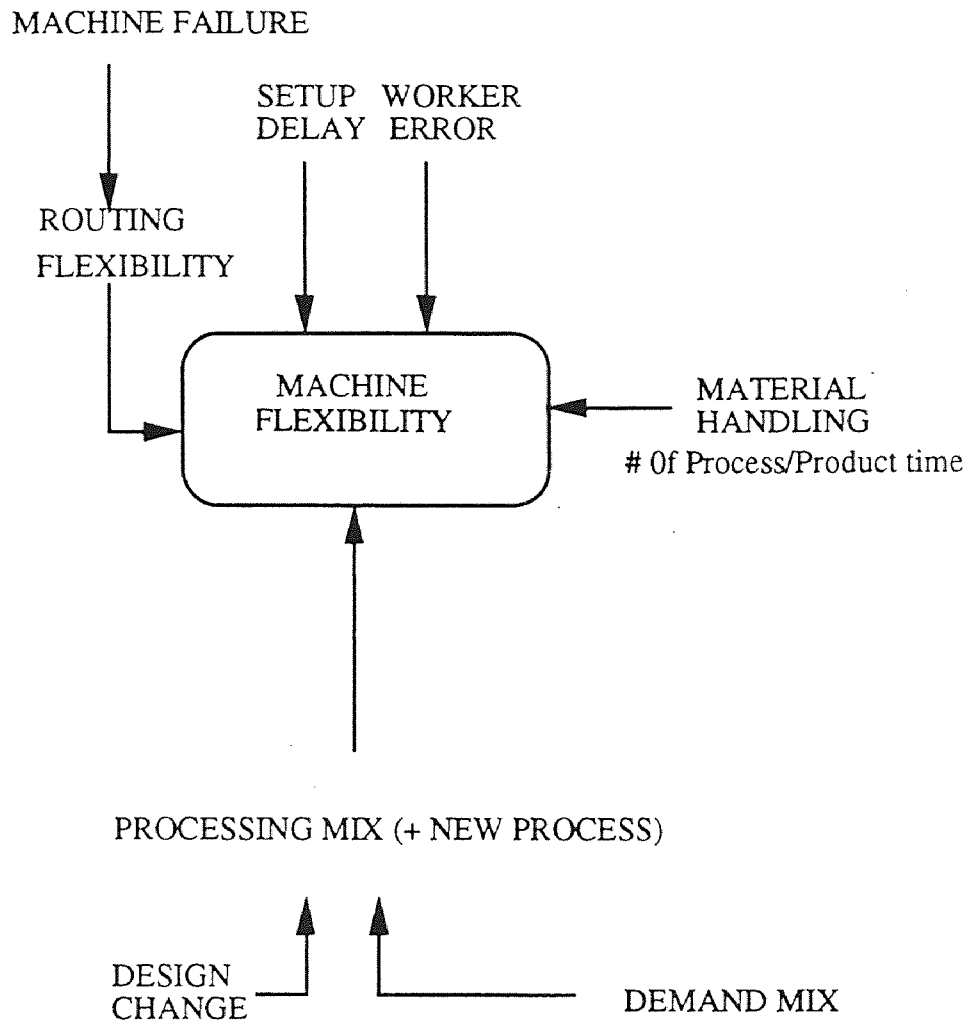


Figure 9. Machine Flexibility Arrow Analysis

## ARROW ANALYSIS

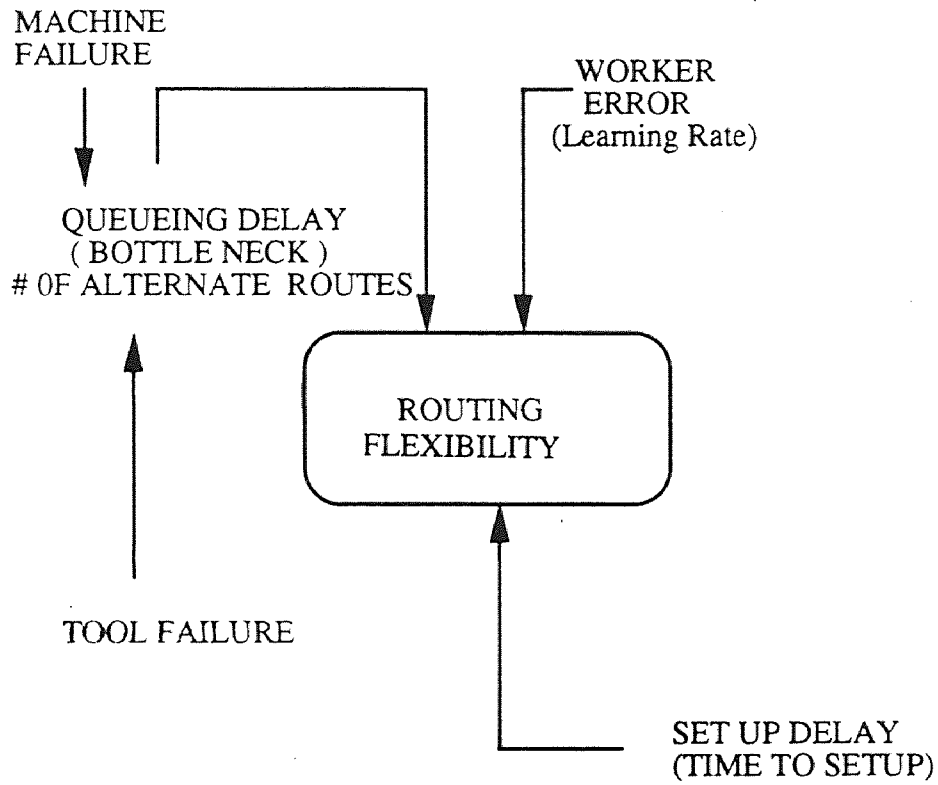


Figure 10. Routing Flexibility Arrow Analysis

i.e a bottle neck situation arises. Similarly in the case of tool failure, the products accumulate at the machine center thus resulting in a bottle neck. Similarly other factors that arise are shown in the figure.

### **3.7.3 Product Flexibility Analysis**

Figure 10 shows arrow analysis of product flexibility. As a result of market changes, new products are introduced and if we have product flexibility this can be overcome. Similarly cyclic product change results in competitive pressure.

### **3.7.4 Process Flexibility Analysis**

Figure 11 shows the arrow analysis for process flexibility. Any changes in the processing requirements can be determined by the degree of difficulty in terms of skills required in performing that operation. Similarly new products are introduced as a result of the market variation and these products require new process. If the facility has process flexibility then the above change can be overcome.

### **3.7.5 Mix Flexibility Analysis**

Figure 12 shows the arrow analysis for mix flexibility. We know that the product mix varies as a result of market requirements. If the facility has mix flexibility then the product variations can be met. Similarly the other factors that can be solved by mix flexibility is shown in the figure.

