12-1993

An Experimental Study into the Role of Routing Flexibility in the Justification of Advanced Manufacturing Systems

Sanjay Pathak

AN EXPERIMENTAL STUDY INTO THE ROLE OF ROUTING FLEXIBILITY IN THE JUSTIFICATION OF ADVANCED MANUFACTURING SYSTEMS

by

Sanjay Pathak

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Industrial Engineering

Western Michigan University
Kalamazoo, Michigan
December 1993

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to my thesis advisor and committee chairperson, Dr. Tarun Gupta. I also wish to offer my appreciation to the other members of my committee, Dr. Frank Wolf and Dr. Bob White. Last, but not least, I thank all those who have helped me directly or indirectly in completing this research.

Sanjay Pathak

AN EXPERIMENTAL STUDY INTO THE ROLE OF ROUTING FLEXIBILITY IN THE JUSTIFICATION OF ADVANCED MANUFACTURING SYSTEMS

Sanjay Pathak, M.S.

Western Michigan University, 1993

Increased competition in manufacturing has focussed attention on advanced technologies. These costly technologies lead to difficulty in purchase justification using traditional methods. New methods quantify attributes relating to the flexibility of advanced systems. One such attribute is routing flexibility.

This thesis presents results of experiments into evaluation of routing flexibility. The performance of conventional dedicated machinery when compared with that of machines having routing flexibility indicates an advantage of flexible machinery. The thesis indicates a procedure for evaluation of different flexibilities and their comparison with conventional machinery in reality.

An empirical formula is developed that helps in quantifying routing flexibility and thus in the process of justification. This research opens other avenues for developing similar quantification procedures for other forms of flexibilities associated with advanced manufacturing equipment.

TABLE OF CONTENTS

LIST OF TABLES

List of Tables - Continued

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The nature of research on the justification of flexible manufacturing systems and advanced manufacturing technologies is difficult to understand within the confines of any one specific discipline. Material on the subject is scattered throughout the literature in a variety of journals. More than three hundred articles in more than a hundred literature sources have been cited in various bibliographies, [Son, 1992].

Basically, the need to improve manufacturing competitiveness in global markets, as characterized by the attributes of greater complexity and diversity makes many companies consider making investments in advanced manufacturing technology. Modern automation techniques and their implementation offer the promise of a wide range of advantages and associated benefits; however, integration and implementation have not registered the rate of success anticipated.

New technology justification studies have failed to include all relevant attributes and qualities of flexibility. Furthermore, the literature is rife with complex and wordy mathematical techniques whose application is limited by computational complexity and implementation difficulties.

World manufacturing made great strides during the 1940s and 1950s due to the presence of a new emerging market of free economies and the ensuing manufacturing boom that took place. However, due to short-term financial tendencies western corporate decision makers were more interested in the bottom line with accompanying flourishes of flamboyant drifts in company policies that initially emphasized mass-production techniques, then marketing and finally financial jugglery. The associated plethora of acquisitions, mergers and such-like dissipated behavior distracted companies from their avowed mandates of manufacturing and related core activities. Things worsened as a result of the corresponding lack of investment in new equipment, manufacturing technology and allied activities [Naik and Chakravarty, 1992].

Unfortunately, within the world economy there were pockets of activity that were increasing their production capabilities due to rising competitive pressures, and these economies imposed their own competitive pressures on the western economies. There was a resulting shift from the religion of mass-production to that of the production of a greater variety of custom-made products with shorter and truncated product life cycles. The conclusion after the dust has settled is that one factor of significance in the resulting scenario is the sensible acquisition of production capabilities that will lower manufacturing costs for smaller batch sizes with a greater product-mix complexity, both having consistent and correspondingly required increases in product quality. Product development and time-to-market cycle times have also shortened and continue to do so.

Experience has indicated that companies that have attained success in harnessing the benefits of computer integrated manufacturing are precisely those companies that have succeeded in introducing and adapting new technology with state-of-the-art capital acquisitions. A basic strategy of such companies has been the utilization of a combination of techniques that involve accounting and quantifying methods with appropriate factory modeling and such. The impact of different technologies on existing and proposed factory environments can be predicted to a certain degree of accuracy leading to a greater understanding of the situation.

The number of companies that have experienced success is, however, numerically very small when compared with the scope that exists in today's manufacturing environment for automation and modern practice. This does not mean that mere automation will solve the problems associated with asserting one's competitiveness; most organizations have experienced disappointing returns from automation as a result of poor planning and mainly unrealistic expectations. One reason for this is that the biggest hurdle faced by such organizations is that major capital equipment acquisitions present a series of unique challenges. These investments are more complex, much greater in magnitude and have longer implementation periods when compared to traditional capital expenditures. As an example industrial grade stand-alone robots can easily cost up to a million dollars. Investments in fully automated factories such as the IBM Proprinter facility cost more than a hundred million dollars [Discenza and Gurney, 1990].

Traditional cost accounting and other purchase justification methods do not, however, support investment in advanced manufacturing technology. The published literature blames the problem on the inability of accounting systems to quantify and formally consider so-called intangible benefits; other writings point out the shortcomings of contemporary and allegedly outmoded cost accounting systems that inhibit the use of relevant, but often unconventional measures of performance. These traditional methodologies when used in conjunction with the high hurdle (minimum attractive) rates that are prevalent in today's uncertain and capital-scarce environment often result in the rejection of proposed high technology equipment and systems.

A significant section of writers have gone so far as to totally discredit attempts to justify modern automation through traditional capital budgeting evaluation procedures. In the midst of this debate, manufacturing has been the sufferer. What were typically successful manufacturing plants associated with large companies with guaranteed markets for their goods are now but a shadow of their past strong selves. They contain machinery and capital equipment that was purchased within a series of annual budgeting constraints rather than a manufacturing system tuned to the needs of its customers [Burstein and Graham, 1990].

Even today, the number of companies that have successfully automated or implemented flexible manufacturing systems is very small. There are several reasons for this, companies have made bad investment decisions; they have invested in a wrong selection of portfolio i.e. machinery. There is not enough company-wide co-operation and support for advanced manufacturing machinery and techniques before, during and after the said machinery has been purchased. Also, the investment justification process has not been revised to adequately account for the opportunities offered by new technologies. Finally, implementation after the purchase decision has been carried out is not done properly by which is meant that intra-company follow-up procedures so essential after the installation of new capital equipment are not carried out satisfactorily.

The problem is exacerbated by the fact that it is very difficult to reduce company manufacturing objectives and product attributes down to quantifiable, tangible, and universally common parameters. Each organization thus has its own set of parameters that define its set of operations, plant factors and line of business. What is perhaps more common is the set of tools that could be drawn upon in the analysis and arrival of some tangible understanding of the link between the need for flexible machinery and the above-mentioned parameters.

Table 1. gives a brief idea of the benefits accruing due to various flexible system attributes. Thus there are a variety of benefits attributable to certain system parameters. Clearly any analysis or quantification of the justification process must involve some quantified estimation of some of the benefits indicated in Table 1. Thus the cumulative benefits accruing due to a flexible manufacturing system can be arrived at. In this thesis, a methodology for the estimation of flexibility due to

routing is developed. The method strives to be simple in essence and comprehension. Its primary aim is to have a utilitarian worth. Use is demonstrated of commercially available simulation software for the purposes of analysis. Finally, the results obtained are aimed at a simple demonstration of the benefits of routing flexibility.

This thesis is organized logically. It starts off with a brief literature review, then discusses the characteristics of flexible manufacturing systems. A discussion on methods of economic justification follows with a chapter on the use of simulation techniques in the justification process. A methodology of experimentation is evolved and finally, there is a presentation and discussion of the experimental results.

Table 1

System Attributes Versus Benefits

BENEFITS / ATTRIBUTES	ROUTING FLEXIBILITY	LARGE NO. OF PRODUCT DESIGNS	VARIABLE BATCH SIZE	LOW SET-UP TIME	LOW MATERIAL MOVEMENT TIME
REDUCED DIRECT LABOR	Y	?	?	Y	Y
REDUCED SUPPORT LABOR	Y	?	?	Y	Y
FASTER RESPONSE TO MARKET CHANGES	Y	Y	Y	Y	Y
MANUFACTURING CYCLE TIME	Y	Y	Y	Y	Y
IMPROVED PRODUCT QUALITY	?	?	?	?	?
WIDE PRODUCT RANGE	Y	Y	Y	Y	Y
REDUCED SCRAP AND REWORK	?	?	?	?	?
FUTURE OPTIONS	Y	Y	Y	Y	Y

Table 1 - Continued

BENEFITS \ ATTRIBUTES	EFFICIENT QUALITY INSPECTION	QUICK DESIGN MODIFICATION	LOW TOOL CHANGE TIME	EFFICIENT STORAGE & RETRIEVAL	EFFICIENT INFORMATION HANDLING
REDUCED DIRECT LABOR	Y	Y	Y	Y	Y
REDUCED SUPPORT LABOR	Y	Y	Y	Y	Y
FASTER RESPONSE TO MARKET CHANGES	Y	Y	Y	Y	Y
MANUFACTURING CYCLE TIME	Y	Y	Y	Y	Y
IMPROVED PRODUCT QUALITY	Y	?	?	?	Y
WIDE PRODUCT RANGE	Y	Y	Y	Y	Y
REDUCED SCRAP AND REWORK	Y	Y	?	?	Y
FUTURE OPTIONS	Y	Y	Y	Y	Y

CHAPTER II

LITERATURE REVIEW

As discussed before, the literature on the subject of justification of flexible manufacturing systems is vast. The subject is touched upon in different disciplines such as Accounting, Engineering Economy, Finance, and Manufacturing to name but a few. The methods presented for justification range from the analysis of simple mathematical models to very complex graph theory derivations.

Included in the bibliography are several articles that were consulted for obtaining a brief but deep understanding of the subject from as wide a viewpoint as possible.

The approaches presented are as varied as are the backgrounds of the authors of the different works. The limitations of the more esoteric and highly theoretical presentations is their applicability to a small, microscopic point of view. This is because of the vagueness of the word flexible. With respect to manufacturing the term flexibility can take on many different meanings. Many authors writing in the accounting field have stressed the linkage of investment opportunities towards meeting company goals [Engwall, 1988]. The formulation of decision models is emphasised and stressed. These decision models consist of multiple attributes which are evaluated, weighted and for each alternative under consideration, compiled. Comparative evaluation of each alternative is the next step.

Operations Management specialists have strived to push forward the view that strategic benefits are paramount and outline processes that identify distinctive competences at the plant level that would allow the meeting of present market conditions as well as future needs [Burstein & Graham, 1990].

Those authors with a mathematical inclination, and there are several, insist on foisting values upon flexibility in relation to well-defined parameters of the manufacturing scenario [Hutchinson & Sinha, 1989]. In their zeal to outdo other previously derived mathematical mumbo-jumbo these relationships are either long-winded pompous attempts at mathematical showmanship or are simplified to such an extent that they are utterly unrealistic and would be applicable to operations at only a hypothetical level.

There are attempts made at lumping the different types of flexibility available from advanced manufacturing equipment and evaluating a measure for different such systems that allows systematic comparison [Abdel-Malek & Wolf, 1991]. Others in an attempt to keep things simple yet meet some sort of respectability as regards credibility have dissected the aspect of technology acquisition to new previously uncharted depths. In particular, evaluation procedures have been laid down that establish hierarchical levels of a high order and then develop methodologies for overall comparison using analytical hierarchy process methods [Naik & Chakravarty, 1992].

Routing flexibility as considered by this thesis has hardly been addressed in the literature. There are some exceptions, however. The effects of routing on scheduling, order release and MRP are looked at with results indicating cost-benefit trade-off implications [Ghosh & Gaimon, 1992]. The mathematical abilities required of someone from the corporate world would, unfortunately, result in such documents gathering dust in some obscure table drawer.

Other commentators on the justification scene have pointed out the importance of intangible benefits, those that escape quantification in simple terms [Discenza & Gurney, 1990]. There is a crucial need to be able to quantify the intangibles such that they make their contributions count in the overall justification scenario. This is definitely a serious problem and notwithstanding major attempts to quantify the cost of quality, quality is still unquantified in most well-run companies. Its benefits with respect to the introduction of advanced manufacturing equipment still await the serious touch.

This thesis attempts to apply simple tools and simple, yet rigorous thinking to the modeling of equipment, both conventional and advanced, in a simple, easy to comprehend manner. Having understood the limitations of the methods espoused in the bibliography, this author is convinced of the need to bring together a variety of tools available in the marketplace that have inherent utility in the corporate world and leave aside esoteric mathematical practice within the bounds of obscure journals and the like.

Though the literature has applications of simulation addressing the subject of flexible manufacturing systems in general, simulation being used as a tool in the justification process via comparison of flexibility attributes such as routing is barely touched upon. This author was unable to locate any specific articles in the established literature on justification.

In summary, the literature consists of articles that describe methods that attempt to quantify various individual attributes and benefits of flexibility with, however, a limited applicability.

CHAPTER III

CHARACTERISTICS OF FLEXIBLE MANUFACTURING SYSTEMS

The term Flexible Manufacturing System (FMS), appears with consistent regularity in the literature. The definition of FMS is not something definite! In fact, there are a number of ways in which the term is defined in the literature; by describing equipment components, by describing operating strategies and by describing system behavior.

These methods of definition are apparent if one looks at the following different characteristics of flexibility:

1. Machine Flexibility: the ability to change tools in a tool magazine, assemble or mount a variety of fixtures, without human intervention or long set-up times. This also allows these machines to be used for a variety of operations.

2. Process Flexibility: the ability to vary the steps necessary to complete a task. This allows several different tasks to be completed in the same system using a variety of machines.

3. Product Flexibility: the ability to change over to produce a new product, within the defined part spec-

trum, economically and quickly.

4. Routing Flexibility: the ability to vary machine visitation sequences, for example in the case of break-downs, and to continue producing the given set of part types. This exists when there are several viable process-ing routes or when each operation can be performed on more than one machine.

5. Volume Flexibility: the ability to operate an FMS profitably at different production volumes.

6. Expansion Flexibility: the capability of building a system and expanding it as needed, easily and modular-ly.

These characteristics, when implemented, yield a system which has the following operational behavior:

1. A variety of parts can be produced by simple changes at software level.

2. Material Handling and queuing times can be re-duced by the use of machine centers since these centers can do multiple operations on a work piece.

3. Set-up times can be reduced by the use of quick change tooling mechanisms.

4. The effect of breakdowns can be reduced by re-routing work pieces to available machines.

Every FMS consists of similar components, but the specific number and types of machines, tooling and handling devices can be quite different. It is apparent that flexibility will be a hard thing to define considering the definitions we have above. Since different types of flexibility exist will one system having one type of flexibility be more flexible than another having a different type? Is there a common point of consideration or comparison? The literature has attempted to quantify different types of flexibility with limited success. The main limitation appears to be the prevalence of these different types of flexibility which demands the exact, initial specification of the types of systems being considered and only these being considered in the complete process of attempted quantification. This implies a lack of ability to formulate mathematically exact relationships that can be applied across the board to all possible known flexible systems. This limitation has, however, not affected the literature in its ability to define different types of generic flexible manufacturing systems, namely:

1. Flexible Machining Cells: the simplest, most flexible type of FMS is a Flexible Machining Cell (FMC). It consists of one general purpose CNC machine tool interfaced with an automated material handling device, which provides raw castings or semi-finished parts from an input buffer for machining, loads and unloads the

machine tool, and transports the finished work pieces to an output buffer for final removal to the next destination. A robot or pallet changer is sometimes used to load and unload.

2. Flexible Machining System: this type of FMS usually has real-time , on-line control of part production. It should allow several routes for parts, with small volume production of each, and consists of FMCs with different types of general-purpose metal-removing machine tools. Important characteristics include high machine flexibility, along with process and routing flexibility.

3. Flexible Transfer Line: for all part types each operation is assigned to and performed on only one machine. This results in a fixed routing for each part through the system. The material handling device is usually a carousel or a conveyor. The storage area is usually local and between each machine. This type of FMS is less process flexible and less capable of automatically handling breakdowns.

4. Flexible Transfer Multi-line: this consists of multiple interconnected flexible transfer line type FMSs. This duplication does not increase process flexibility. The main advantage is the redundancy that it provides in a breakdown situation resulting in an increase in its

routing flexibility.

Thus we can say that the flexibility of a manufacturing system can be basically defined as a measure of its capacity to adapt to changing environments, conditions and process requirements. It is apparent also that every type of FMS is composed of similar components but the number and types of machine tools may differ largely determined by the type of industry being operated in. The level of desired flexibility is an important strategic decision in the planning, justification and implementation of an FMS. The first question that comes up is that of quantifying or deciding upon the extent of flexibility desired. This will determine the capability of the system to adapt to changing environmental and system considerations along with process requirements; these would include variations in product design, product mix and demand patterns. The crux of the matter is to ensure that these demands and considerations fall well within the determined limits and specifications of the FMS in mind.

For example, is the system flexible enough to take action to meet new circumstances? If production volumes change on a monthly basis is it still economical to run a particular FMS at its usual volumes? It is important that the flexibility of such an FMS be defined at all times in its projected life-cycle. Thus one can fully appreciate the importance of the decision that is to be made. The key issues are the design of a system which is flexible i.e. adaptable over the long run of its life; its utilization and effectiveness along with economic justification must be considered with both the short and long-term considerations.

CHAPTER IV

METHODS OF ECONOMIC JUSTIFICATION

Traditional methods and procedures for economic justification have not changed over the years. Investment proposals are typically appraised independently of each other, or rather in competition with each other. Appraisals are based primarily on the estimated financial merits of the investment. Let us discuss these traditional methods in turn:

1. Payback Period Method: Essentially this is the time taken to recover the initial investment through the cash flows generated. If, say, a new machine costs $100,000.00 and results in savings at the rate of $50,000.00 per year then the payback period is two years. This is the simplest and most commonly used method of investment appraisal. It is an easy concept to comprehend and is extremely useful as a first financial check on a new project to see whether it is likely to be financially viable. Its limitations are that it ignores income after the payback or break-even point, it is biased against investments with the highest return in the latest years of the project and it is inadequate for rigorous analysis of all the variables and systematic comparison purposes.

