1-1-1995

FMS loading with reliability consideration.

Abi M. Philipose
University of Windsor

FMS LOADING WITH RELIABILITY CONSIDERATION

By

Abi M. Philipose

A thesis submitted to the
Faculty of Graduate Studies and Research
through the Department of Industrial
and Manufacturing Systems Engineering
in partial fulfilment of the requirements for
the Degree of Master of Applied Science
at the University of Windsor

UNIVERSITY OF WINDSOR
Windsor, Ontario, Canada

1995

To

God

be the Glory.

I hereby declare that I am the sole author of this thesis. I authorize the University of Windsor to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Abi M. Philipose

I further authorize the University of Windsor to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Abi M. Philipose

The University of Windsor requires the signatures of all persons using or photocopying this thesis. Please sign below, and give an address and the date.

ABSTRACT

Availability, flexibility, and productivity are the major reasons luring manufacturers to opt for Flexible Manufacturing Systems (FMSs). Experience has shown that the equipment and hardware alone does not get the production facility to this goal. Scheduling and production planning, especially loading, plays an important role in determining the efficiency of the production facility. This research deals with loading a FMS, with reliability considerations.

It is desirable to run a production plant at 100% reliability. However, the costs involved in increasing the reliability varies in a non-linear trend. Realising the importance of the reliability factor in production planning, three mathematical models were developed. Two of the models were full loading problems, while the third is a partial loading problem. With the objective of minimizing the tooling costs, the larger models partition the demand into batches, assign batches to machines, assign tools to machines, and determine the location of the spare tools. The smaller model assumes that the batches are assigned to machines, by other means, and so this model assigns tools to machines and determines optimal spares. Although newer and true FMS have tool sharing capability, the older systems do not. Mathematical models were developed for both these cases.

For the first time, the reliability factor has been coupled directly with the mathematical loading model. Hypothetical, but realistic problems have been solved using the model.

ACKNOWLEDGMENTS

I would like to express my appreciation to my supervisor Dr. S.M. Taboun, for his advice, criticism, patience, and moral support during the course of this research. I would like to thank to my committee members, Dr. M. Ahmadi and Dr. M. Wang, for their time and advice.

I would like to thank Mr. Tom Williams, computer system manager, and Ms. Jacquie Mummery, secretary of the Industrial and Manufacturing Systems Engineering, for their help and assistance.

I wish to express my gratitude to all my friends, especially V.K. Damodran, S.R.V. Majety, Alper Ozdemir and A. Atmani for their support, stimulating discussions and friendship.

I would like to thank my parents for their love, support and encouragement during the entire period of my education.

Finally, I thank my wife and children, who patiently endured difficult times, and their support has contributed to the completion of this dissertation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 An Overview

Since the turn of the century, the markets of the world are progressively integrating into one global market. At the same time, the market has been steadily drifting from a seller's market to a buyer's market. In the earlier days of the century, a flourishing businessman stated, "people can order any colour of car as long as it is black". Today, the company offers hundreds of colour and shade combinations for its customers to choose. Besides variety, it is important to treat time as a critical source of competitive advantage. So, trimming manufacturing lead time and product development time are also of great importance. Thus, the changing market trend demands efficiency, quality, flexibility and ingenuity from the manufacturers.

To compete in such a global economy, flexible manufacturing systems has emerged to be a key operating strategy, especially for the discrete parts manufacturers.

Flexible manufacturing has the potential to achieve the productivity of mass production, while still offering a wide range of flexibility. A Flexible Manufacturing System (FMS) can be defined as a set of CNC machines and supporting workstations that are interconnected by an automated material handling system and controlled by a central computer (Askin 1993). Reduced labour, improved machine utilization, improved operational control, improved product quality, reduced floor space requirement and reduced inventory are some other benefits of using FMS.

Although FMS provides significant economic production in the long run, such systems are highly capital intensive. Financial justification forms an integral part of an FMS implementation. While too much or too soon creates excessive work in progress, too little or too late leads to under-utilization of the facility. To maximize the return of investment, one has to use the facility optimally. Flexible manufacturing being different and similar to conventional manufacturing systems, it provides new and extensions of older problems of operation research. The problems include designing the required system, planning the operation to maximize the plant utilization, carrying sufficient redundancies like tools, for an uninterrupted operation, and scheduling for the production period. A high degree of system reliability is imperative in the operation of the system and in justifying the investments.

In setting up an FMS, two groups of problems have to be addressed - Design and Operational. The Operational problems can be further sub-divided into Planning, Scheduling, and Control problems -(Stecke 1983). This research focuses on the loading of the FMS, which is a part of the planning sub-section of the operational problem.

When FMS is employed for machining, assembly, or fabrication, they use a set of tooling to perform the function. The system calls these tools sequentially, to perform the desired operations. The tools wear out, break, or require resetting and maintenance, from time to time, during the production run. Industrial data indicate that tooling accounts for 25-30% of the fixed and variable cost of production in an automated machining environment (Ayres 1988). Shaw (1980) described tool breakage as the single most significant factor that reduces the productivity of manufacturing systems.