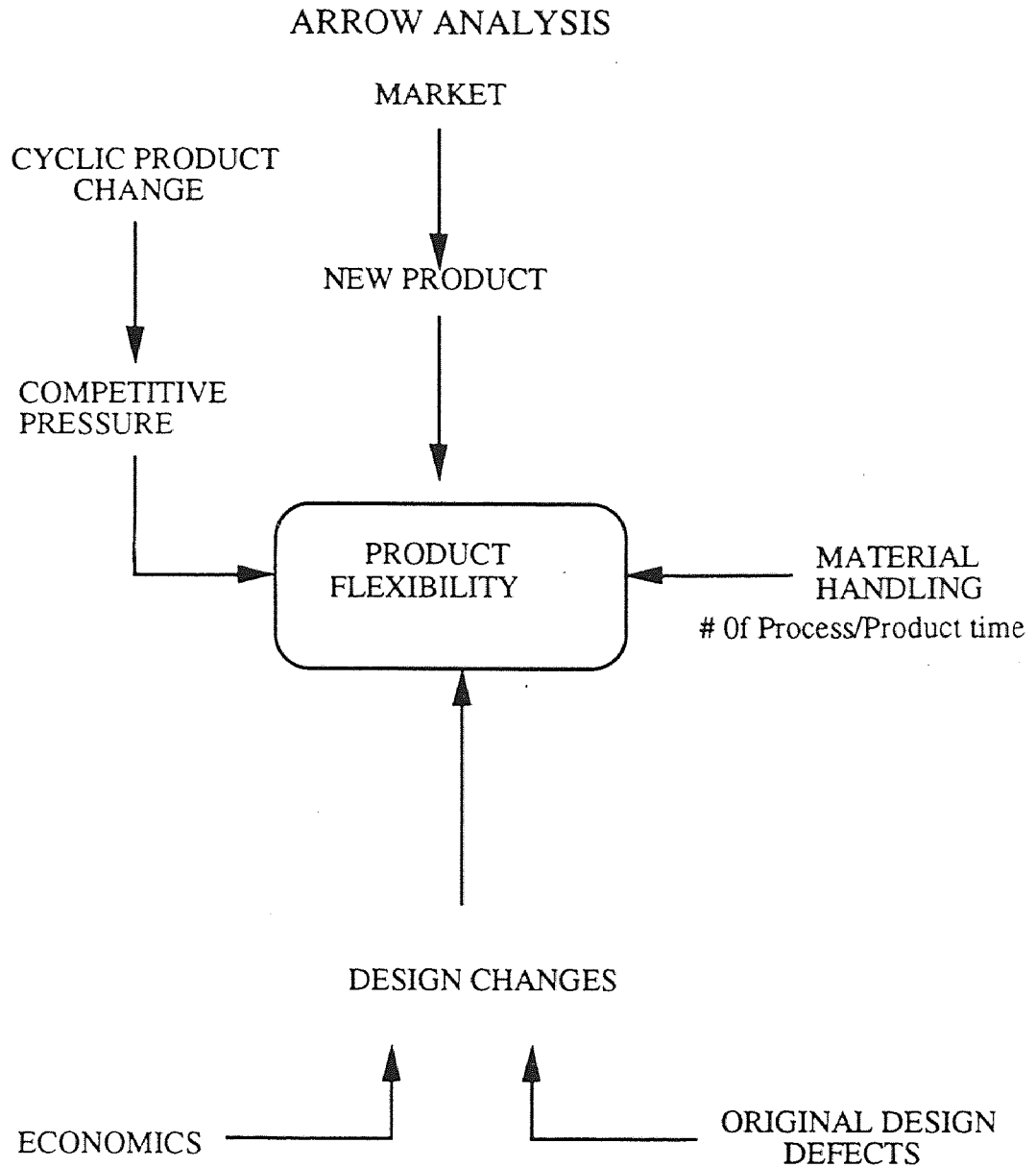


Figure 11. Product Flexibility Arrow Analysis

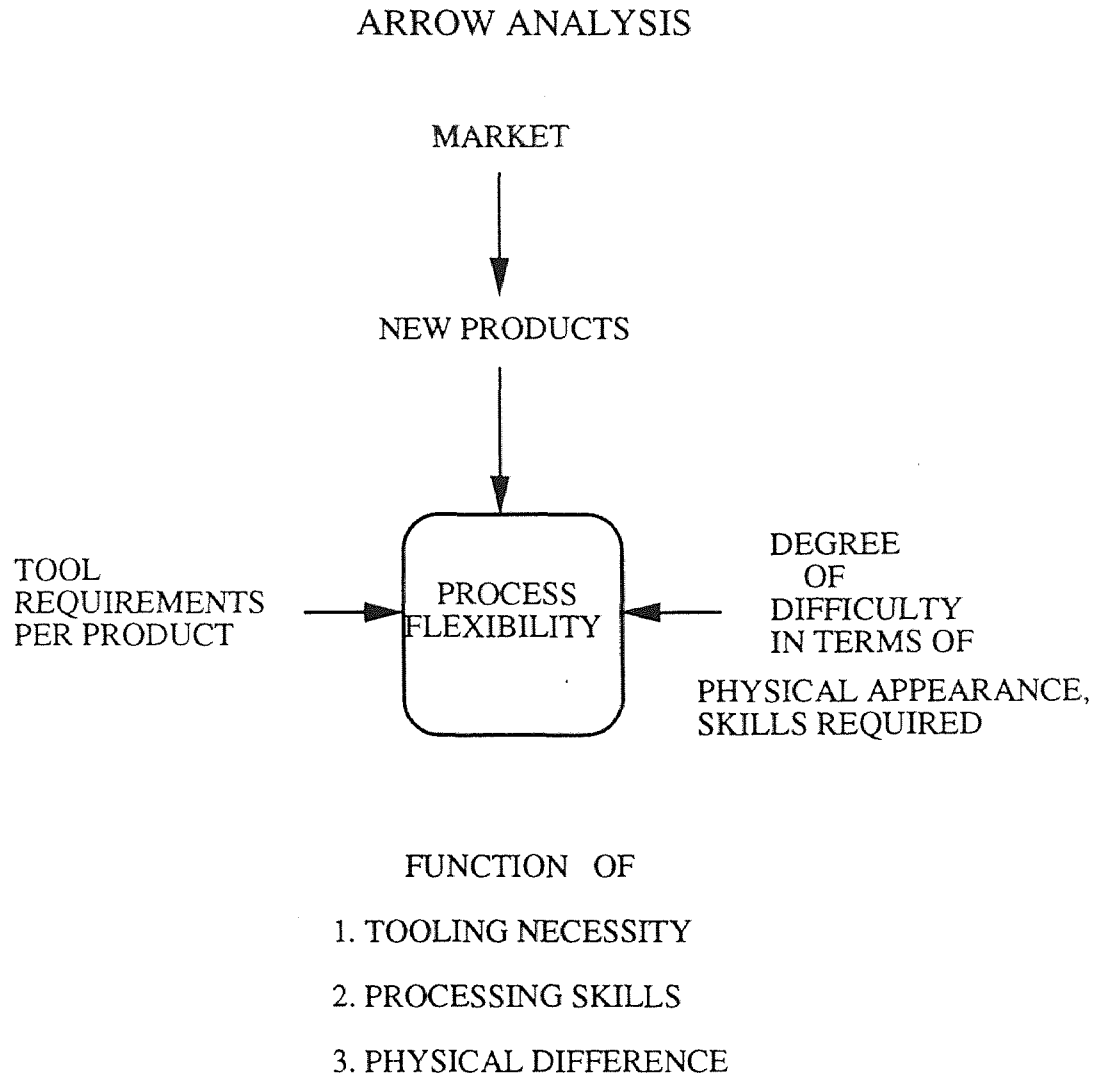


Figure 12. Process Flexibility Arrow Analysis

## ARROW ANALYSIS

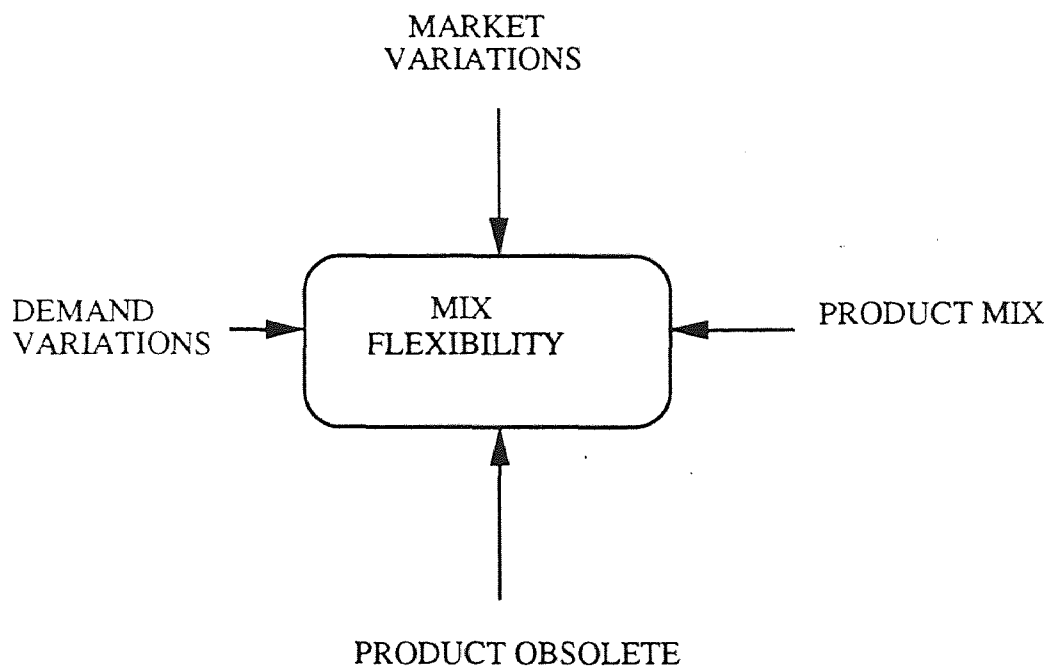


Figure 13. Mix Flexibility Arrow Analysis

## CHAPTER FOUR

### DEVELOPMENT OF NECESSITY MEASURES

#### 4.1 Importance of Necessity Measures

The objective of necessity measures is to determine the required flexibility in a manufacturing facility based on the given set of parameters, such as number of resources, type of resources, availability of resources, etc. The advantage of the necessity measures is to avoid investing on greater flexibility than the required flexibility or building the wrong flexibility. In this chapter we define necessity measures, their purpose, and their potential application. Measures are provided for each of the following flexibilities namely, Mix flexibility, Product flexibility, Process flexibility and Machine flexibility.