The second point is particularly important in the case of flexible manufacturing systems where the full advantages of flexibility and responsiveness are only likely to be reached in the long term.

2. Return on Investment Method: this method uses the ratio of annual net benefit to capital employed, expressed in percentage terms. The ROI concept can provide a useful gauge for measuring the previous performance of an existing project or business but is less useful for assessing future projects because it ignores the life of the project and is unsuitable for optimizing investments.

3. Discounted Cash Flow Method: the concept of discounted cash flow is concerned with the flow of money and its timing over the life of the project. It takes account of the time value of money, a dollar today is worth more than a dollar at a later date. There are several different applications of the basic DCF method, namely the internal rate of return and the net present value. The internal rate of return expressed as an annual rate in percentage terms is the most widely used application of DCF. It is similar to the ROI method but without its disadvantages. It is popular because it is easy to understand. The higher the DCF return, the better and companies can set a target level which new projects must exceed if they are to be considered and implemented. Some

institutions regard the net present value as more realistic. With this application of DCF the flows of money are discounted during the estimated project life by a rate which is specified by the company, usually the company's cost of capital. If the calculated net present value is positive, then the projected rate of return is higher than specified. If it is negative, then the return is less than the required rate.

4. Life Cycle Costing Method: in the cases discussed so far, deriving vital Figures on expenditure and benefits becomes progressively more difficult as one moves further away from the simple matters of labor, materials cost savings and such. Costs associated with feasibility studies, research, maintenance and such are difficult to assess and are often omitted from the appraisal calculations. Life cycle costing is an attempt to include all the relevant and associated costs in a systematic manner and thus comprehend all financial implications of a particular project.

All the methods detailed here make use of figures that are best guesses of future events. The only certainty is that these figures will turn out to be inaccurate to a greater or a lesser extent. If each input figure is re-assessed, first on a pessimistic basis and then on an optimistic basis, or a single point estimate with appropriate confidence limits a range of values can be obtained. If all input figures are compared in such a manner then a comparison of the deviations can provide a measure of the sensitivity of the project to particular input values. This technique is helpful in optimizing projects. Analysis helps in identifying the areas where the greatest potential exists for improving returns so that correct efforts can be applied profitably.

The previously mentioned financial methods of project appraisal are fine for investments in conventional equipment, however, they are unsuitable for the purpose of application to computer controlled and flexible manufacturing systems. Their limitations stem from the fact that they are based on the following assumptions regarding manufacturing equipment:

1. The impact of the equipment is limited to the immediate and isolated environment, namely the shop floor area, in which it operates.

2. The capabilities of the equipment and technology are assumed to be well-known and will continuously decline over the period of its use.

3. The investments and associated savings can be quantified on a highly accurate basis.

Such assumptions are not applicable to capital investment in the advanced manufacturing equipment we are considering in this thesis. A new set of measures needs to be developed to provide the basis for such investments. It needs to be appreciated that investment in FMS provides the basis for increasing the integration of the various stages of the manufacturing process. The benefits arise from connecting two activities such as metal cutting with inspection and material handling by which we mean integration of various functions in a single piece of equipment. This is particularly true when working with complex parts which have a high added value during the machining process. Whereas FMSs assist in reducing indirect labor in job tracking, transportation, tool control, scheduling and such, computerized numerical control offers direct labor reductions only.

The traditional assumption that equipment capabilities are well-known and fixed or that they decline slowly over time does not apply to FMSs or FMS-related equipment. In actuality the contributions of such systems usually keep increasing for increasing periods beyond initial installation. This is because of the following reasons:

1. With rapid progress in hardware and software, equipment and systems are becoming upward compatible.

2. The increasing understanding that users gain of the system's operating characteristics as they continue

to operate it.

3. The flexibility of the systems being considered, an FMS has the inherent ability to acquire increments in its production capabilities with the consequence that a great number of part types can be processed with the ability to increase capacity at will.

When compared with the main competitor of the FMS in the high-volume region, the transfer line, we must invest colossal amounts of money at the initial setting-up stage and after that the equipment so installed is dedicated to a specific part. Conventional transfer lines cannot provide the ease of design change, product-mix and production volume change which is a must in the competitive manufacturing scenario of today. The values of utilization of FMSs in today's environment are correspondingly much higher than those available with transfer lines.

For conventional equipment, costs and benefits are quantifiable with a high degree of accuracy. For the case of advanced manufacturing equipment quantification of costs is straight-forward as far as pure equipment and associated software is concerned. Training costs along with the cost of bringing the equipment into the mainstream of operations are little understood phenomena. To overwhelm matters the benefits associated with FMSs, which if quantified substantially would push decisions well towards them, are nearly impossible to measure mathematically. These intangible benefits are important and in well-integrated advanced equipment installations make all the difference.

In conclusion FMS investments should also be considered from a strategic perspective. In fact, a view rapidly gaining ground is that strategic considerations should be used to short-list feasible projects namely that those with lesser strategic consequences should be dropped first even in those cases where lesser strategic projects have higher chances of justification using traditional methods of justification. The overall importance of strategic benefits is all important in the long-term operation plan of any organization.

Intangible benefits should be quantified, hypothetically if necessary. The longer the time horizon they can be made to encompass the better. Since this thesis demonstrates the use of simulation as a tool in the justification process we would say that whenever possible stochastic values of the flexibility attributes be used to simulate the functioning of any proposed manufacturing set-up.

CHAPTER V

SIMULATION AND FLEXIBLE MANUFACTURING SYSTEMS

Computer simulation is an effective tool for analyzing different aspects of a flexible manufacturing system. Simulation using suitable analysis can improve productivity. This can increase cost-effectiveness. Simulation has been around for many years and has been used quite a lot in manufacturing analysis. Nevertheless, the use of simulation has not become prevalent in industry. Amongst the many reasons for this are:

1. The time to develop simulation models and associated designs has been a very time-consuming process. Simulation results with their procedures of verification and validation have created vast pools of disappointment in the minds of the people in the design teams waiting for results. Model development, a critical first phase which involves a complete understanding of the system components and their working can be an involved process. This does not mean that it cannot be shortened and with more co-operation and teamwork between the interested parties reduced times to arrive at results are a definite possibility.

2. Computer simulation is a costly process. Major

costs include those associated with people and hardware. The longer the time spent in development, the larger the software personnel costs incurred for modeling. If computer time is inordinately large due to the use of inefficient modeling languages then costs due to computer usage can spiral out of control.

3. Quite often poor modeling due to a lack of experience on the part of the software personnel can result in inaccurate results. Similar results will be obtained if poorly designed and inferior simulation languages are used. Errors usually arise in this case when the modelers translate the system under consideration to a simulation model.

Be that as it may, simulation is a useful tool to be used in the process of evaluating new manufacturing systems and also during the implementation phase of FMSs. Though mainframe costs remain high, the use of microcomputer based packages has resulted in lowered computer costs. Furthermore, the availability of animation has resulted in greater understanding and thus use of simulation in industry. In selecting a simulation language, the potential buyer must consider a number of factors such as: (a) syntax, (b) structural modularity, (c) modeling flexibility, (d) modeling conciseness,(e) statistical considerations, and (f) cost.

The great advantage of applying simulation to the manufacturing environment is that it allows the engineer to determine and thus understand the effects and implications of changing conditions at various points in the complete system. Performance evaluation, namely, makespan (time in system) analysis, throughput analysis and bottleneck (utilization) analysis can be carried out with ease. Results from such studies can provide information that provides a greater understanding of a system; this can lead to the determination of benefits which previously would have been difficult or impossible to ascertain.

There exist several alternate world views for simulation modeling. The objective of a particular view is to determine a defined framework within which the system under consideration can be described and thus modelled. Modeling using process orientation provides a concise and easy to learn framework but as frameworks go it can lack flexibility. Event oriented frameworks are not as simple but can, if used properly, provide a highly flexible modeling framework.

The simulation language chosen for this thesis--SLAM II has the advantage of modeling both world views thus providing a unified framework within which one can work. The process orientation framework of SLAM II employs a network structure which consists of specialized symbols called nodes and branches. These symbols model elements in a process such as queues, servers and decision points. The modeling task consists of combining these symbols into a network model which pictorially represents the system of interest. The network thus represents a pictorial representation of the process [Pritsker, 1986].

A simulation of the model under consideration will need to have the appropriate number of runs; this is part of the statistical background needed to be determined prior to carrying out any simulation of the model under consideration. This thesis has used SLAM II as the simulation language with network representation as the modeling medium. Results of the modeling exercise are presented further on in this thesis.

CHAPTER VI

METHODOLOGY

To this point relevant details and features regarding financial justification, flexibility and the application of simulation have been discussed. The main thrust of this thesis and the associated methodology are discussed now.

Any major purchase decision must provide for a distinct cost advantage over either the existing available option or any other option being considered. If, therefore, we wish to obtain some understanding of the difference between the advantages accruing to an organization by deciding in favor of either course then we must consider each particular course in turn. Manufacturing systems as considered here consist of a group of machines each of which is either dedicated in the sense that it can perform only one operation in a series of operations required to complete a particular job or it is flexible in the sense that it can perform all or several of the required operations.

Depending on the number of flexible machines in a particular group as compared to the number of dedicated machines in it we can have a range of flexibility that varies for the group from fully dedicated to fully flexible. Consider routing flexibility again; it is the ability to vary machine visitation sequences, in the case of machine breakdowns for instance, and to continue producing the given set of part types. It exists when there are several viable processing routes or when each operation in a set of operations can be performed on more than one machine. The implications of such flexibility are obvious when compared to the dedicated machine alternative. Set-up and lead times are reduced in the case of the flexible alternative, the flexible alternative eliminates bottlenecks in case of breakdowns and finally,in the case of a change in product mix, the flexible alternative is more useful since it can undertake the manufacture of different types of parts. In the dedicated case once the line is set up for a particular product then no change is allowable in the product handled.

Routing flexibility thus raises the competitive advantage of the flexible machine system, namely its ability to be able to perform significantly with respect to competitive system configurations. If we consider these points with the machine group consisting of dedicated cells, then we realize that within the dedicated scenario disadvantages exist because lead times and set-up times cannot be eliminated substantially, since the machines are defined as dedicated they can perform only the tasks they are assigned or configured for. Furthermore, any breakdown in any machine in the process sequence results in the complete line being down, whereas in flexible systems, generally speaking, parts can be rerouted through different machines without delay. For the sake of simplicity, breakdowns were not modeled in the current study. Also, in the case of dedicated machines set-up times were ignored. Finally, since each machine in an FMS with routing flexibility can perform each operation in a set of operations then the total amount of time spent by a workpiece in the processing stage, within the work cell should be reduced considerably.

With this in mind, we can, with a knowledge of individual operation times simulate the complete process of carrying out one set of operations on a particular workpiece. The considerations in this thesis lead to our having a batch of a certain number of workpieces each of which has a given constant number of operations to be carried out on it by each machine in the group. Individual operation times are considered stochastic in nature and are assumed to be normally distributed with a mean value and associated standard deviation.

Thus, to recap, we have a group of machines. The number in the group is a variable and depends on the number of operations to be carried out on the associated workpiece. As regards to the set of workpieces we consider a particular number for each group of machines with its associated ratio of flexible to dedicated machines. We also consider the total amount of time it takes the machine group to process the total particular number of workpieces; this is known as the makespan. Depending on the ratio of dedicated to flexible machines in the group, the associated makespan will change. Since makespan is an indicator of the processing time associated for a particular number of workpieces being processed then the lower the corresponding makespan then the better the situation since in a fixed time interval, with no downtime associated with all machine groups being considered, larger numbers of workpieces can be processed.

Furthermore, depending on the simulation model used, information on the amount of work in process and queue length associated with each machine can be obtained. The relative values of these process parameters gives an idea of the cost-benefit associated with each machine group. By taking into consideration different cost factors associated with each machine group we can obtain an idea of the relative worth of the separate group configurations.

The simulation models used in this study are based on the SLAM II simulation language. The models and networks used are not necessarily identical; they are, however, made up of identical network components organized in different configurations. This is due to the different frameworks available for modeling and indicates an advantage as far as SLAM II is concerned with respect to its use as a simulation language. Depending on the object or parameters of interest appropriate modeling can be done. A sample network and corresponding coding are shown in Appendix A, for the case of simulating a two machine work cell, both flexible machines with 20 workpieces.

CHAPTER VII

EXPERIMENTAL RESULTS AND DISCUSSIONS

The simulation of various machine groups was carried out with machine groups divided into three configurations, namely cells with two machines, four machines and ten machines. Since we are considering a comparison of dedicated with flexible machines with respect to routing flexibility, we simulate the functioning of each work cell with varying configurations as follows: a machine cell with two machines can be completely dedicated, both machines dedicated, or have one machine dedicated and one flexible or both flexible. We have defined dedicated as the ability of a machine to do only one operation and flexibility as the ability to do all operations under consideration. In the case of the two machine group each flexible machine can do both the operations carried out in the cell.The same concept applies to the four and ten machine groups.

Initially, the number of workpieces being processed in each cell configuration was twenty with this being varied to ten and then five. Simulation was carried out for one cycle. This meant completion of only the twenty, ten or five workpieces was considered. Five replications were carried out for each machine group and its subsets. Mean values were calculated for parameters under consideration for all five replications. The parameters under consideration were Average Time in System, Average Makespan, Average Queue Length, Average Wait Time and Average Utilization. Average Time in System, Average Makespan and Average Wait time are measured in time units, Average Queue Length is measured in number of jobs and Average Utilization is number of machines.

The simulation run values are tabulated and presented in Appendix B, Tables 2 to 19. Graphical results, namely, plots of Makespan and Average Queue Length versus Average Utilization are presented in Figures 1 and 2 for the 2 machine, 20 workpieces case, in Figures 3 and 4 for the 2 machine, 10 workpieces case, in Figures 5 and 6 for the 2 machine, 5 workpieces case, Figures 7 and 8 for the 4 machine, 20 workpieces case, Figures 9 and 10 for the 4 machine 10 workpieces case, Figures 11 and 12 for the 4 machine, 5 workpieces case, Figures 13 and 14 for the 10 machine, 20 workpieces case, Figures 15 and 16 for the 10 machine, 10 workpieces case and Figures 17 and 18 for the 10 machine, 5 workpieces case.

For the 2 machine case we have a special application of Johnson's Rule; this optimizes the makespan in the 2 dedicated machine case. From the results it is seen that

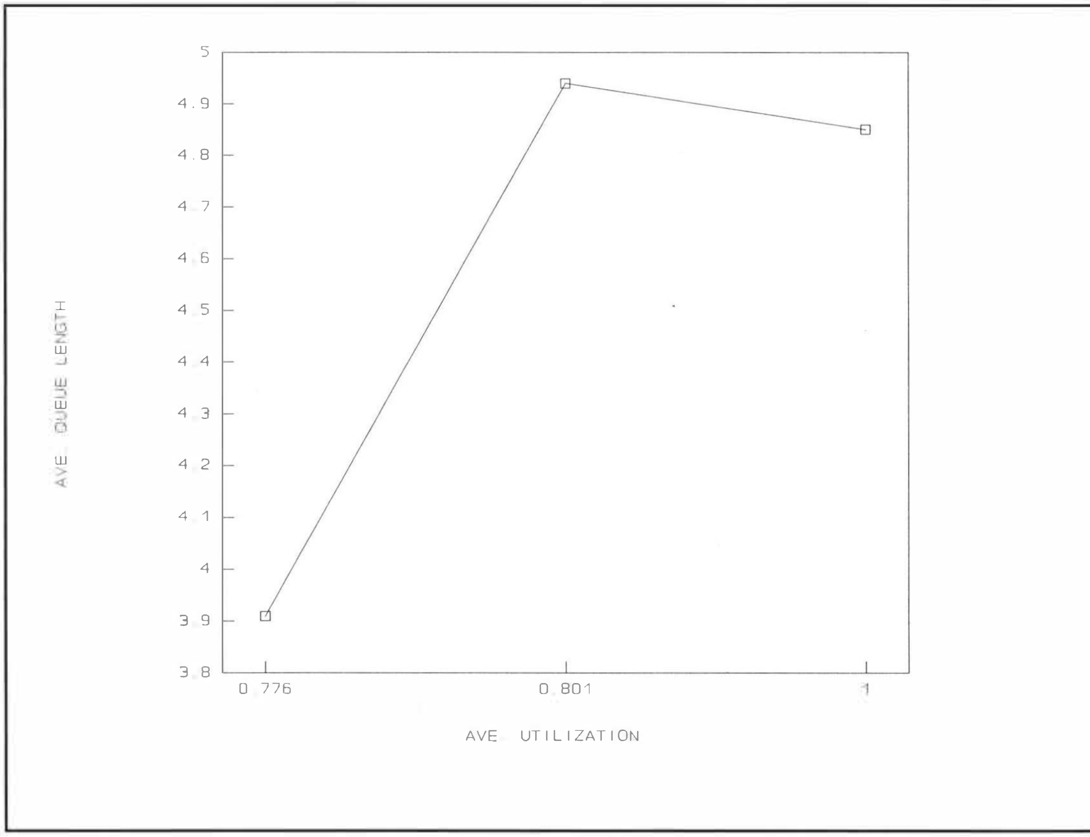

Figure 1. 2 Machine Case 20 Workpieces.