The hierarchical flexibility classification scheme proposed by Das (1990) is used as the basis for the development of necessity measures. Using the figure 1 of chapter 1, the classification scheme has been enhanced so as to determine the different types of changes that each flexibility can overcome.

From the figure we see that the market flexibility is primarily affected by external changes such as design changes, demand changes, product obsolete, availability of resources, etc. As a result of these factors the various components of the system are affected such as mix, product, routing, etc. In order for these components to overcome these changes they have to be flexible. The necessity measure will provide the required flexibility.

#### 4.2 Necessity Measure of Mix Flexibility

*Definition:* Gerwin (1982) defined Mix flexibility can be defined as the ability of the system to vary the product mix as per the demand requirements and operate profitably at all output levels.

*Purpose:* Every firm faces uncertainties in the demand quantity for each individual item that is manufactured. Mix flexibility permits the facility to



adjust production in different ratios within wide limits thereby allowing the firm to compete in a market where different ratios are frequently demanded.

*Means:* Mix flexibilities depends on the variety and the versatility of the machines that are available, the flexibility of the material handling system, and the factory information and control system.

*Necessity measures:* Any measure for mix flexibility is indicative of the range of product mixes that the facility can sustain, without experiencing considerable setup cost. Here we define as the vector of production ratios, such that the sum of the ratios equals one. As per the figure 1, it can be seen that mix flexibility is affected directly by only the market requirements and hence we assume that necessity measure can be obtained based on the market variation which occur as a result of various factors such as demand changes, design changes, etc. The measure should take into consideration the different types of product mixes the occur in the manufacturing facility under varying scenarios.

Let the following notation denote the variables associated with mix flexibility.

$F_{Mix_N}$	=	Necessity measure for mix flexibility.
$K$	=	1,-----, N an index for the products produced.
$S$	=	1,-----, M an index for the different mix scenarios the facility experiences.
$R_{K,S}$	=	Production ratio for product K in scenario S.

Note:

$$\sum_K R_{K,S} = 1$$

for all S

$P_S$  = Probability that scenario 'S' will be experienced by the facility.  
 Alternating  $P_S$  may be the percentage of time that scenario is prevalent.

Our intent is to make  $FMix_N$  indicative of the range of production ratio mixes the facility is anticipated to experience. Clearly the simplest measure for  $FMix_N$  is the number of scenarios it encountered. But this is an insufficient measure since scenarios may be quite similar or quite different from each other. Therefore the first step in deriving  $FMix_N$ , is to compute the difference between scenarios. Letting  $D_{S1,S2}$  denote the difference between two scenarios, then

$$D_{S1,S2} = \frac{\sum_{K=1}^N |R_{K1,S1} - R_{K2,S2}|}{2}$$

Observe that  $D_{S1,S2}$  is defined in the 0 to 1 range. In the extreme case where in each scenario only a single product is produced  $D_{S1,S2} = 0$ . Alternatively if both scenarios are identical, that is  $R_{k1s1} = R_{k1s2}$  for all  $K$ , then,  $D_{S1,S2} = 0$ . Since mix flexibility enables a facility to move from one set of production ratios to another.  $D_{S1,S2}$  is indicative of the extent of change the facility is expected to undergo.

Summing this expected change over all scenarios we get the necessity measure for mix flexibility that is

$$FMix_N = \sum_{S1=1}^N \sum_{\substack{S2=1 \\ S1=S2}}^N P_{S1} D_{S1,S2}$$

Observe that Mix Flexibility is upper bounded by  $M1$  and lower bounded by zero

### 4.3 Necessity Measure of Process Flexibility

*Definition:* Browne et.al. (1984) defined Process flexibility of a manufacturing systems as the ability of the system to produce a given set of parts in more than one way.

*Purposes:* The main purpose of process flexibility is to reduce batch sizes and reduce inventory costs. Process flexibility satisfies the strategic need of being simultaneously able to offer to customers a range of product lines.

*Means:* Process flexibility of a system derives from the flexibility of machines, operation flexibility of parts, and the flexibility of the material handling system composing the system.

*Measurements:* One measure is the average number of possible ways in which a part type can be processed in the given system (Browne et al, 1984; Jaikumar, 1986). The draw back of such a count is its inability to consider the range of differentiation between the products. Proth (1982) suggests measures which consider the range of product size and shape.

We shall define a production entity as a specific combination of machines, tools, skills, and other processes required to manufacture a product or a part of a product.

Where

$i = 1, \dots, R$  an index of production entities.

Let  $P_{i,K}$  = The amount of utilization time of entity  $i$  by product 'K'.

$V_K$  = Daily production volume of product K.

$T_i$  = Production time available of each unit of entity 'i'

$W_{i,\hat{i}}$  = Weighted difference between entities  $i, \hat{i}$ , which is specified in the range 0 to 1 range.

In the extreme case when the machine, tools, skills, and processing needs are completely different then  $W_{i,\hat{i}} = 1$

$$\text{Total requirement of entities } \hat{i} = \sum_K P_{i,k} V_k$$

$$\text{Required number of entities } \hat{i} = \frac{\sum_K P_{i,k} V_k}{T}$$

$$\text{Fractional requirements of entities } \hat{i} \quad F_i = \left\{ \frac{\sum_K P_{i,k} V_k}{T} \right\}$$

Therefore the necessity measure of process flexibility is given by :

$$CFI_{X_N} = \sum_{\hat{i}} \left[ \frac{1 - F_i \sum_{i, \neq \hat{i}} W_{i,\hat{i}}}{R-1} \right]$$

#### 4.4 Necessity Measure of Product Flexibility

*Definition:* Brown et.al (1984) defined Product flexibility as the ease with which new products can be added or substituted for existing products. It is also defined as the ease with which the part mix currently being produced can be changed inexpensively and rapidly.

*Purpose:* Product flexibility allows the company to be responsive to the market by enabling it to bring newly designed products quickly to the market. Since the future product designs are usually unknown, it becomes important to design and develop the production facility to be product flexible. Product flexibility along with a sophisticated computer-aided design capability provides the company with a formidable competitive weapon.

*Means:* Product flexibility depends on machine flexibility, material handling flexibility, efficient CAD/CAM interface, group technology, flexible fixtures, etc.

*Measurements:* Product flexibility can be measured by time or cost required to switch from one part mix to another. Similar to mix flexibility the product flexibility is also affected only by market variations. We know that the product undergoes a number design changes as a result of competition, better quality, etc.