Makespan, Time in System and Wait Time values reduce successively as we increase the number of flexible machines in the work cell. Average Queue Length and Average Utilization, however, do indicate something different. From the completely dedicated case to the in-between case of one dedicated and one flexible there is a reduction in queue length and utilization. However, from this case to the totally flexible case there is an increase in these parameters. In fact, the value of utilization equals

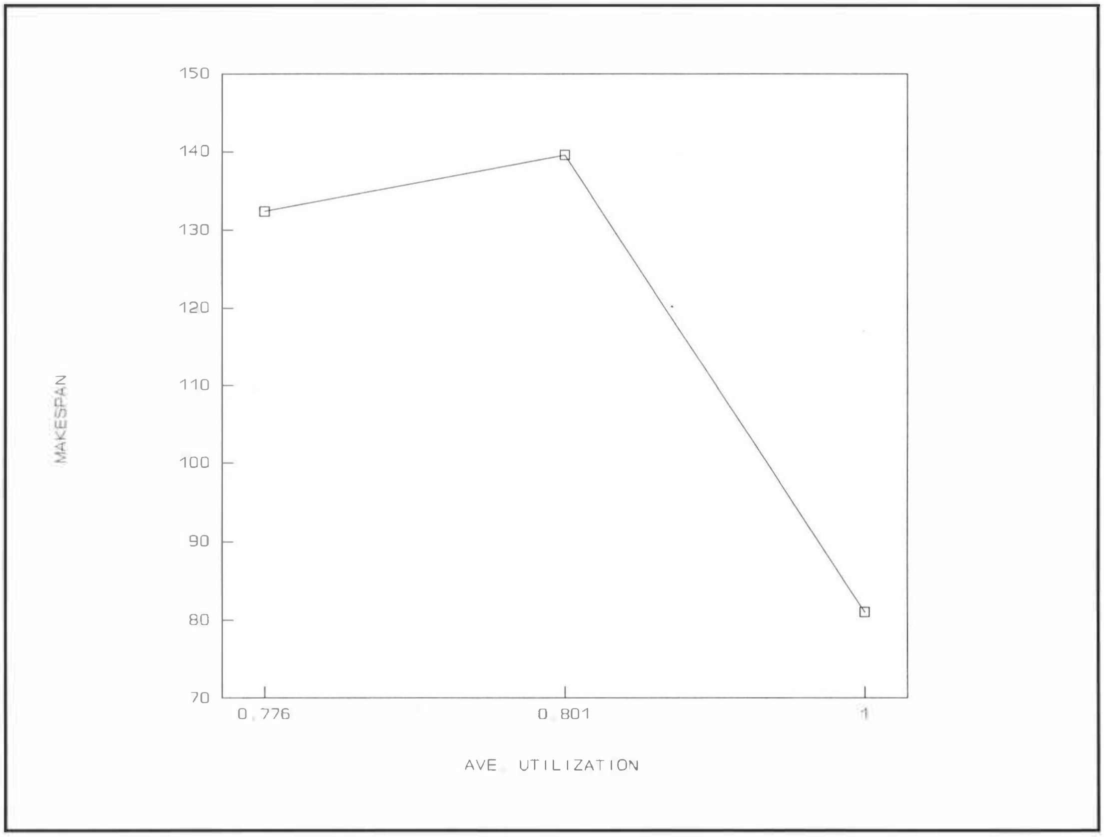

Figure 2. 2 Machine Case 20 Workpieces.

unity. This indicates that average queue length is linked to utilization. If machine utilization increases beyond a certain value then average queue length will also increase since machine usage increases within the makespan period. On the other hand, the consequences are not serious for the system since the wait time reduces with an increase in flexible content and thus the benefits of using flexible machines is observed quite clearly. The respective graphical results, as mentioned, are shown in

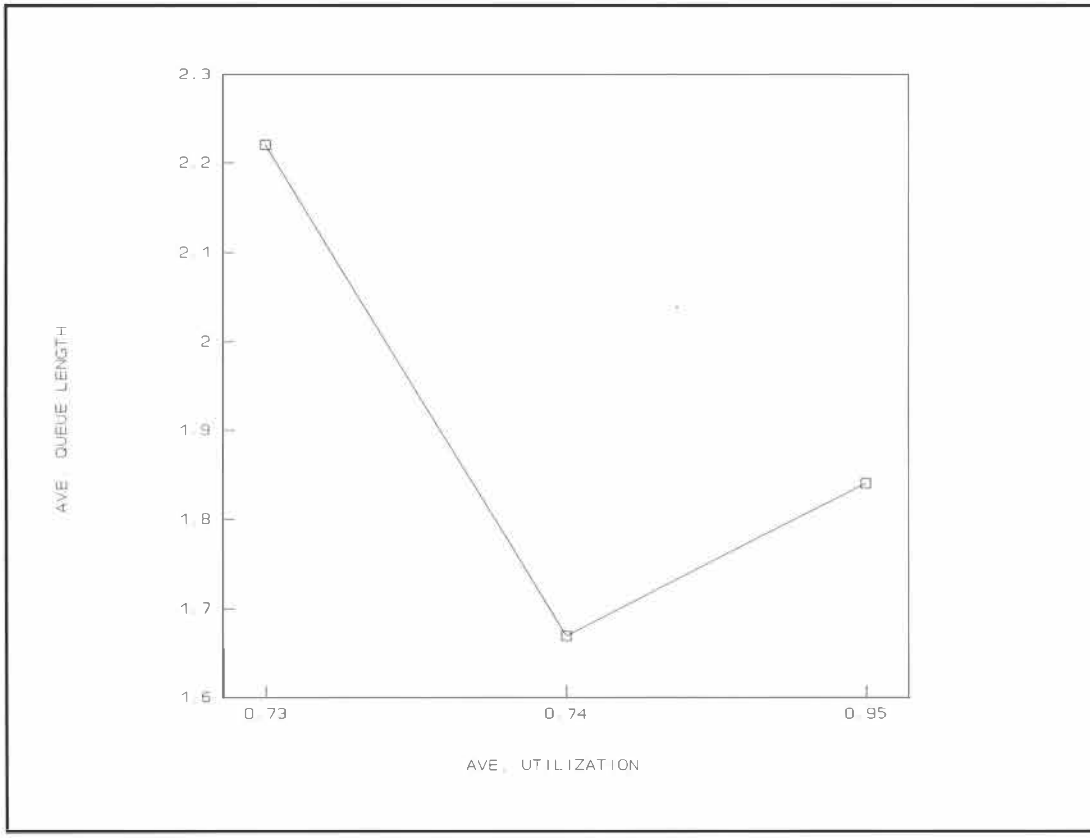

Figure 3. 2 Machine Case 10 Workpieces.

Figures 1 to 6. Barring the points discussed above it is seen that all other trends are as expected, namely, that all parameter values reduce successively with reducing numbers of workpieces handled.

For the 4 machine case it is observed that, as in the 2 machine case, values of Makespan and Time in System successively reduce over the complete set of readings with increasing use of flexible machines. There is, initially, for the case of 20 workpieces the same reduc-

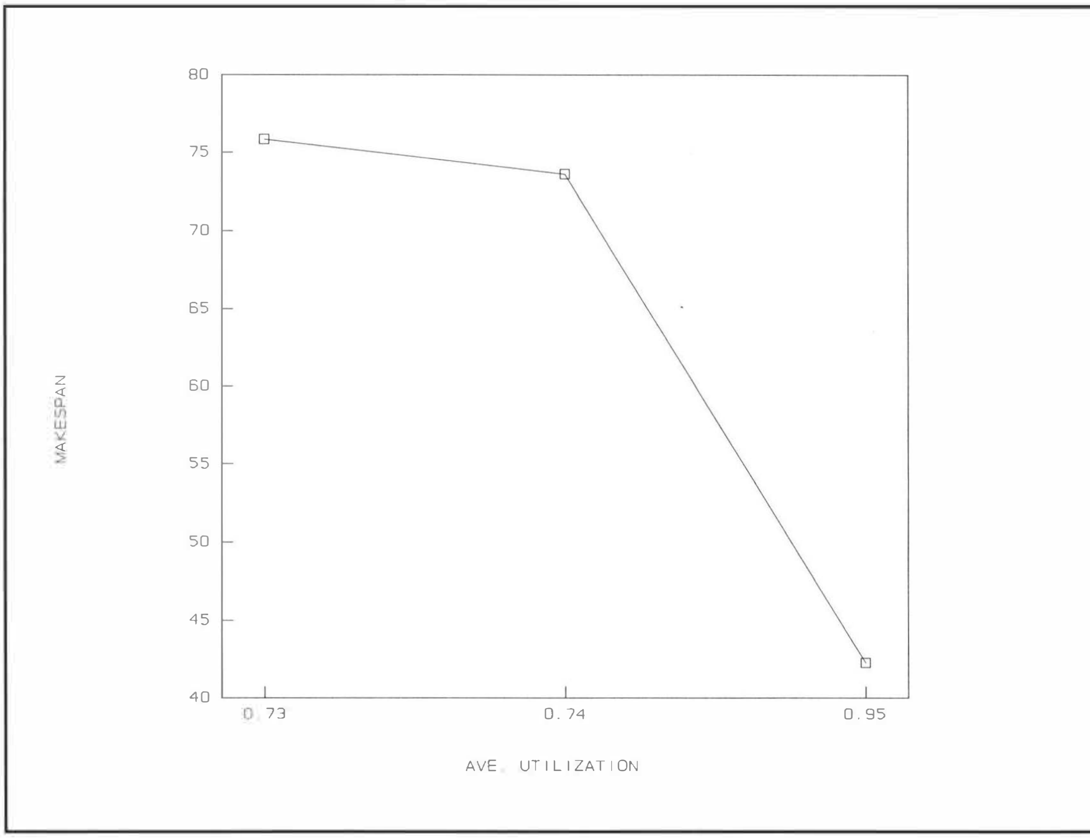

Figure 4. 2 Machine Case 10 Workpieces.

tion and then increase in Average Queue Length; however, we also see the same trend in values of for Average Wait Time. Obviously, in this case, an increase in average queue length also results in an increase in average wait time, but, if considered in absolute magnitude, the increase is not significant, and the value for average wait time for the totally flexible case is still much lower than that for the totally dedicated case.

For the 4 machine case, with 10 and 5 workpieces it

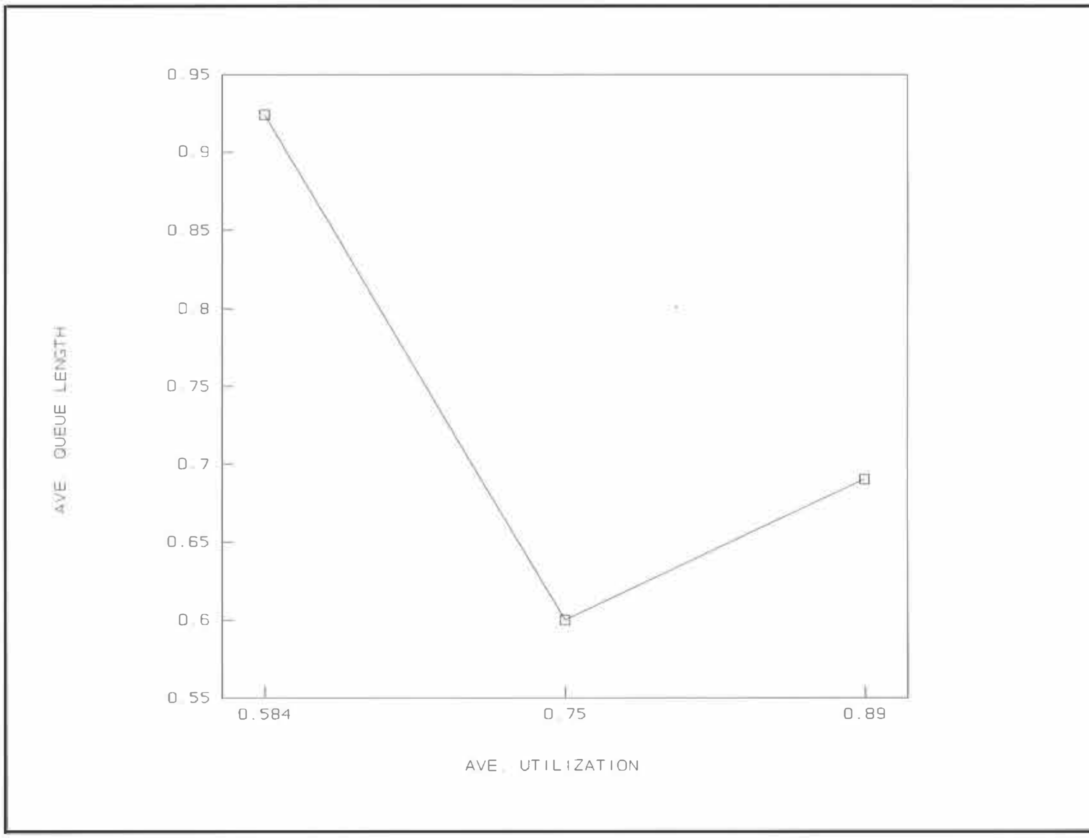

Figure 5. 2 Machine Case 5 Workpieces.

is seen that the benefits of flexibility are realized. There are all-round reductions in all parameters of interest with increasing numbers of flexible machines in the work cells. Average Utilization, however, continues to increase. The graphs in Figures 7 to 12 , as mentioned previously, represent the relevant results for the 4 machine case.

In the 10 machine case it is seen that the corresponding results for the processing of 20 workpieces show

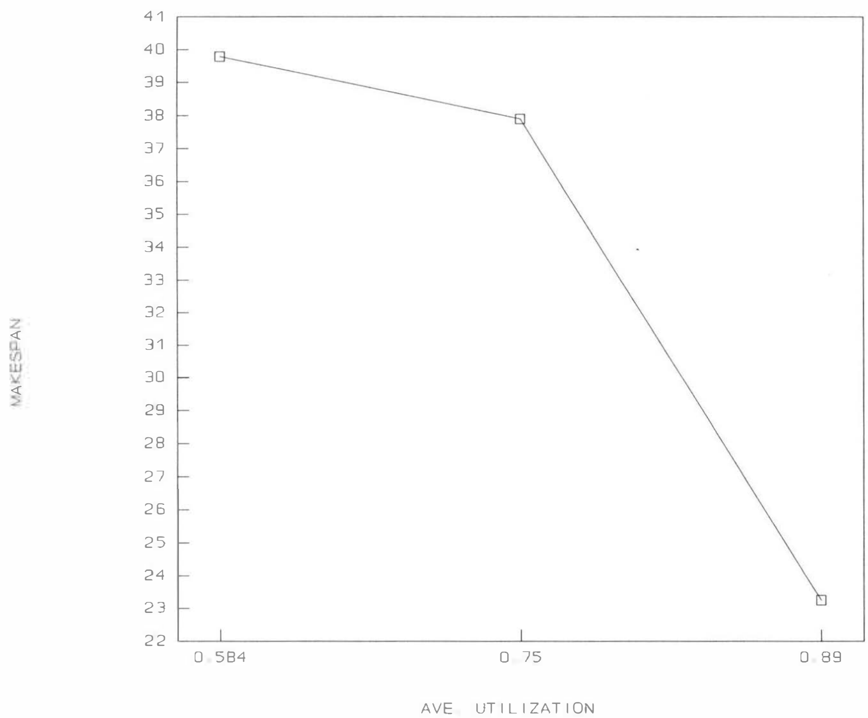

Figure 6. 2 Machine Case 5 Workpieces.

the same fall and increase in queue length with utilization as seen in the previous cases with 2 and 4 machines. However, with reduced workpieces processed, namely 10 and 5 workpieces, the reductions in parameters of interest with increasing numbers of flexible machines is observed. In fact, limiting values for all the parameters considered are attained in the case of 5 workpieces handled. The graphs, as mentioned previously, in Figures 13 to 18 depict the complete case of the 10 machine work cell.

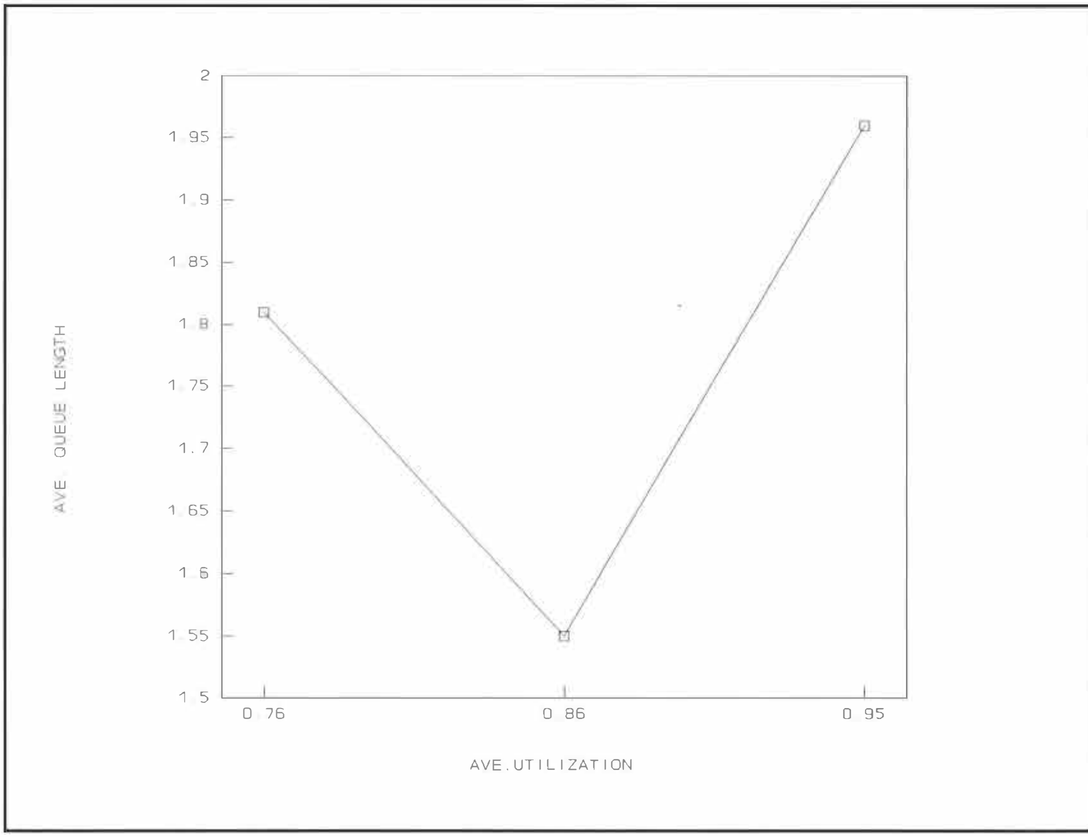

Figure 7. 4 Machine Case 20 Workpieces.