Buzacott (1982) and Zelenovic (1982) propose that product flexibility be measured by the total effort, in cost and time, required to add a product. The drawback of this approach is its inability to differentiate between long and short cycle time facilities.

Sethi and Sethi (1990) observe that the set of candidate products to be added cannot be arbitrary. These products should not require a major setup effort, or significant tool and fixture fabrication.

We assume the set of candidate products be denoted by  $\Pi$  is known to the facility's manager. For the necessity measure we simply count the number of new products that need to be added form set  $\Pi$  per standard time.

Let

- G = Number of products in set  $\Pi$
- $S_{b/w}$  = Standard time interval between additions.
- T = Total time period.

$S_{b/w}$  will be dependent on the cycle time of the plant. It could possibly be set equal to the interval between expected additions.

Letting  $B_t$  be the number of new products added in each sub-period, then the necessity measure of product flexibility is given by

$$PFLX_{T,NEC} = \frac{S_b/w}{T} \sum_{t=1}^T B_t$$

The necessity measure of product flexibility will give the number of products that can be introduced into the system with any given set of conditions.

#### 4.6 Necessity Measure of Machine Flexibility

*Definition:* Machine flexibility of a machine refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another.

*Purposes:* The machine level provides the basic framework for flexibility. Software functions cannot help provide any extra flexibility, if the machine are hard and expensive to change. At its own level, machine flexibility allows lower batch sizes and resulting savings in inventory costs, higher machine utilization, production of complex parts, shorter lead times for new product introductions, and better product quality realizations in the face of random variations in input quality.

*Means:* Technological sources of machine flexibility are numerical control, easily accessible programs, rule-based languages, sophisticated part-loading, tool-changing devices to ensure changeability of work pieces and tools, size of tool magazine, etc.

*Measurement:* Machine flexibility can be measured by the number of different operations that a machine can perform without requiring more than a specified amount of effort.

Other reasons include the number of tools or the number of programs that the machine can use. Brill and Mandelbaum (1989) suggest a measure which considers the relative importance of the operations a machine performs, and the efficiency at which they are performed.

Let

- $i$  = 1, . . . ,  $N$  operations to be performed in the plant  
 $T$  = Time allotted for a given set of operations. Smallest scheduling window.  
 $X_j$  = Total time needed for operation  $i$  during  $T$ .

Then

$$\text{Maximum \# of dedicated Machines} = \sum_i \text{HI} \left[ \frac{X_i}{T} \right] = A$$

where HI is the operator that defines the next highest integer, and LI is the operator that defines the next lowest integer.

$$\text{Minimum \# of dedicated Machines} = \sum_i \text{LI} \left[ \frac{X_i}{T} \right] = B$$

Assuming the remaining machines must do all operations, then

$$\text{Number of Flexible machines} = \text{Hi} \left[ \frac{\sum_i X_i}{T} - B \right] = C$$

The necessity measure of machine flexibility is given by

$$\text{MFLX}_{\text{NEC}} = \frac{C N + B}{C + B}$$

The necessity measure of machine flexibility provides the number of machines required, given the set of operations and operation time for each operation.

## CHAPTER FIVE

### ILLUSTRATIVE EXAMPLES

Having derived the equations for the necessity measure the next step is to validate the equations. The factors affecting the flexibility have also been identified. It is important to validate the derived equations by experimentation. Experimentation with a full fledged manufacturing system might prove as a costly trial and virtually impractical for various reasons. This chapter illustrates the application of these measures with one example taking into consideration each of the measures individually.

#### 5.1 Mix Flexibility

Let G1, G2, G3, G4 & G5 be denoted by the product 1, 2, 3, 4 & 5. respectively.

Let S1, S2 & S3 denote the different scenarios.

Number of Products = 5

Number of Scenarios = 3

The ratio of different products in different time periods are given as follows:

#### CASE I

	S1	S2	S3
G1	10	25	5
G2	20	35	15
G3	20	10	30
G4	30	15	25
G5	20	15	25

The above table gives the ratio of product mix at different Scenarios



Occurrence of Scenario is given by 42%

Occurrence of Scenario is given by 45%

Occurrence of Scenario is given by 15%

The difference between any two scenarios is given by:

$$D_{S1,S2} = \frac{\sum_{K=1}^N |R_{K1,S1} - R_{K2,S2}|}{2}$$

$$D_{12} = \frac{15+15+10+15+5}{2} = 0,30$$

$$D_{13} = \frac{5+5+10+5+5}{2} = 0.15$$

$$D_{23} = \frac{20+20+20+10+10}{2} = 0.40$$

$$FMix_N = \sum_{S1=1}^N \sum_{S2=1}^N P_{S1} D_{S1,S2}$$

$$Mix Flex_{Nec} = S1[D_{12} + D_{13}] + S2[D_{12} + D_{23}] + S3[D_{13} + D_{23}]$$

$$= 0.45 (0.30+0.15) + 0.40 (0.30+0.40) + 0.15 (0.15+0.40)$$

$$= 0.562$$

Given the following constraints and product mix ratios such as the scenarios and their occurrence rate etc, the necessity measure of mix flexibility is 0.562. Thus the necessity measure will vary based on the scenarios under consideration. If the occurrence rate of the different scenarios are less than the value of the necessity measure of the mix flexibility will also be lower.

## 5.2 Product Flexibility

$G$  = Number of products in the set = 5

$S_{b/w}$  = Standard time interval between addition = 6 sub-periods

$T$  = 20 sub-periods

Time	T=3	T=6	T=10	T=14	T=17	T=19
Product	2&3	1	3&4	1&5	4&2	5&2

$$PFLX_{T,Nec} = \frac{S_{b/w}}{T} \sum_{t=1}^T B_t$$

$$PFLX \text{ Necessity} = [6 ( 2+1+2+2+2+2 )] / 20$$

$$= 3.30$$

Given the conditions that the various products are added to the manufacturing facility at different time intervals as shown in the table above. The necessity measure of product flexibility for the above given conditions was found to be 3 products.

### 5.3 Process Flexibility

Let us consider that the system has the following types of resources:

Number of Machines = 7

Number of Tools = 2 (A&B)

Type of Skills = A & B

Product Type = X & Y

Entities = 4

Entity i	Machine	skills	Tools	Product type	$W_{i,i}$			$W_{i,i}$	
					1	2	3	4	5
1	1	A	A	X	-	.3	-	1	.4
2	2	A	B	X	.3	-	.5	.9	.3
3	2	A	A	X	-	.5	-	.8	.6
4	3	B	A	Y	1	.9	.8	-	1

Let  $W_{i,i}$  = Weighted difference between two entities.

Let  $P_{i,k}$  = Utilization of entity i by product K.

i	$P_{i,k}$ k=1	$P_{i,k}$ k=2	$P_{i,k}$ k=3	$P_{i,k}$ k=4
1	0.25	0.42	0.17	0.21
2	0.12	0.38	0.13	0.19
3	0.47	0.51	0.30	0.11
4	0.31	0.73	0.27	0.17

The volume of the different products that are required at a given time interval are as follows

$$V_{k=1} = 70 \qquad V_{k=3} = 100$$

$$V_{k=2} = 130 \qquad V_{k=4} = 125$$

Total Requirements of entity i

$$\begin{aligned} \text{Entity 1} &= (0.25 \cdot 70) + (0.42 \cdot 130) + (0.17 \cdot 100) + (0.25 \cdot 125) \\ &= 17.5 + 54.6 + 100.7 + 26.25 \\ &= 199.05 \end{aligned}$$

$$\begin{aligned} \text{Entity 2} &= (0.12 \cdot 70) + (0.32 \cdot 130) + (0.13 \cdot 100) + (0.19 \cdot 125) \\ &= 8.4 + 41.6 + 13 + 23.75 \\ &= 86.75 \end{aligned}$$

$$\begin{aligned} \text{Entity 3} &= (0.47 \cdot 70) + (0.51 \cdot 130) + (0.30 \cdot 100) + (0.11 \cdot 125) \\ &= 32.9 + 66.3 + 30 + 13.75 \\ &= 142.95 \end{aligned}$$

$$\begin{aligned} \text{Entity 4} &= (0.31 \cdot 70) + (0.73 \cdot 130) + (0.27 \cdot 100) + (0.17 \cdot 125) \\ &= 21.7 + 94.9 + 27 + 21.25 \\ &= 164 \end{aligned}$$

Fractional requirements of entity i

$$\begin{aligned} \text{Entity 1} &= 199.04/240 \\ &= 0.83 \end{aligned}$$

$$\begin{aligned} \text{Entity 2} &= 86.75/240 \\ &= 0.36 \end{aligned}$$

$$\begin{aligned} \text{Entity 3} &= 142.92/240 \\ &= 0.59 \end{aligned}$$

$$\begin{aligned}\text{Entity 4} &= 164/240 \\ &= 0.67\end{aligned}$$

Therefore the Necessity measure of Process flexibility is given by

$$\begin{aligned}&= [(1-0.83) (0.3) + (1-0.36) (0.5) + (1-0.59) (0.9) + (1-0.67) (0.8)] / 3 \\ &= (0.051 + 0.32 + 0.37 + 0.27) / 3 \\ &= 0.34\end{aligned}$$

The necessity measure of process flexibility was found to be very sensitive and the accuracy of the measure is largely dependant on the choice of the individual system components and its attributes such as the weighted difference between the entities and processing time of different products on different machines.