In summary, it is seen that increasing the flexible content of the respective work cells results generally in decreasing values of Time in System, Makespan, Average Queue Length, Average Wait Time and increasing values of Average Utilization. It is also observed and understood that there are cases where, due to the utilization level of a particular cell configuration, with increasing content of flexible machines there is an increase in the value of either queue length or wait time. The importance

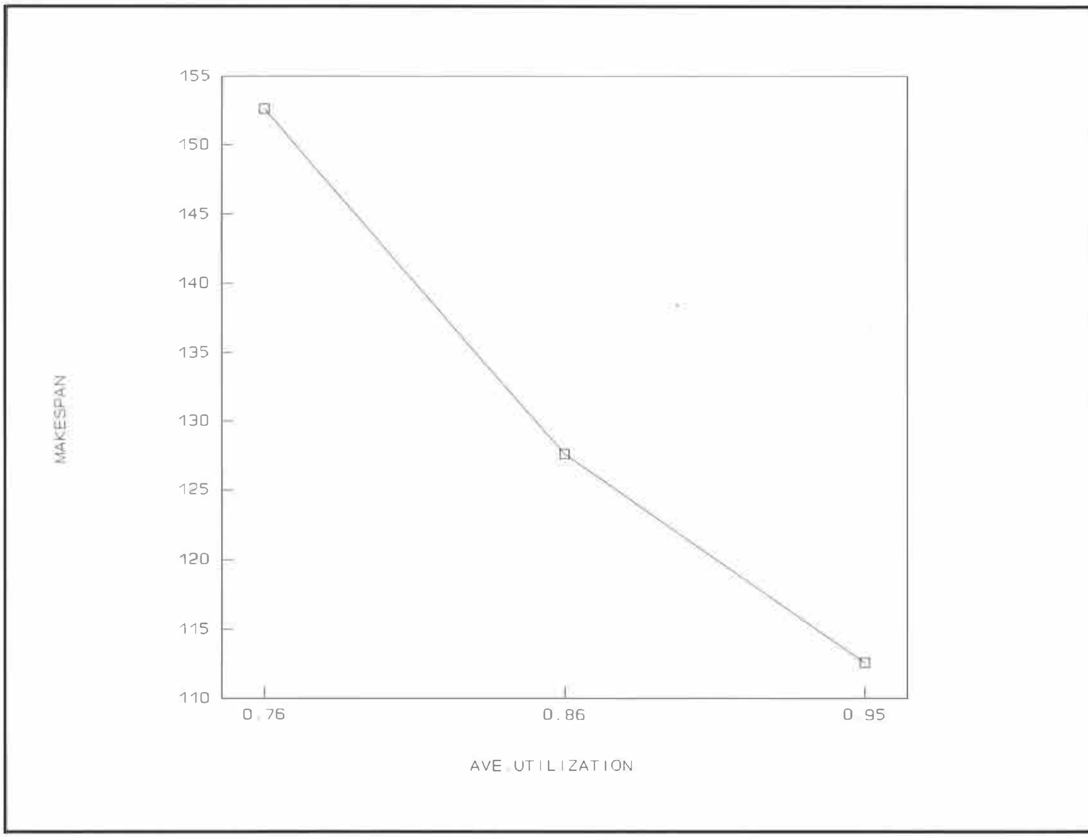

Figure 8. 4 Machine Case 20 Workpieces.

of utilization can thus be commented upon. Figures 19 and 20 depict variations in Time in System and Utilization with varying configurations for the 2 dedicated machine case. Figures 21 and 22 depict the same for the 2 flexible machine case. Figures 23 and 24 depict results for the 4 dedicated machine case and Figures 25 and 26 depict the results for the 4 flexible machines case. Figures 27 and 28 depict results for the 10 dedicated machine case and finally, Figures 29 and 30 depict results for the 10

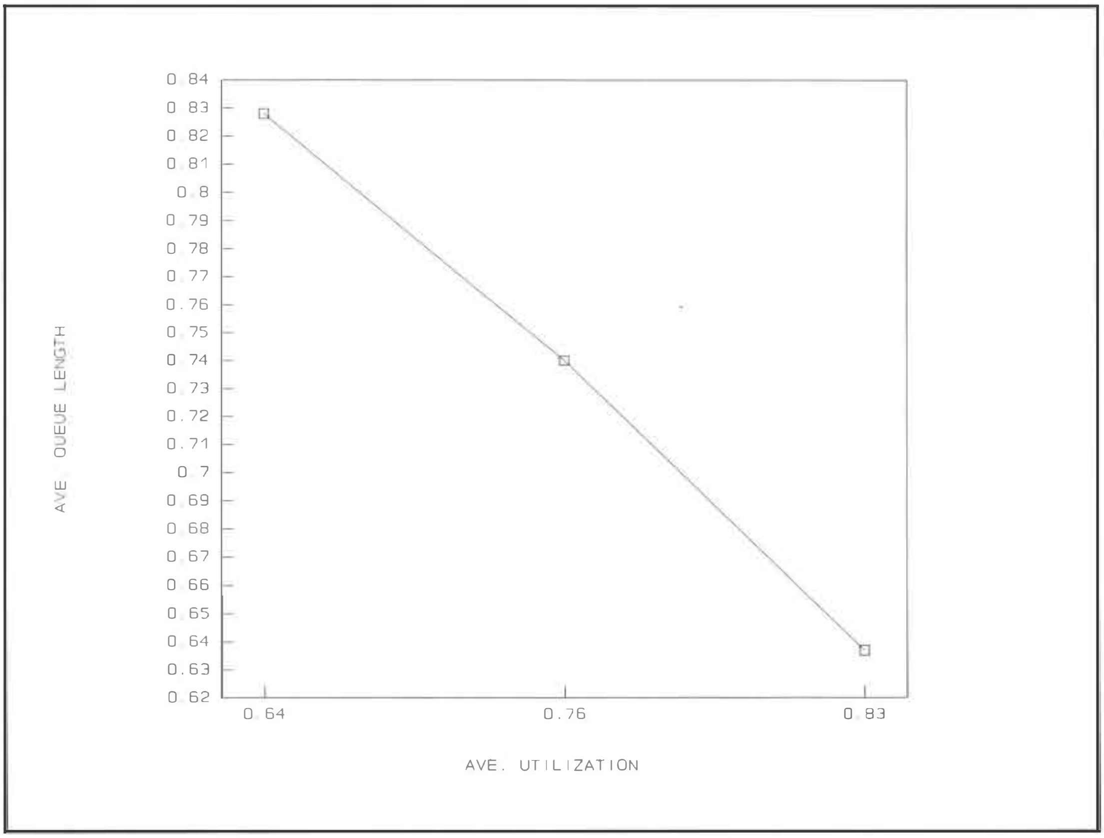

Figure 9. 4 Machine Case 10 Workpieces.

flexible case.

It is seen that in all cases utilization tapers off to higher values as time in system values reach increasing values. Thus as utilization increases with an increasing number of workpieces within the same machine cell configuration we have a corresponding increase in the average time in system i.e. time spent in the system per workpiece. This explains the previously mentioned results where average queue length was seen to display

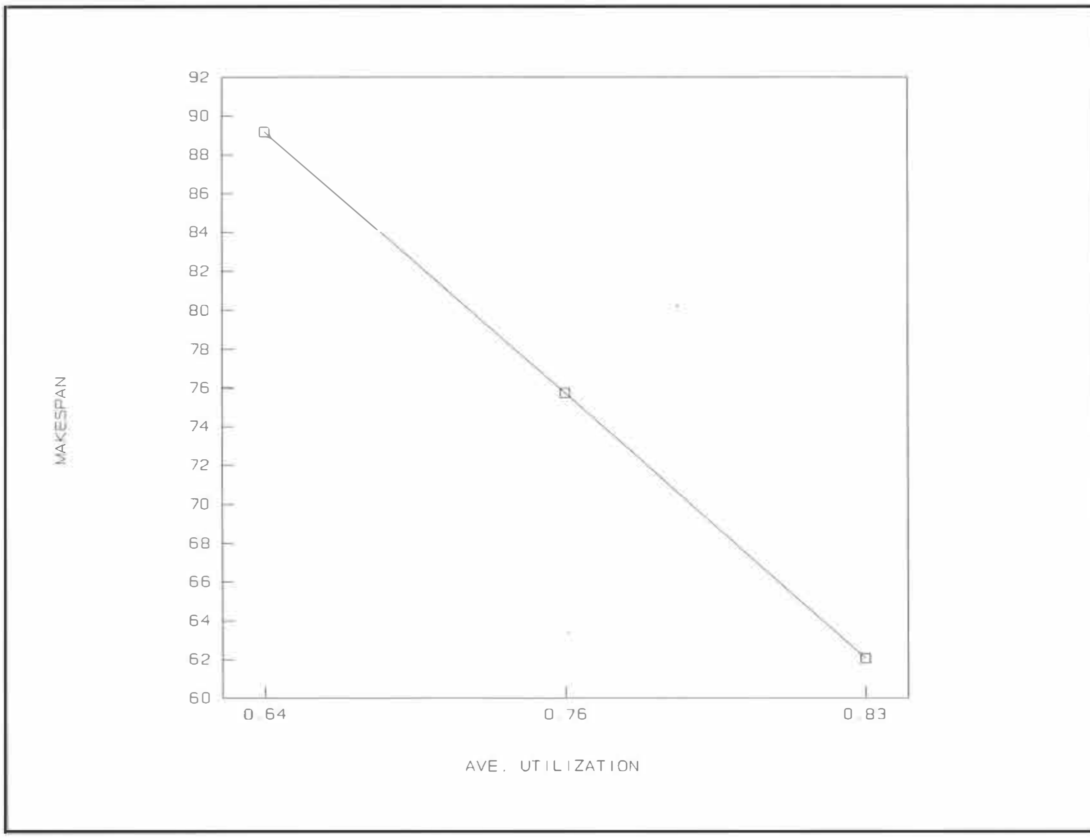

Figure 10. 4 Machine Case 10 Workpieces.

the change that it did. The present graphs also show time in system increasing at higher rates towards the high end as utilization tapers off.

The significance of utilization can now be discussed. Low values of utilization can result in larger breakeven periods for a particular investment. Too high a value for utilization can cause the sacrifice of an organization's ability to meet market changes, namely, customer requirements and suchlike. It can also, as we

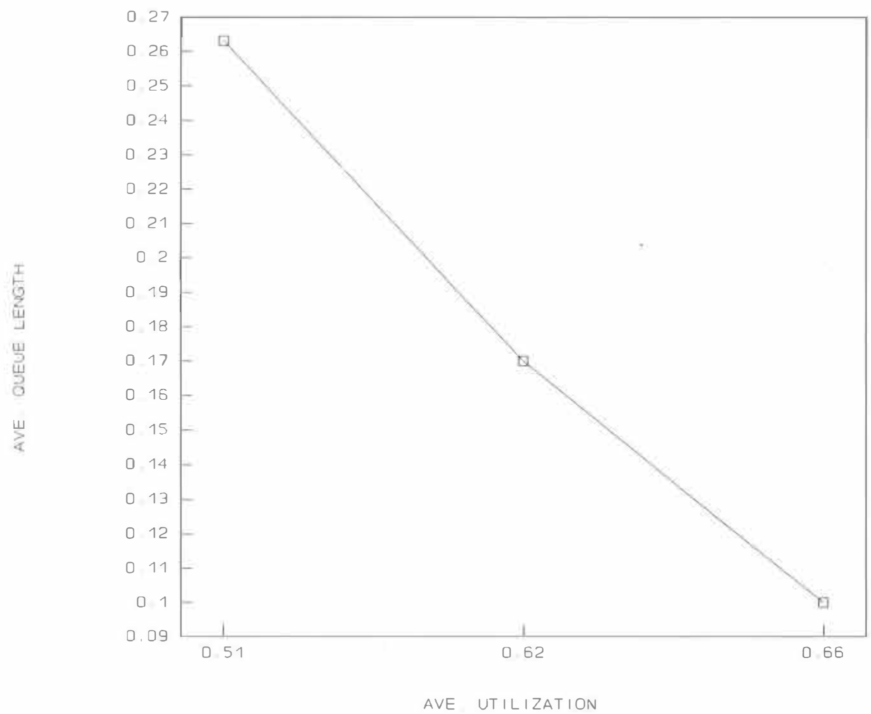

Figure 11. 4 Machine Case 5 Workpieces.

have seen, adversely affect time in system and work in process values. These factors will then, rather than result in increasing cost benefits, imply a decrease in associated overall cost benefits.

The extension and implication of these results to the world of cost justification is now dwelt on. Since, with increasing amounts of flexible machinery in a particular work cell decreasing values of makespan and time in system are obtained, then it follows that over a given

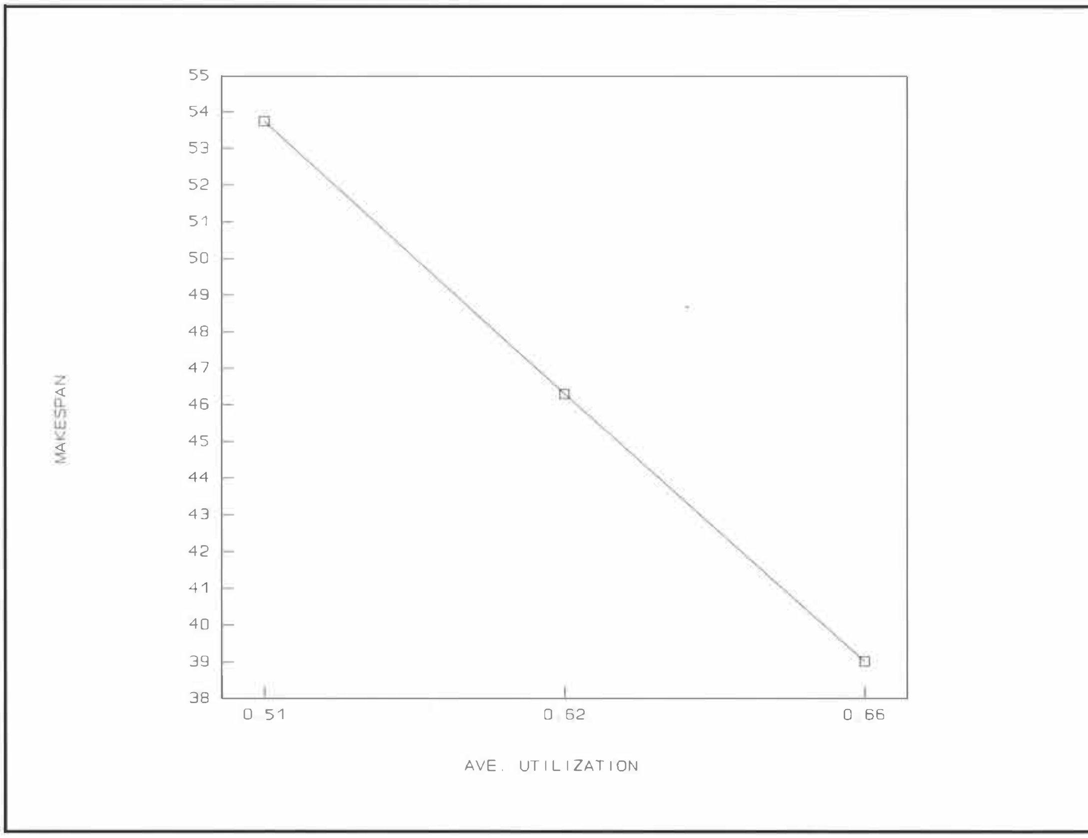

Figure 12. 4 Machine Case 5 Workpieces.

equivalent span of time, barring unforeseen circumstances, the number of workpieces processed per machine cell configuration will increase with increasing numbers of flexible machinery within the cell. This is tantamount to greater amounts of volume of workpieces produced, which in turn means greater projected revenue turnover, over the span of time considered. Within the work cell we see that considerations of the number of dedicated and number of flexible machines arise. By this is meant the rela-

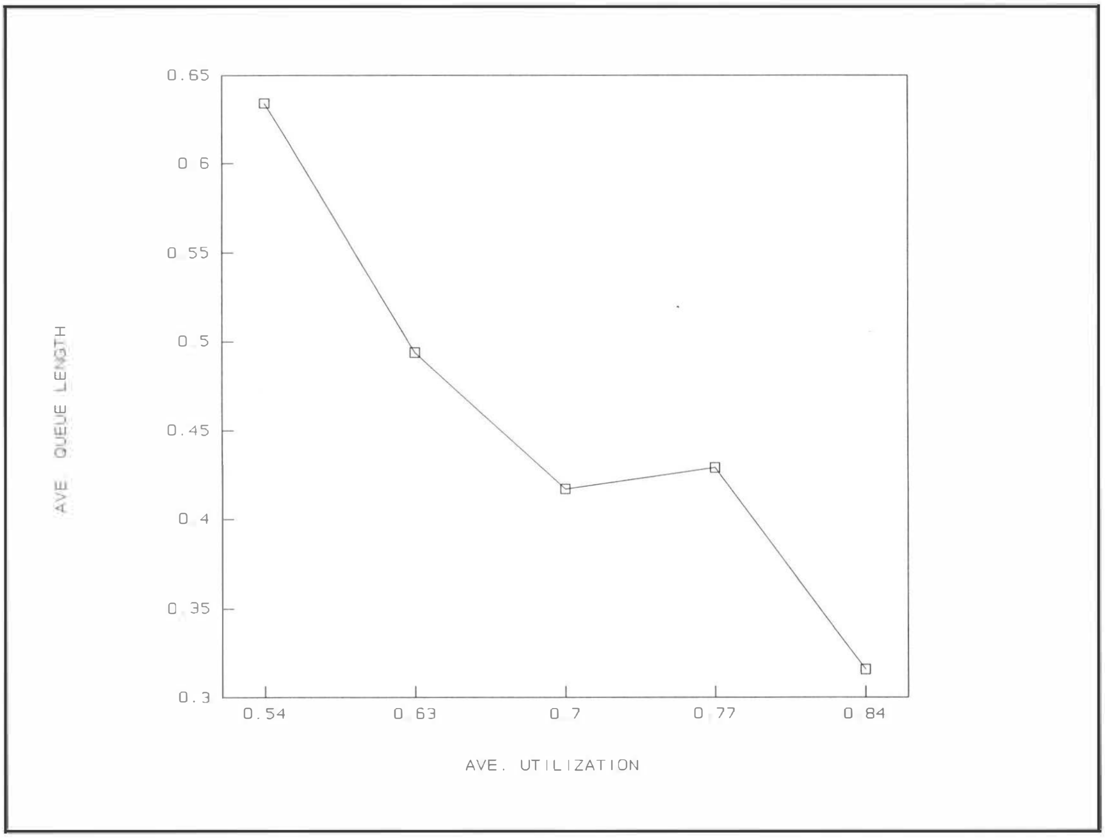

Figure 13. 10 Machine Case 20 Workpieces.

tionship that queue length observes with utilization; utilization increases, with maximum values being observed for cells with totally flexible machines. As regards utilization it is a good sign to have increasing values since this means that, provided volume produced is also increasing then there is a chance that a particular system is generating a reasonable return on its investment. This, of course, depends on the initial amount of capital invested, which in turn depends on the types of

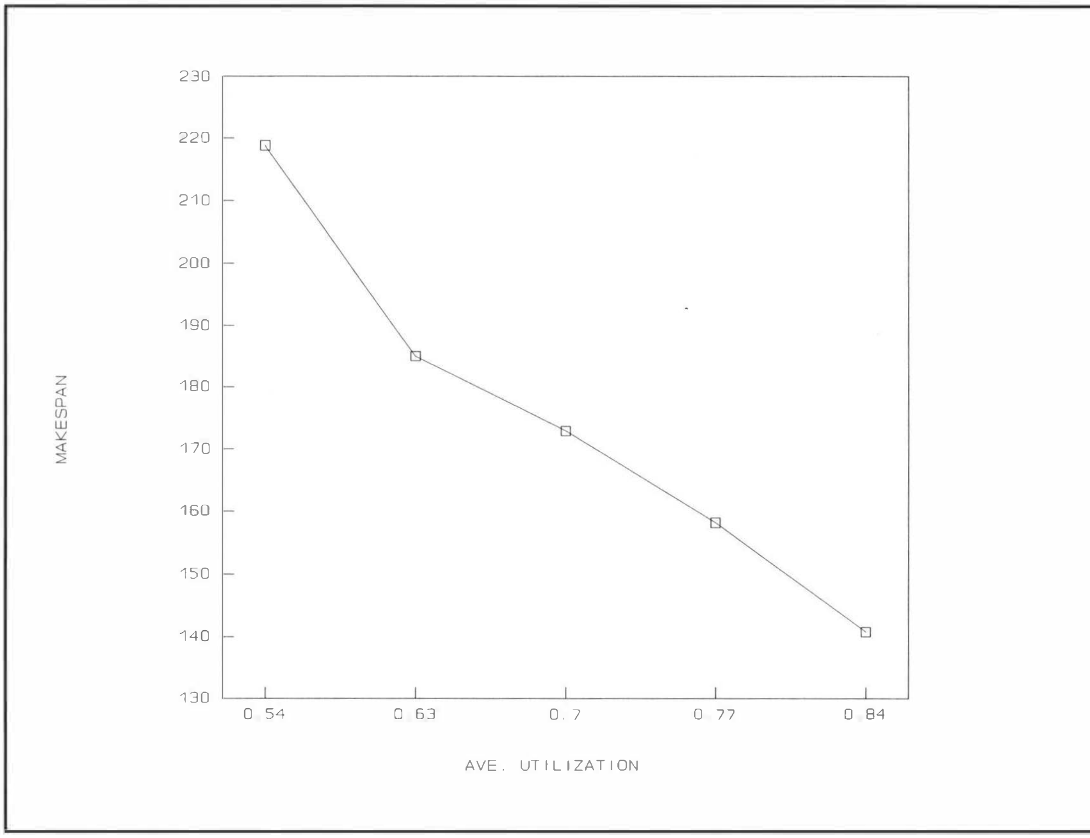

Figure 14. 10 Machine Case 20 Workpieces.

machinery purchased. The significance of utilization has already been commented upon.

At lower levels of investment, there are small differences in dollar values between dedicated and flexible equipment. In such cases the results of this study will assist in being able to quantify the particular parameter of interest once the variables of a particular system, such as operations to be carried out and operation time, are identified. Lower levels of investment

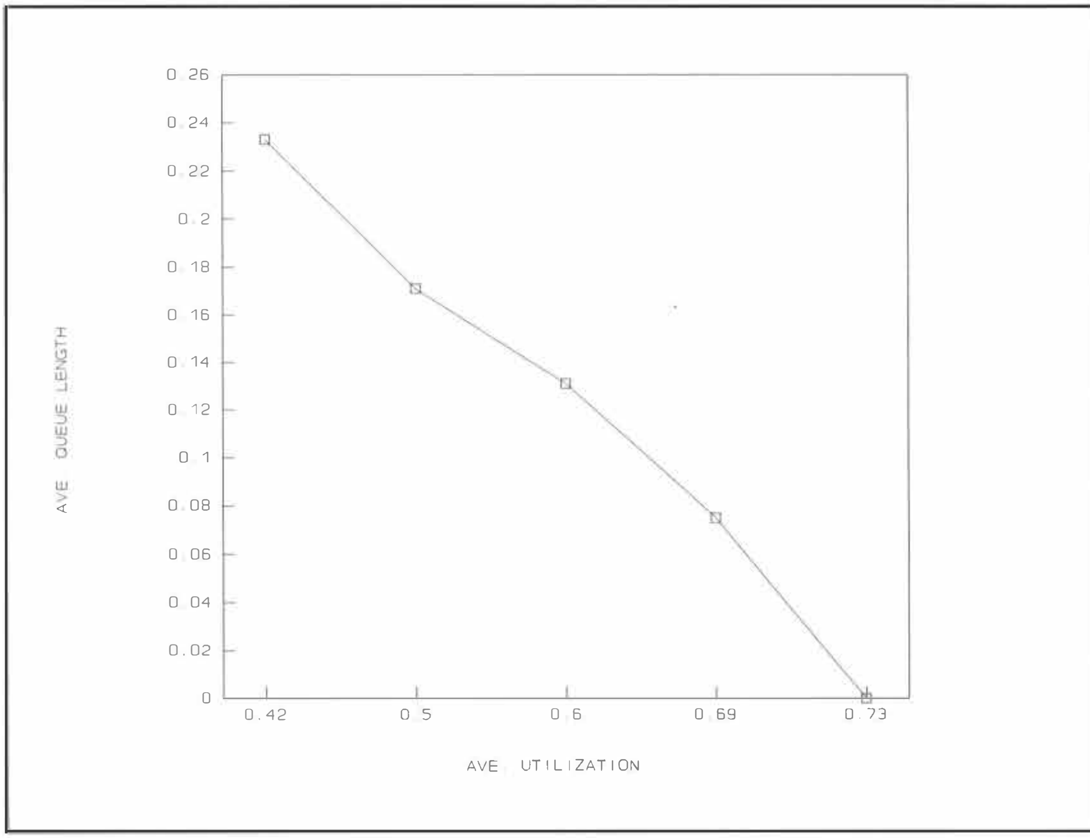

Figure 15. 10 Machine Case 10 Workpieces.

encompass dollar values up to $ 100,000.00. For the medium and higher levels of investment ranges, up to half of the investment can and usually is spent towards paying for the software needed to provide the flexibility content of the work cell. Since advancements in hardware, namely electronics, are being obtained at lesser and lesser distributed costs, then the significant cost differences between dedicated and flexible equipment are due mainly to the software content referred to above.

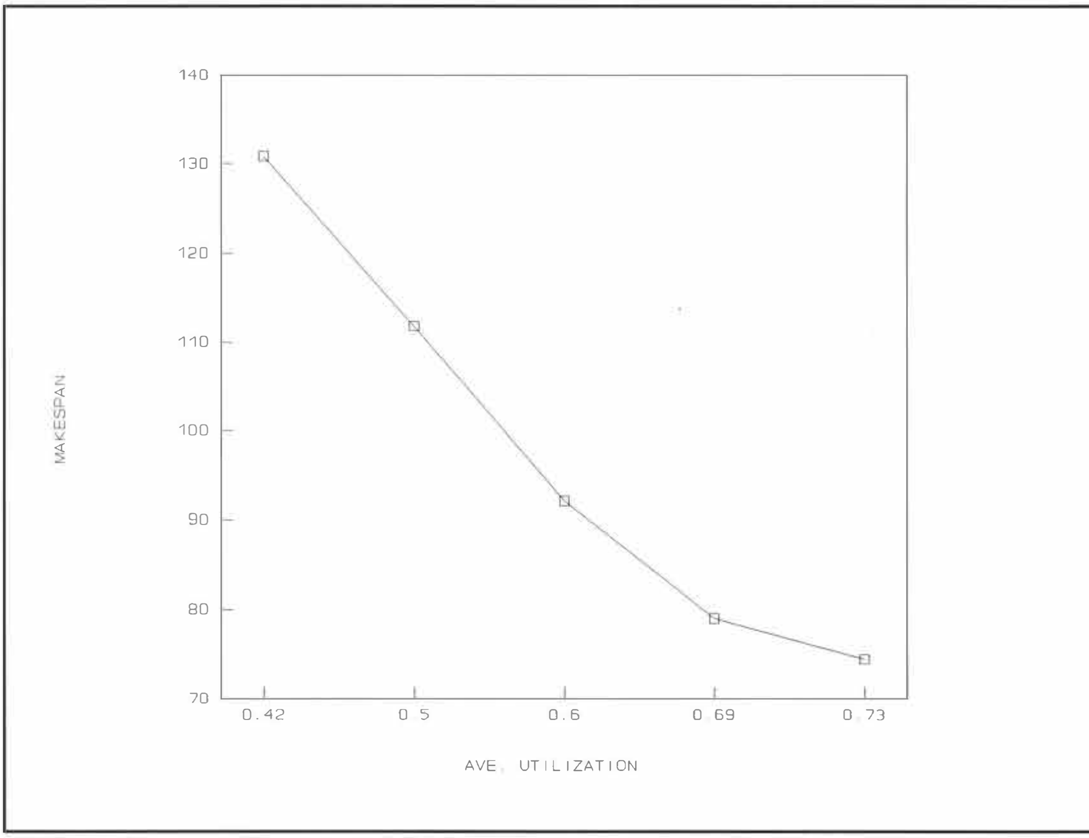

Figure 16. 10 Machine Case 10 Workpieces.

Therefore, at a rough estimate, equivalent flexible systems can at the least be up to twice the cost of a dedicated system.

Since routing flexibility is a part of the total flexible functions of advanced manufacturing systems, the value of this study can be towards quantifying the benefits due to routing in conjunction with other benefits. The contribution of queue length and wait time are evident in reduced overall values of Work in Progress,

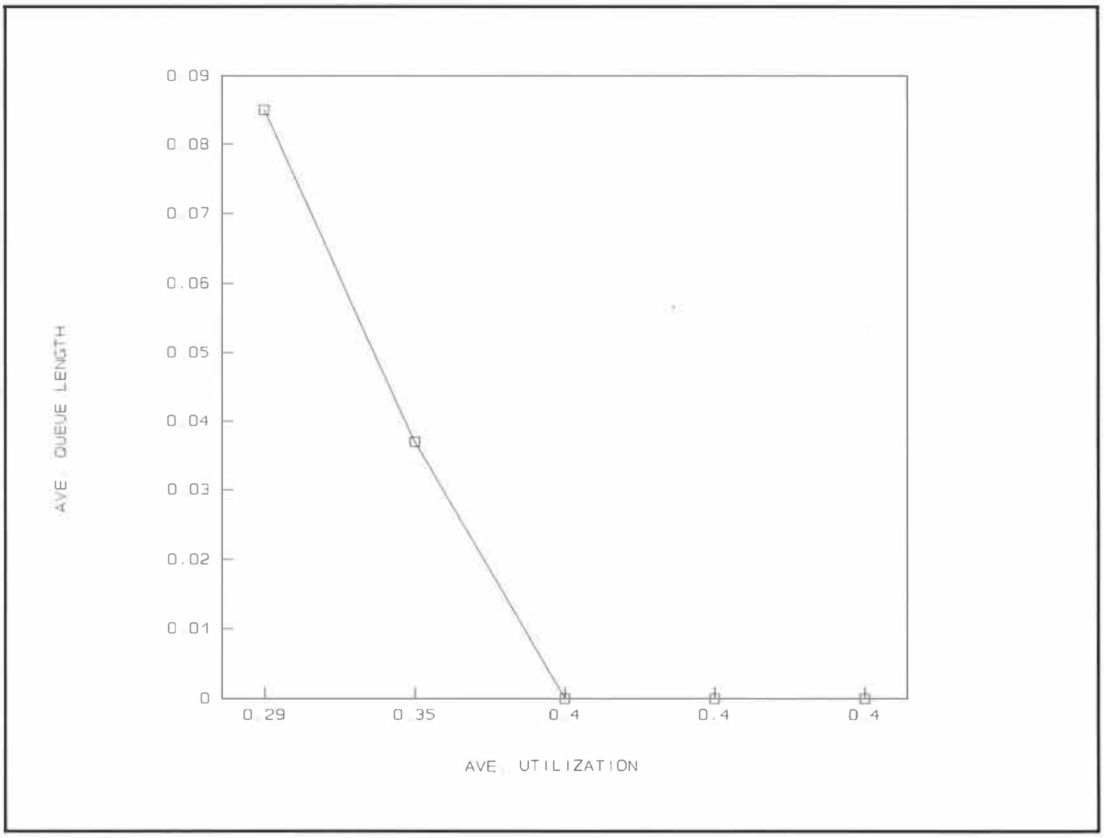

Figure 17. 10 Machine Case 5 Workpieces.

Inventory and buffer space or space needed for the intermediate storage of workpieces. Just how these advantages relate to overall quantified values depends on the constants related to the particular system concerned. A knowledge of these constants assists in the quantification process.

An empirical relationship of any cost benefits arising and accruing due to routing flexibility as discussed in the course of this thesis would concern and

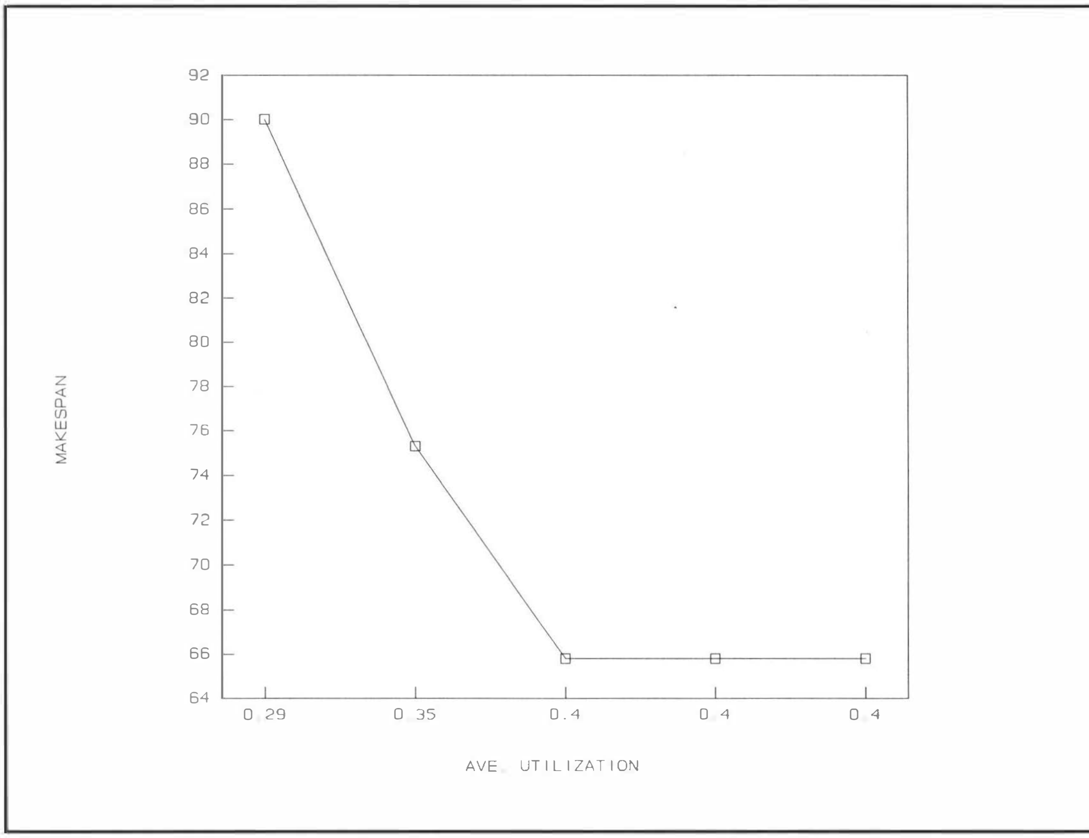

Figure 18. 10 Machine Case 5 Workpieces.

involve time in system, makespan, queue length, wait time, utilization and number of workpieces handled in process.