#### 5.4 Machine Flexibility

$$\begin{aligned}\text{Number of Operations} &= 3 \\ \text{Smallest Window (T)} &= 2 \text{ hours} \\ \text{Time needed for operation } i \text{ during time T}\end{aligned}$$

$$X_{1,i} = 385 \text{ min}$$

$$X_{2,i} = 205 \text{ min}$$

$$X_{3,i} = 83 \text{ min}$$

$$\text{Maximum \# of dedicated Machines} = \sum_i H_i \left[ \frac{X_i}{T} \right] = A$$

$$\begin{aligned}\text{Max \# of dedicated Machines} = A &= \left[ H_i \left( \frac{385}{120} \right) + H_i \left( \frac{205}{120} \right) + H_i \left( \frac{83}{120} \right) \right] \\ &= 4 + 2 + 1 = 7\end{aligned}$$

$$\text{Minimum \# of dedicated Machines} = \sum_i L_i \left\lceil \frac{X_i}{T} \right\rceil = B$$

$$\begin{aligned} \text{Minimum \# of dedicated Machines} &= \left\lceil L_1 \left( \frac{385}{120} \right) + L_2 \left( \frac{205}{120} \right) + L_3 \left( \frac{83}{120} \right) \right\rceil \\ &= 3 + 1 + 0 = 4 \end{aligned}$$

$$\text{Number of Flexible machines} = H_i \left[ \frac{\sum_i X_i}{T} - B \right] = C$$

$$\begin{aligned} \# \text{ of Flex} &= H_i \left[ \frac{385 + 205 + 83}{120} - 4 \right] \\ &= H_i [5.6 - 4] = 2 \end{aligned}$$

$$\text{Therefore } MFLX_{NEC} = \frac{CN + B}{C + B}$$

$$MFLex_{nec} = \left[ \frac{2(3) + 4}{(2 + 4)} \right] = \frac{10}{6} = 1.67$$

A Plant manager has two options in setting up the facility. First, to provide a dedicated machine and hence pay the price of under utilization. Or second, to have B dedicated machines and access the remaining capacity from a flexible machine.

## CHAPTER SIX

### CONCLUSION AND SUMMARY

In this thesis, we have surveyed the relevant literature dealing with the concept of manufacturing flexibility. Because of the multidimensionality of this concept, several different types of flexibilities have been defined in the literature. Definitions of some of these flexibilities are provided since they are considered to be important, in order to clarify and to survey the literature.

Various operational or raw measures are described since operational measures help manufacturing managers to understand the kind and extent of flexibility embedded in their production process and allow them to make informal judgement on new equipment.

The experiments and the results from the experiments give number of insights into the effects of manufacturing flexibility. Apart from the actual results obtained from the experiments the following conclusions can be drawn.

Mix and Process flexibility measures were found to be very sensitive to the system components and its attributes. These measures have the interesting property that the value of the necessity measure varies significantly with the introduction of new or additional components and attributes such as the various resources that form the system; thus there needs to be some careful interpretation of these measures before they are used in practice.

Product and machine flexibility were found to be less sensitive. The measure used for our flexibility study are simple and operational. The result obtained by employing the measures are reasonable. These can be employed for further studies in this area. Different necessity measures can be defined and derived by taking into consideration different sets of constraints and variables.

This thesis is intended to promote discussion and thought about measures of flexibility in manufacturing systems. We have defined measures of flexibility to correspond to machine doing or participating in tasks within a production environment. These measures are intended to be used by a decision maker in support of choosing a manufacturing system, set of machines, products to produce, or adding a machine to an existing production system, or designing a machine for a particular industry, etc.



## REFERENCES

- Chatterjee, A., Cohen, M.A., Maxwell, W.C., and Miller, L.W. (1984), "Manufacturing Flexibility : Models and Measurement." *Procs of the ORSA/TIMS Special Interest Conf.*, pp. 49-64.
- Das, Sanchoy K. (1989). "Design and Measurement of Flexibility Manufacturing Systems." *Proceedings of IIE Conference*, Nov. 1989.
- Gupta and Buzacott (1989), "A Framework for Understanding Flexibility of Manufacturing Systems." *Journal of Manufacturing Systems*, vol.8(2), pp89-99.
- Malek, Abdel and Carl Wolf (1990), "Evaluating Flexibility of Alternative FMS Designs - A Comparative Approach." *Sixth Internal Working Seminar on Production Economics*, Igls, Austria.
- Jaikumar, R. (1984), "Flexible Manufacturing Systems: A Managerial Perspective," *Harvard Business School*.
- Son, Young Kyu and Park, Chan S., (1987), "Economic Measures of Productivity, Quality, and Flexibility in Advanced Manufacturing Systems." *Journal of Manufacturing Systems*, vol. 6(3).
- Suri, Rajan and Whitney, C.K. (1984), "Decision Support Requirements in Flexible Manufacturing." *Journal of Manufacturing Systems*, Vol. 3(1).
- Swamidas, Paul M. (1986), "Competing with Manufacturing Flexibility" *Working Papers*, Indiana University, School of Business.