It is difficult to derive an exact relationship at this stage with any reasonable level of accuracy. We cannot extrapolate beyond the existing ranges considered in the experimental results presented. Although in reality an extrapolation may result in the same trends being repeated outside the ranges considered, the scope of this

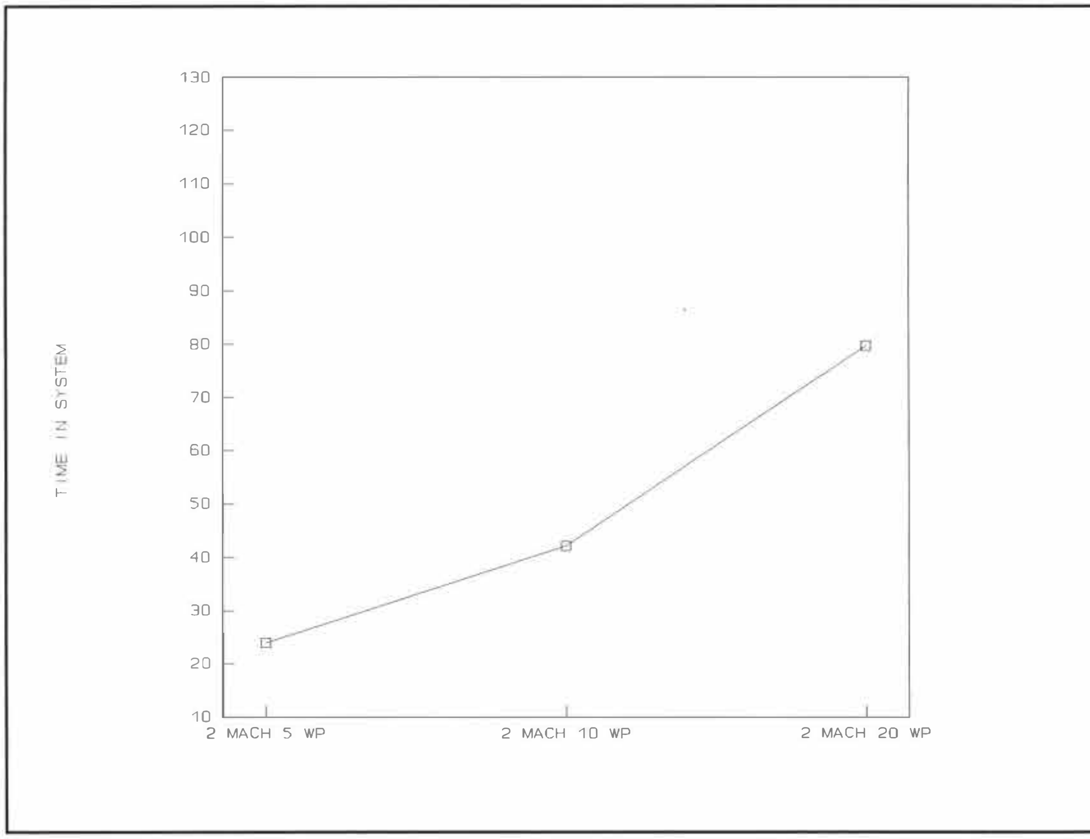

Figure 19. 2 Dedicated Machines 5, 10, 20 Workpieces.

thesis is limited to and within the experimental values considered and presented.

Thus we obtain the empirical relationship denoted in Figure 31. Values of the constants are dependent firstly, on the machine group type and then on the configuration of dedicated and flexible machines. The cost benefit function will show increasing values with increasing values of utilization till we reach the turning point of utilization value from whereon the negative contributions

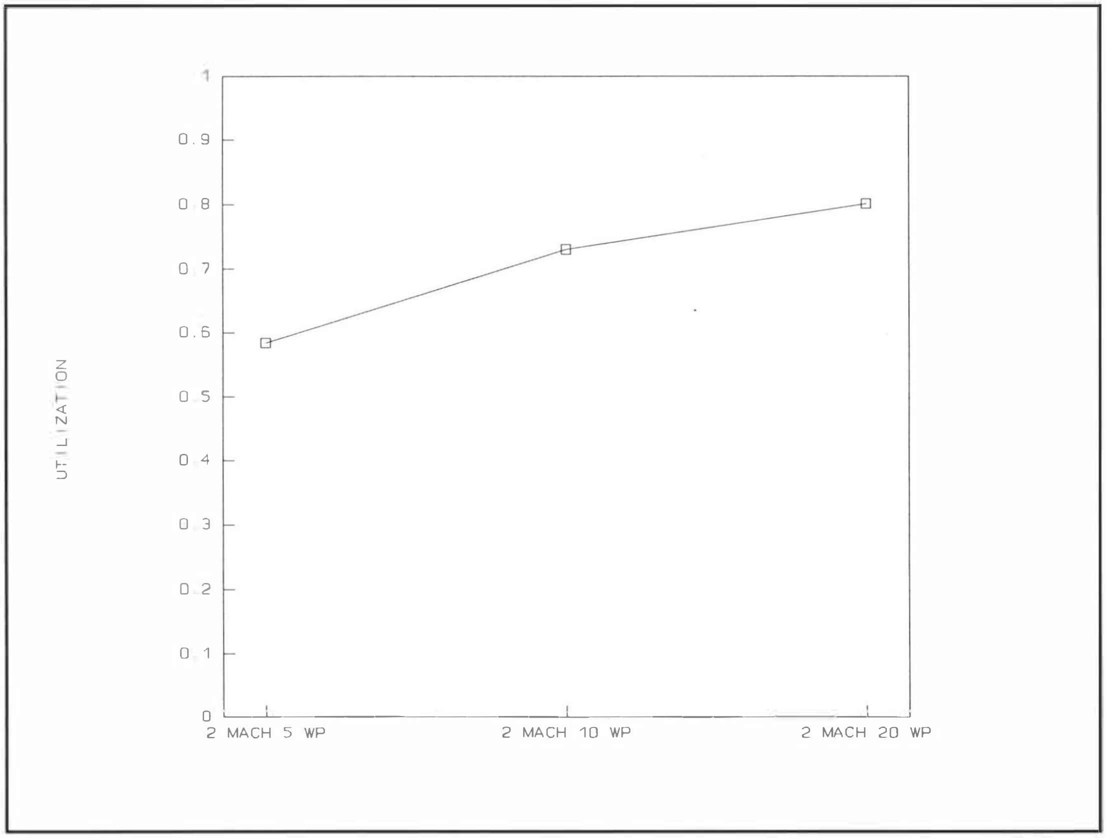

Figure 20. 2 Dedicated Machines 5, 10, 20 Workpieces.

of increasing utilization will result in reducing values of overall benefits.

The application of the methodology proposed in this thesis now becomes apparent. The utility of the different method proposed for justification also becomes apparent and its value in quantifying flexibility can be seen. The value and utility of simulation techniques in analyzing and quantifying flexibility are seen and the case for its application in justification exercises is reinforced.

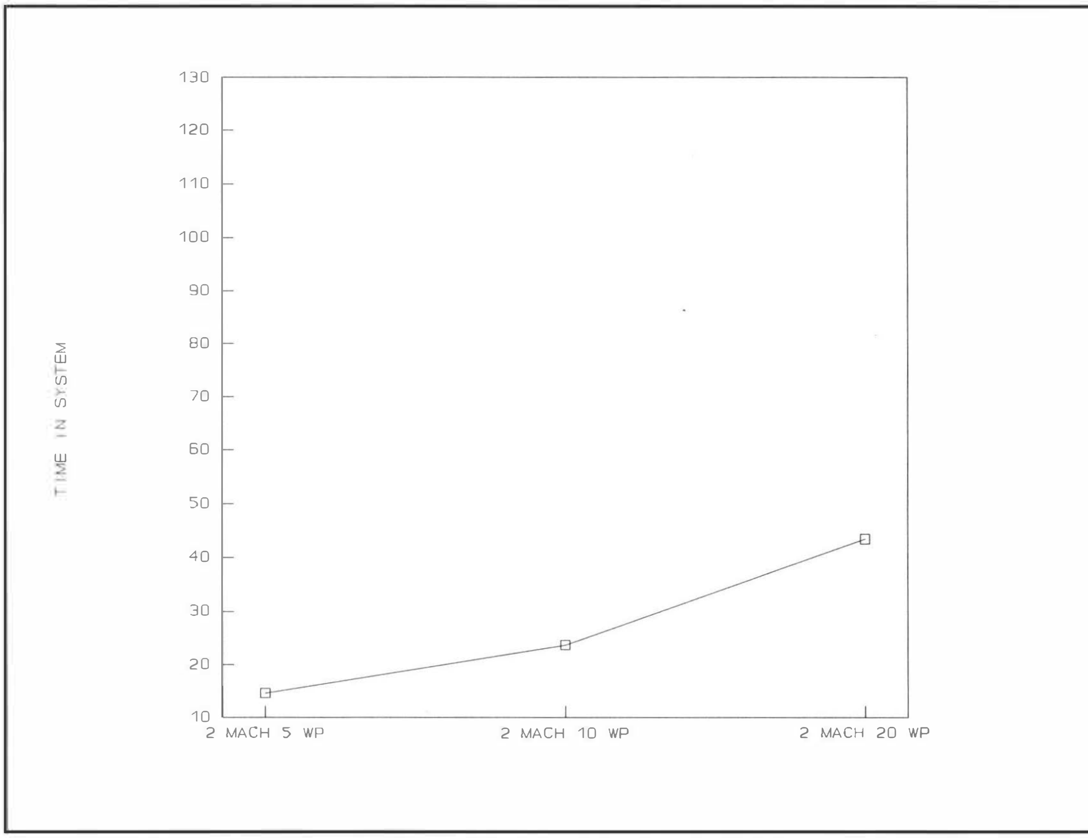

Figure 21. 2 Flexible Machines 5, 10, 20 Workpieces.

Modern managers cannot avoid using simulation as a decision-making tool, if they are to obtain a better idea of what they are up against. The difference lies in the new ability to quantify previous intangibles.

Modeling of machine configurations will depend on conciseness and user-friendliness of the simulation package considered.

Scope for further research exists in devising exact methods for the formulation of all constants. The effect

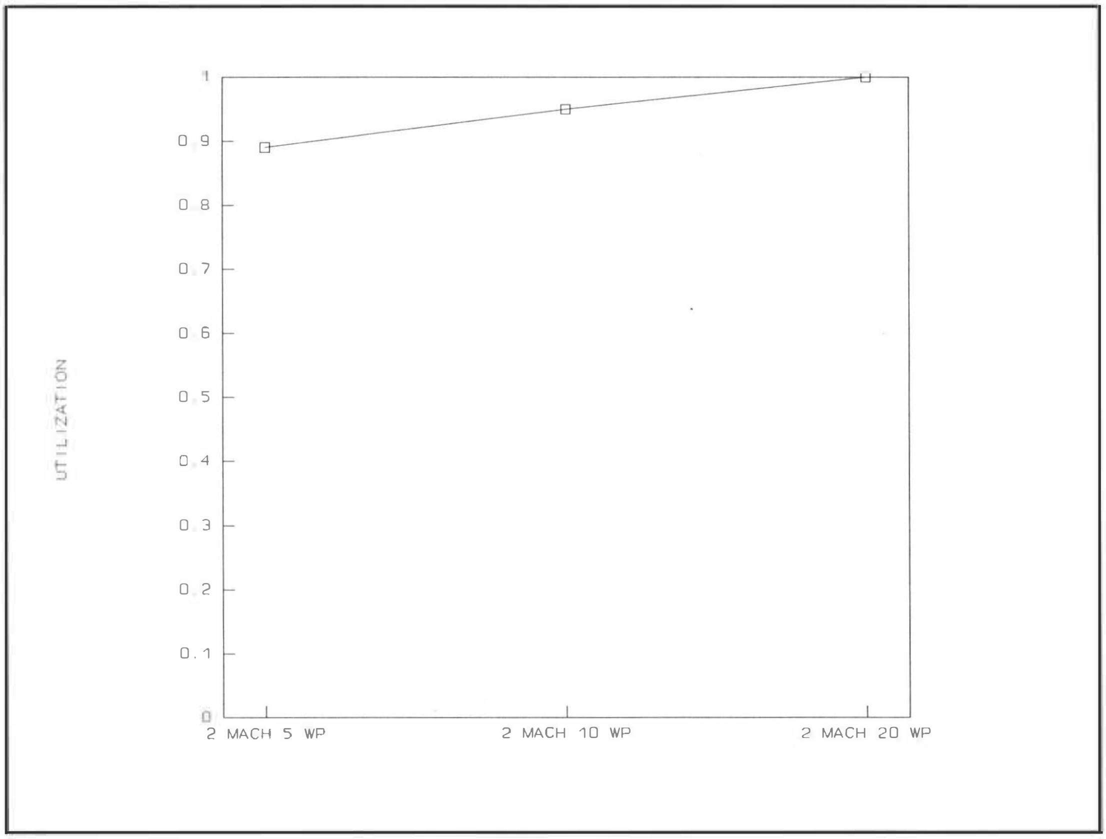

Figure 22. 2 Flexible Machines 5, 10, 20 Workpieces.

of individual operation times is important to the final results obtained, however, the constants are important and play a significant part. The essence of this thesis has been its simplicity in terms of its presentation and complete methodology of experimentation. The results and conclusions arrived at are also presented in a simple manner. Any further research should strive for the same simplicity.

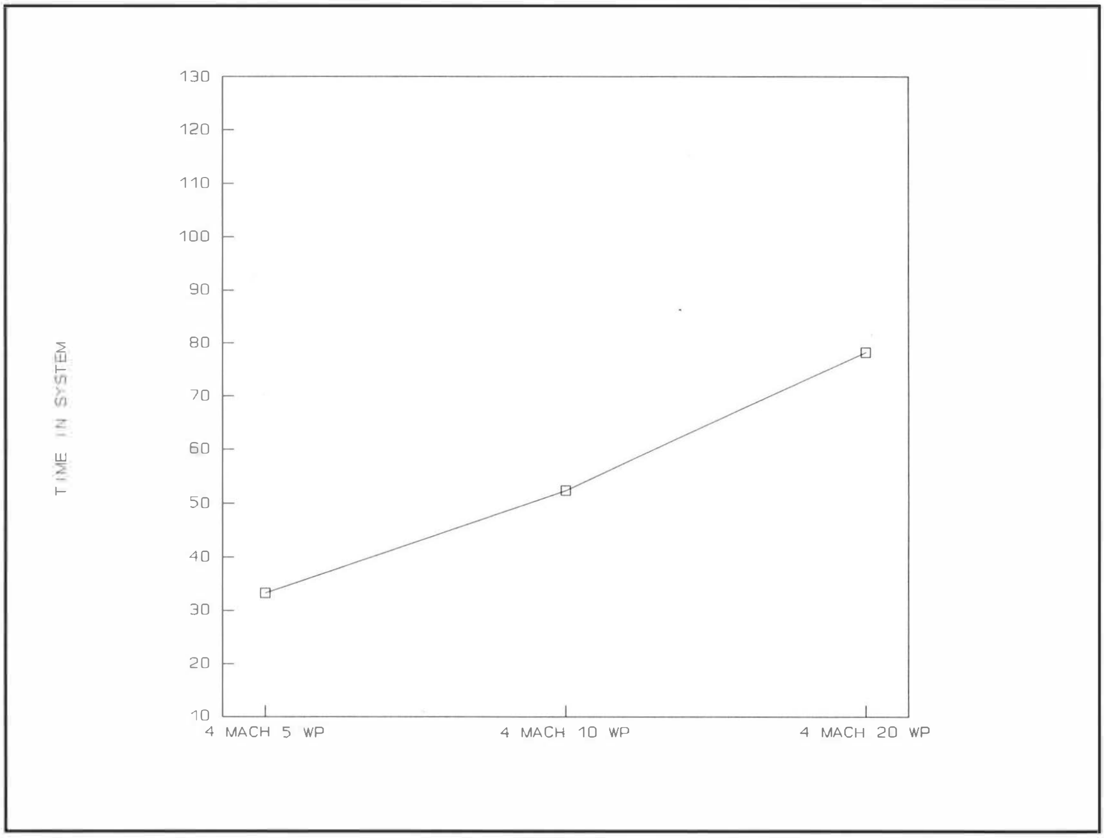

Figure 23. 4 Dedicated Machines 5, 10, 20 Workpieces.

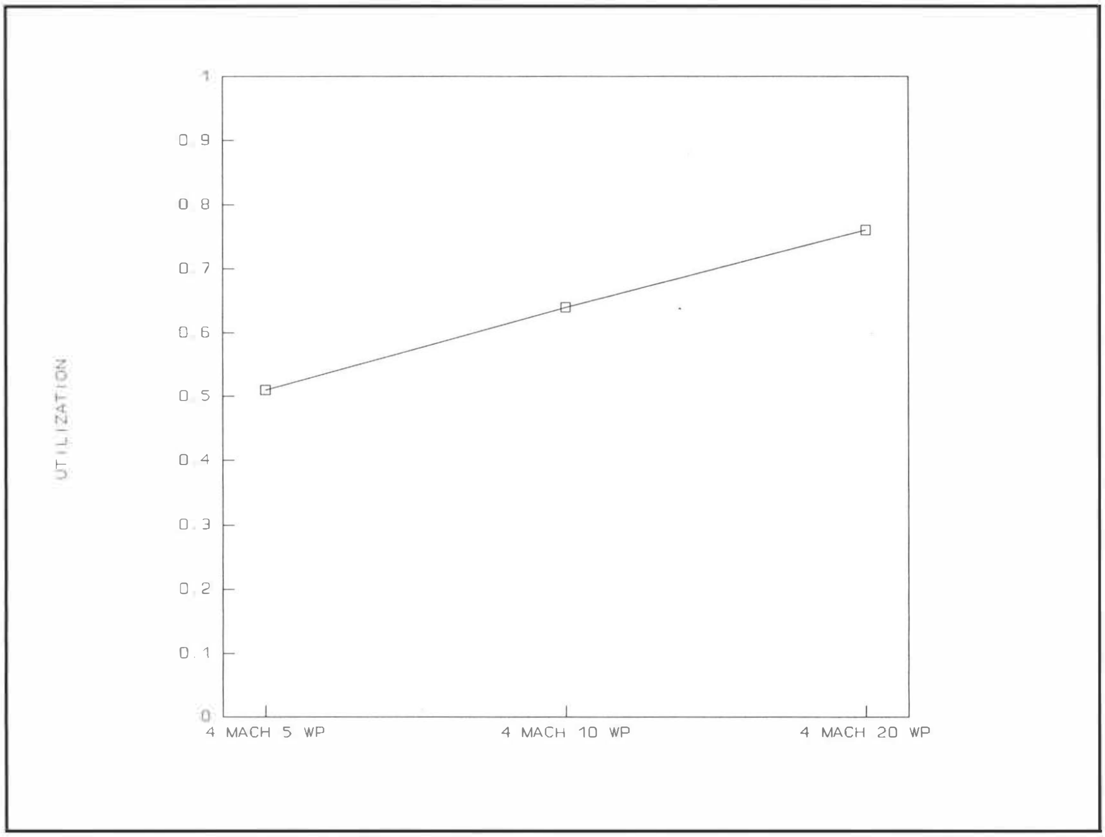

Figure 24. 4 Dedicated Machines 5, 10, 20 Workpieces.

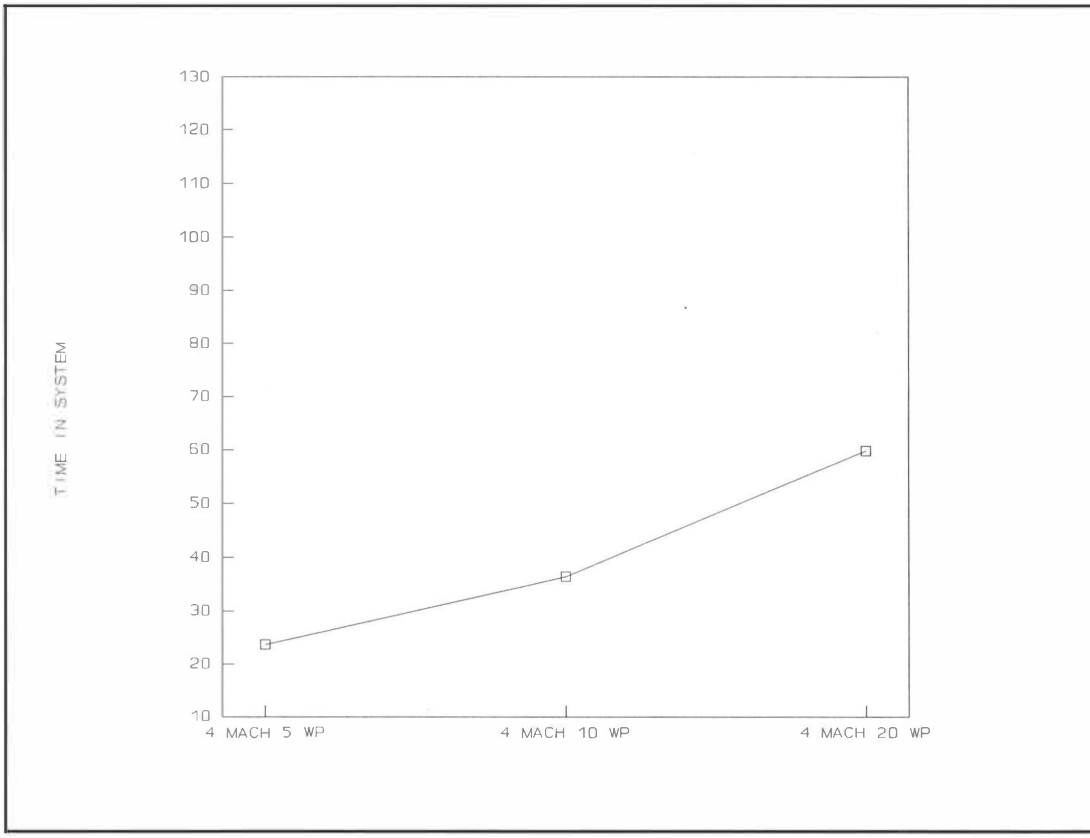

Figure 25. 4 Flexible Machines 5, 10, 20 Workpieces.

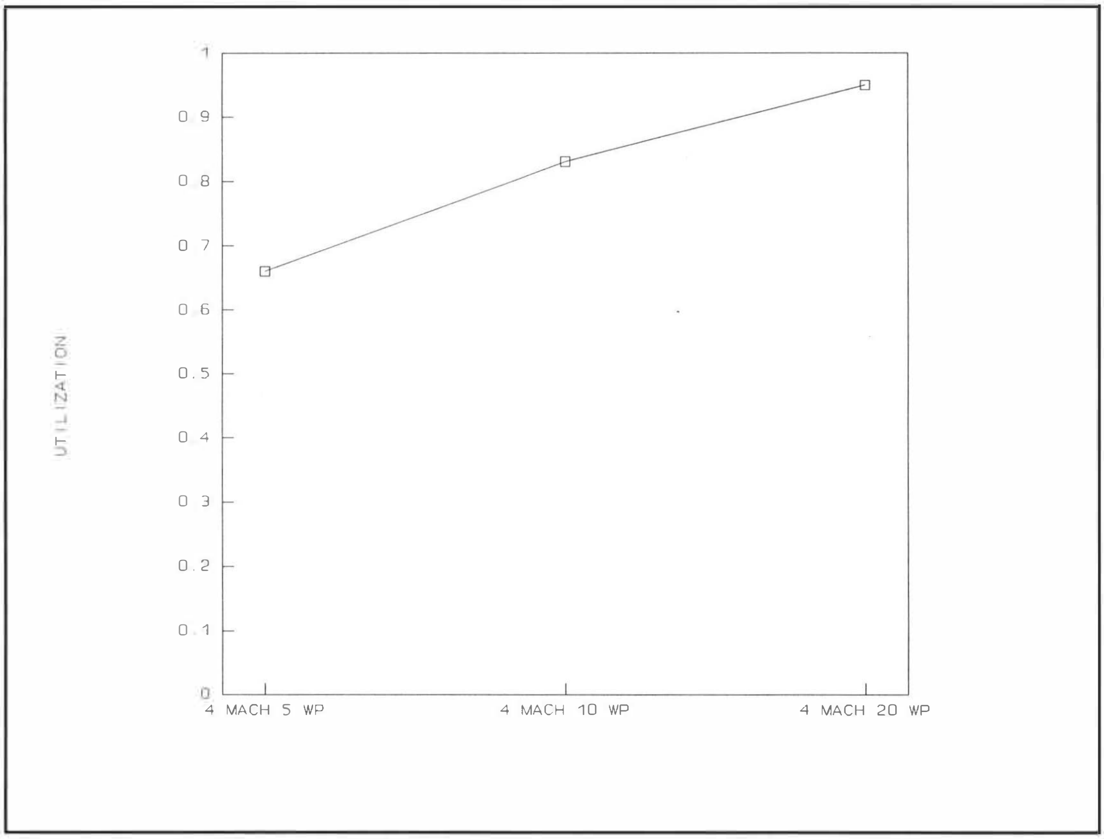

Figure 26. 4 Flexible Machines 5, 10, 20 Workpieces.

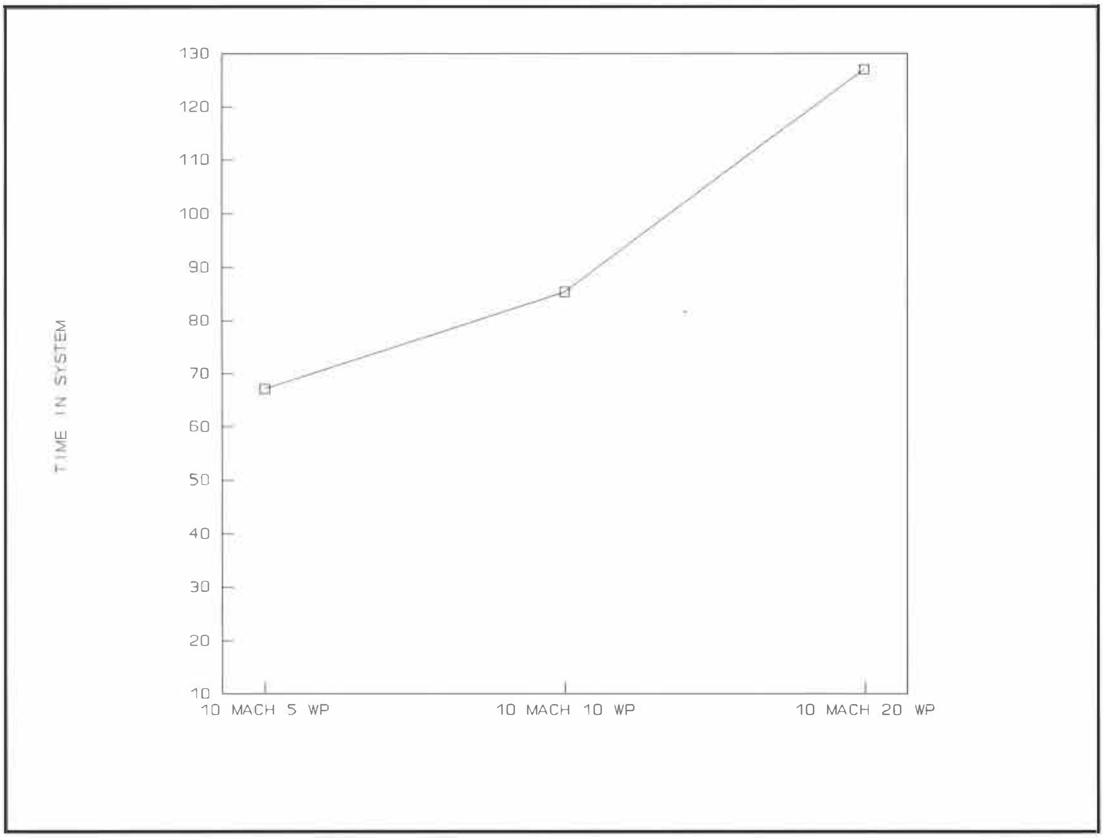

Figure 27. 10 Dedicated Machines 5, 10, 20 Workpieces.

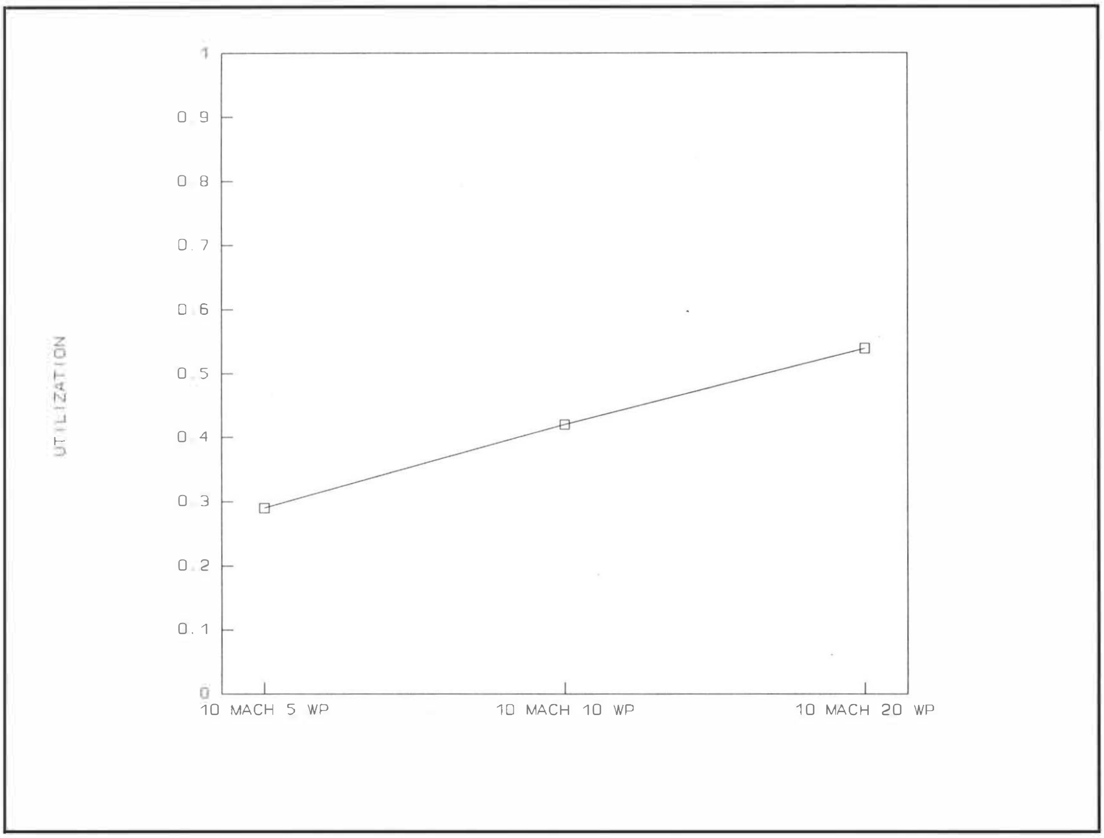

Figure 28. 10 Dedicated Machines 5, 10, 20 Workpieces.

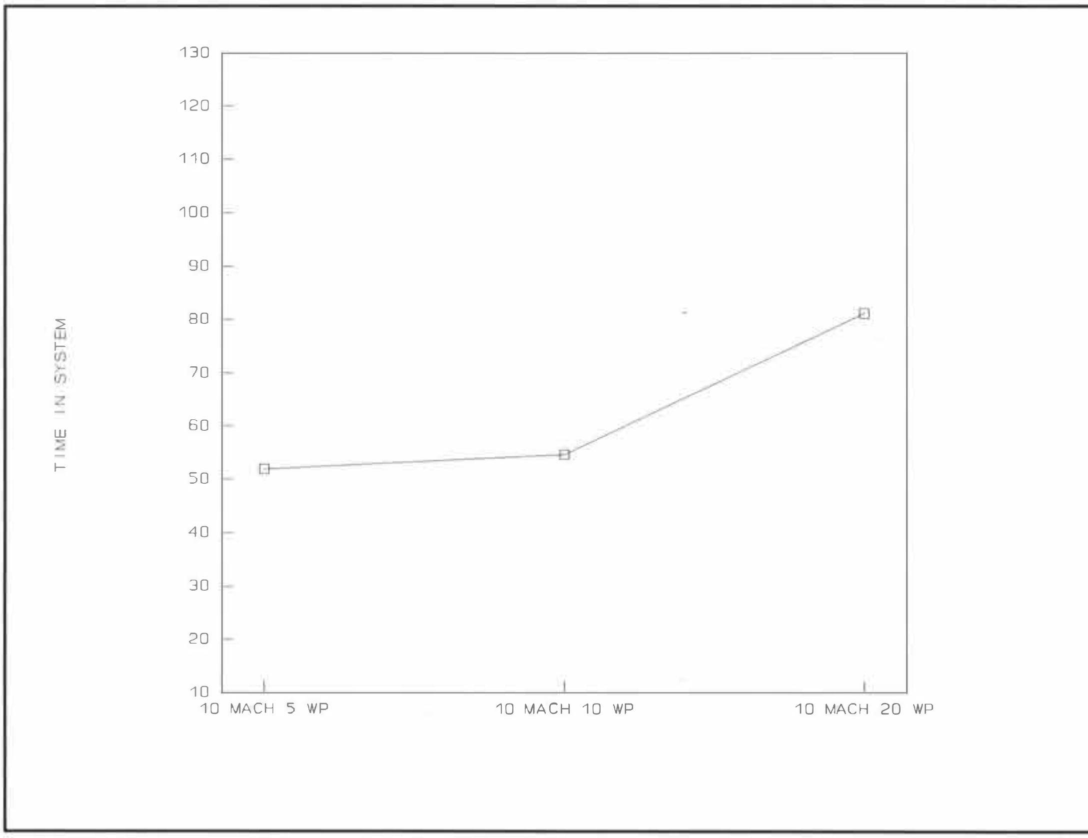

Figure 29. 10 Flexible Machines 5, 10, 20 Workpieces.

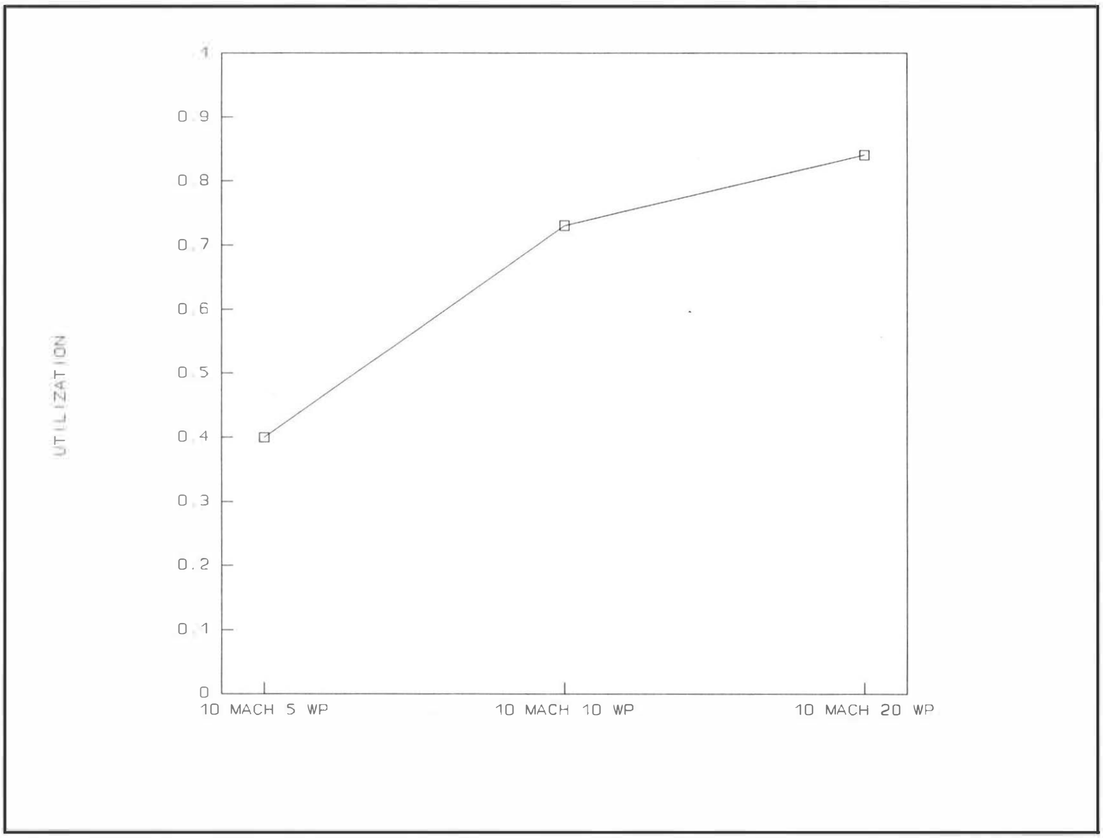

Figure 30. 10 Flexible Machines 5, 10, 20 Workpieces.

$$Z = (A*S)+(B*Q)+(C*W)+(D*U)+(E*N)+(F*T)$$

Where:
Z = Cost Benefit Function
S = Makespan
Q = Queue Length
W = Wait Time
U = Utilization
N = Number of Workpieces Processed
T = Time in System

(Where A, B, C, D, E, and F are constants associated with the relevant machine group)

And:
S = K1*U
T = K2*U
W = K3*U
Q = K4*U

(K1, K2, K3, and K4 are constants derived from system analysis)

Figure 31. Empirical Relationship.

Appendix A

Supplementary Figures

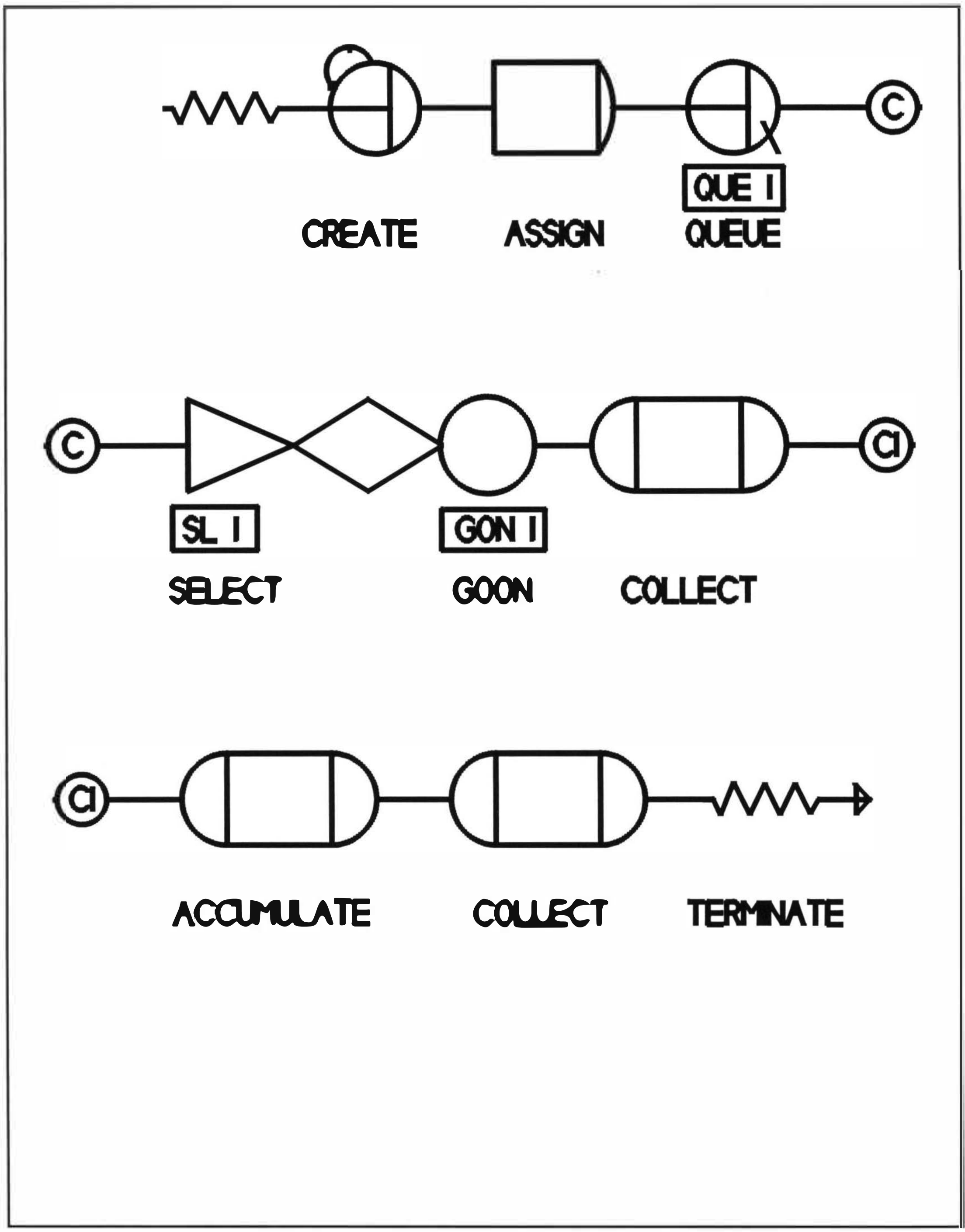

Figure 32. Network Diagram for 2 Machine Case, Both Flexible, Common for 20, 10, 5 Workpieces.

```
GEN,PATHAK,THESIS,3/31/93,5,,,,,,80;
LIMITS,1,3,21;
ARRAY(1,21)/2,3,1,4.5,3,7,6,4,5,9,5,4,6,9,8,4,3,7,6,8,9;
ARRAY(2,21)/6,4,7,8,7.8,4.5,4,6,5,8,7,3,9,6,5,7,8,3,4,5
,2;
ARRAY(3,21)/1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1;
ARRAY(4,21)/1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1;
EQUIVALENCE/ATRIB(1),TJ1/
            ATRIB(2),TJ2;
;Atrib(1) & atrib(2) are operations time for op 1 & 2
resp. ;Atrib(3) to store creation time.
NETWORK;
      CREATE,0,0,3,21,1;
      ASSIGN,II=0;
ASSIGN,II=II+1,TJ1=ARRAY(1,II),TJ2=ARRAY(2,II),XX(1)=AR
RAY(3,II),

ATRIB(1)=RNORM(TJ1,XX(1)),XX(2)=ARRAY(4,II),ATRIB(2)=RN
ORM(TJ2,XX(2)),1;
      ACT;
QUE1  QUEUE(1),,,,SL1;
SL1   SELECT,,CYC,,QUE1;
      ACTIVITY(1)/1,ATRIB(1)+ATRIB(2),,GON1;
      ACTIVITY(1)/2,ATRIB(1)+ATRIB(2),,GON1;
GON1  GOON,1;
      COLCT,INT(3),TIMEINSYSTEM,,1;
      ACCUMULATE,20,,LAST,1;
      COLCT,FIRST,MAKESPAN;
      TERMINATE,1;
      END;
INIT;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
MONTR,TRACE,50,100;
```

Figure 33. Network Code for 2 Machine Case, Both Flexible, 20 Workpieces.

Appendix B

Supplementary Tables

APPENDIX B

SUPPLEMENTARY TABLES

Tables 2, 4 and 6 present values for Time in System and Makespan for the 2 machine case with 20, 10 and 5 workpieces respectively, whereas, Tables 3,5 and 7 present values for Average Queue Length, Average Wait Time and Average Utilization for the 2 machine case with 20, 10 and 5 workpieces respectively. Tables 8, 10 and 12 present the Time in System and Makespan values for the 4 machine case with 20, 10 and 5 workpieces respectively, whereas, Tables 9, 11 and 13 present values for Average Queue Length, Average Wait Time and Average Utilization for the same 4 machine cases. Tables 14, 16 and 18 present the Time in System and Makespan for the 10 machine case with 20, 10 and 5 workpieces respectively, whereas, Tables 15, 17 and 19 present values for Average Queue Length, Average Wait Time and Average Utilization for the same 10 machine case.Individual workpiece machine operation times are assumed to be stochastic conforming to a normal distribution with mean and standard deviation. Each observation of interest obtained from the simulation report was checked for accuracy and confidence interval testing. The confidence intervals and accuracy levels are indicated under CONF. An entry of 5,95 under CONF indicates an accuracy of +/- 5 percent with a confidence level interval of 95 percent.

Tables 2 to 7 summarize the results of simulating the 2 machine work cell with 20, 10 and 5 workpieces. Tables 8 to 13 summarize the results of simulating the case of the 4 machine work cell with 20, 10 and 5 workpieces. Tables 14 to 19 summarize the results of simulating the case of the 10 machine work cell with 20, 10 and 5 workpieces respectively.

Table 2

2 Machine Case: 20 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	79.64	5,95	139.60	5,95
2 Machines 1 Dedicated and 1 Flexible	61.68	5,95	132.40	5,95
Both Machines Flexible	43.46	5,95	81.06	5,95

Table 3

2 Machine Case: 20 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	4.94	5,95	63.09	5,95	0.801	5,95
2 Machines 1 Dedicated and 1 Flexible	3.91	5,95	19.62	5,95	0.776	5,95
Both Machines Flexible	4.85	5,95	18.71	5,95	1.000	5,95

Table 4

2 Machine Case: 10 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	42.14	5,95	75.83	5,95
2 Machines 1 Dedicated and 1 Flexible	37.42	5,95	73.62	5,95
Both Machines Flexible	23.70	5,95	42.28	5,95

Table 5

2 Machine Case: 10 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	2.22	5,95	29.31	5,95	0.730	5,95
2 Machines 1 Dedicated and 1 Flexible	1.67	5,95	8.97	5,95	0.740	5,95
Both Machines Flexible	1.84	5,95	7.81	5,95	0.950	5,95

Table 6

2 Machine Case: 5 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	23.94	5,95	39.78	5,95
2 Machines 1 Dedicated and 1 Flexible	20.42	5,95	37.89	5,95
Both Machines Flexible	14.60	5,95	23.26	5,95

Table 7

2 Machine Case: 5 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
Both Machines Dedicated (Johnson's Rule)	0.924	5,95	9.61	5,95	0.584	5,95
2 Machines 1 Dedicated and 1 Flexible	0.600	5,95	3.33	5,95	0.750	5,95
Both Machines Flexible	0.690	5,95	3.19	5,95	0.890	5,95

Table 8

4 Machine Case: 20 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	78.30	5,95	152.60	5,95
4 Machines 2 Dedicated and 2 Flexible	61.36	5,95	127.60	5,95
4 Flexible Machines	59.80	5,95	112.60	5,95

Table 9

4 Machine Case: 20 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	1.81	5,95	13.78	5,95	0.76	5,95
4 Machines 2 Dedicated and 2 Flexible	1.55	5,95	9.69	5,95	0.86	5,95
4 Flexible Machines	1.96	5,95	10.48	5,95	0.95	5,95

Table 10

4 Machine Case: 10 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	52.35	5,95	89.19	5,95
4 Machines 2 Dedicated and 2 Flexible	45.45	5,95	75.74	5,95
4 Flexible Machines	36.40	5,95	62.05	5,95

Table 11

4 Machine Case: 10 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	0.828	5,95	7.40	5,95	0.64	5,95
4 Machines 2 Dedicated and 2 Flexible	0.740	5,95	4.70	5,95	0.76	5,95
4 Flexible Machines	0.637	5,95	3.96	5,95	0.83	5,95

Table 12

4 Machine Case: 5 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	33.28	5,95	53.74	5,95
4 Machines 2 Dedicated and 2 Flexible	29.68	5,95	46.30	5,95
4 Flexible Machines	23.74	5,95	39.02	5,95

Table 13

4 Machine Case: 5 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
4 Dedicated Machines	0.263	5,95	2.84	5,95	0.51	5,95
4 Machines 2 Dedicated and 2 Flexible	0.170	5,95	1.19	5,95	0.62	5,95
4 Flexible Machines	0.100	5,95	0.78	5,95	0.66	5,95

Table 14

10 Machine Case: 20 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	127.00	5,95	218.80	5,95
10 Machines 8 Dedicated and 2 Flexible	103.60	5,95	185.00	5,95
10 Machines 5 Dedicated and 5 Flexible	96.54	5,95	172.90	5,95
10 Machines 2 Dedicated and 8 Flexible	94.89	5,95	158.20	5,95
10 Flexible Machines	81.18	5,95	140.80	5,95

Table 15

10 Machine Case: 20 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	0.634	5,95	6.81	5,95	0.54	5,95
10 Machines 8 Dedicated & 2 Flexible	0.494	5,95	4.92	5,95	0.63	5,95
10 Machines 5 Dedicated & 5 Flexible	0.417	5,95	4.33	5,95	0.70	5,95
10 Machines 2 Dedicated & 8 Flexible	0.429	5,95	2.87	5,95	0.77	5,95
10 Flexible Machines	0.316	5,95	2.22	5,95	0.84	5,95

Table 16

10 Machine Case: 10 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	85.38	5,95	130.80	5,95
10 Machines 8 Dedicated and 2 Flexible	74.56	5,95	111.80	5,95
10 Machines 5 Dedicated and 5 Flexible	67.02	5,95	92.14	5,95
10 Machines 2 Dedicated and 8 Flexible	60.18	5,95	79.06	5,95
10 Flexible Machines	54.64	5,95	74.48	5,95

Table 17

10 Machine Case: 10 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	0.233	5,95	3.06	5,95	0.42	5,95
10 Machines 8 Dedicated & 2 Flexible	0.171	5,95	2.19	5,95	0.50	5,95
10 Machines 5 Dedicated & 5 Flexible	0.131	5,95	1.16	5,95	0.60	5,95
10 Machines 2 Dedicated & 8 Flexible	0.075	5,95	0.20	5,95	0.69	5,95
10 Flexible Machines	0.000	5,95	0.000	5,95	0.73	5,95

Table 18

10 Machine Case: 5 Workpieces (TIS & MS)

Machine Group	Time in System		Make Span	
	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	67.16	5,95	90.01	5,95
10 Machines 8 Dedicated and 2 Flexible	58.16	5,95	75.30	5,95
10 Machines 5 Dedicated and 5 Flexible	51.88	5,95	65.82	5,95
10 Machines 2 Dedicated and 8 Flexible	51.88	5,95	65.82	5,95
10 Flexible Machines	51.88	5,95	65.82	5,95

Table 19

10 Machine Case: 5 Workpieces (Av. Q_L, Av. Q_T, Av. U)

Machine Group	Ave. Queue Length		Ave. Wait Time		Ave. Utilization	
	MEAN	CONF	MEAN	CONF	MEAN	CONF
10 Dedicated Machines	0.085	5,95	1.530	5,95	0.29	5,95
10 Machines 8 Dedicated & 2 Flexible	0.037	5,95	0.616	5,95	0.35	5,95
10 Machines 5 Dedicated & 5 Flexible	0.000	5,95	0.000	5,95	0.40	5,95
10 Machines 2 Dedicated & 8 Flexible	0.000	5,95	0.000	5,95	0.40	5,95
10 Flexible Machines	0.000	5,95	0.000	5,95	0.40	5,95

BIBLIOGRAPHY

Abdel-Malek, L. & Wolf, C. (1991). Evaluating flexibility of alternative FMS designs, a comparative measure. International Journal of Production Economics,23, 3-10.

Alptenkin, S., & Webber, D.L. (1988). A systematic transition to flexible manufacturing. Computers and Industrial Engineering,15 ,13-18.

Blank, L. (1987, Fall). Total return requirements for technology investments. Cost Management, 46-48.

Boaden, R.J., and Dale, B. (1990). Justification of computer integrated manufacturing: some insights into the practice. IEEE Transactions on Engineering Management,37(4), 291-296.

Burstein, M.C., & Graham, P. (1990, September). Strategic justification of plant-level investments. Manufacturing Review,3(3), 171-177.

Canada, J.R. (1986, March). Non-traditional method for evaluating CIM opportunities assigns weights to intangibles. Industrial Engineering, 66-71.

Discenza, R., & Gurney, B. (1990, 2nd Quarter). New considerations for evaluating capital equipment purchases. Production and Inventory Journal, 33-37.

Engwall, R. (1988, Spring). Investment evaluation methodologies. Cost Management, 40-44.

Fraker, S. (1984, March 5). High speed management for the high-tech age. Fortune,109(5), 62-64.

Ghosh, S., & Gaimon, C. (1992). Routing flexibility and production scheduling in a flexible manufacturing system. European Journal of Operational Research,60, 344-364.

Grud, J.M. (1984). Can manufacturing systems change be justified? Production and Inventory Management,25(2), 93-105.

Hendricks, J.A. (1988, December). Applying cost accounting to factory automation. Management Accounting, 24-30.

Hutchinson, G.K. & Sinha, D. (1989). A quantification of the value of flexibility. Journal of Manufacturing Systems,8(1), 47-57.

Jelinek, M. & Goldhar, J.D. (1986, Winter). Economics in the factory of the future. CIM Review, 21-28.

Klahorst, T.H. (1983, September). How to justify multi-machine systems. American Machinist ,67-70.

Leung, L.C., & Tanchoco, J.M.A. (1983). Replacement decision based on productivity: an alternative to the MAPI method. Journal of Manufacturing Systems,2(2), 175-183.

Miltenburg, G.J. (1987). Economic evaluation and analysis of flexible manufacturing systems. Engineering Costs and Production Economics,12, 79-92.

Naik, B., & Chakravarty, A.K. (1992). Strategic acquisition of new manufacturing technology: a review and research framework. International Journal of Production Research, 30(1), 1575-1601.

Plossl, G.W. (1990). Cost Accounting in manufacturing: Dawn of a new era. Production Planning and Control,1(1), 61-68.

Pritsker, A. Alan B. (1986). Introduction to Simulation and SLAM II. Chicago: John Wiley & Sons.

Robinson, R. (1982, November). CAD-The financial aspects. Design Engineering, p. 125.

Son, Y.K. (1992, Fall). A comprehensive bibliography on justification of advanced manufacturing technologies. The Engineering Economist,38(1), 59-71.

Swamidass, P.M. (1989). Manufacturing Strategy: A selected bibliography. Journal of Operations Management,8(3), 263-277.

Tombari, H. (1983, July). Analyzing the costs and benefits of CAM methods. P&IM Review and APICS News, 36-40.

Venk, S. (1990). Strategic optimization cycle as a competitive tool for economic justification of advanced manufacturing systems. Journal of Manufacturing Systems, 9(3), 194-205.

Wiely, D.T. (1986). Automation Technology: past, present and future. Production and Inventory Management, 27(4), 10-19.

Yalowitz, M.S. & Levine, S.J. (1983, September). Managing technology: the key to successful business growth. Management Review, 44-48.

Zeschmann, H. (1985, March). The dilemma of economic justification for advanced industrial systems and equipment. Proceedings of the 7th Annual Engineering Managers Conference, 134-140.