A key requirement for an efficient operation of an FMS is the existence of a comprehensive tool management system. A certain level of reliability is required of the individual tools and the tooling system as a whole to ensure an uninterrupted, production run. Sufficient redundancies must be foreseen at the preliminary production planning stage, to cope with the various tool requirements. Whereas the cost of redundancy is a negative factor, the additional reliability gained is a positive factor. So, installation of redundancy is an issue that needs to be optimized, subject to constraints.

1.2 Objectives of the Research

The objective of this research is to develop a model for loading an FMS. Machine Loading is defined as the decision associated with allocating jobs and the required tools among the machining centres, subject to restrictions on the system. The machine loading problem includes three entities; viz, the job, the tool and the machine. A model taking care of all three entities would be a full machine loading model. Otherwise, the problem is called a partial loading problem.

Flexible manufacturing systems in their complete form will allow tool sharing between machines, via a gantry or monorail robot arm. However, tool sharing would need additional investments in terms of equipment required, and more complicated tool management policies. In practice, there are many FMS systems, where tool sharing is not possible.

In this research, three sets of models have been considered. Each model is formulated for two conditions. One, where tool sharing is permitted, and the other, where tool sharing is restricted.

The first model is a formulation to solve a full loading problem. Given the demand of parts to be processed, process plans available to process the parts, number of machines available for the production period, the span of the production period, capacities of the tool magazines, and tool types available, the formulation divides the demand into optimal batches, assigns process plans to the individual batches, assigns batches to machines, assigns tool types to machines, determines their optimal spares level, and the locates the spares in the different magazines. The objective is to minimize the tooling costs.

A manufacturer always desires 100% reliability from the production shop. However, higher reliability also costs more. The second model considers all the loading problems and constraints mentioned above and then minimizes the tooling cost, and also calculates the reliability with which an optimal batch is being processed by the facility.

In many practical cases, the parts may not be assigned to the machines, based on the similarity of their operations alone. In such cases, the demand will be partitioned into batches and assigned to be processed by a particular process plan. Whereas the second model made an evaluation of the reliability of processing a batch, this model provides a generic solution to assigning tool types to machines, and optimizes the number of spares assigned to the machines, such that every batch is processed with minimum specified reliability. A linear program was developed that accommodated the non linear reliability requirement.

Numerical problems were solved using the formulated models to test their validity. The problems and their solutions have been provided.

Organization of the Research :

The documentation of the research is organized as follows. A literature review of the past research works on tool life, tool life management, loading problems and solutions in automated manufacturing, and analogous research is presented in Chapter 2. Some basic and important definitions, concepts and mathematics have been reviewed in Chapter 3. Chapter 4 introduces the definition of the loading problem being considered in this research. Nomenclature used have been shown. Later the three models, each with two case scenarios have been derived. In Chapter 5, hypothetical, but realistic numerical problems were taken up and solved using the derived mathematical models. Some of the results obtained were verified using a simulation model using Witness simulation package. Conclusions and recommendations for future work have been presented in Chapter 6. Various formulations done on Lindo, Lingo, Witness, and C language have been recorded in the appendices.

CHAPTER 2

TERMS AND DEFINITIONS

Before taking up an FMS loading problem, with reliability considerations, and building mathematical models, it would be advantageous to review some fundamental concepts and definitions. A *flexible manufacturing system* can be defined as an arrangement of CNC machines, interconnected by an automated material handling system, where the processing and movements of the workpiece is controlled in conjunction with a central computer. An FMS thus has the advantage of having the capability to process a wide variety of products, in a near random order. One can now visualize that the critical factor determining the performance of an *FMS* is ensuring the optimal availability of machines and tools, as the demand for a certain workpiece comes up, in a random order.

It is thus important to concentrate on the operational problems to achieve an efficient operation. *Loading* is the focal point of production planning. Loading an FMS deals with grouping the wide variety of workpieces into smaller groups, based on their attributes, and assigning the available machines and tools to process the demand. Therefore there have been numerous research studies, dealing with loading an FMS.

Tool management is the capability of having the required tools on the appropriate machines, at the right time, so that the desired quantities of workpieces are manufactured, while maintaining acceptable utilization of assets (Tomek 1986). Gaalman (1987) described *tool sharing* as a situation where the unavailable tool on a machining centre, at a particular time, can be borrowed from other machining centres in the system. Although a modern FMS would have tool sharing between machines, there are older and lower capital systems where this facility does not exist. In this research, both these scenarios were studied and modelled separately, and the numerical results compared.

Reliability can be defined as, "the probability that an item (or system) will perform its function adequately for the desired period of time when operated according to the specified conditions." (Dhillon 1982). In other words, reliability is concerned with determining the probability that a system consisting of many components will perform its function. A system, where all constituent parts must function successfully, in order to get a complete system performance is called a *series system*. Thus, in a system of this kind, the first failure of a constituent part will cause a system failure. A system where at least one of the similar constituent parts has to function well for the system to perform is called a *parallel system*. Schematic representation of a series and parallel systems have been shown in Figure 2.1 and Figure 2.2.

Achieving higher reliability level often leads to the use of functional elements that are interchangeable modular components, or *redundancies*. Redundancy could be system level, or state level. System level of redundancy, also called high level redundancy, often means higher capital costs and lower utilization levels. State level, or component level is a more popular redundancy strategy. The state level redundancy, or lower level redundancy can again be sub-divided into two categories, based upon the presence or absence of the decision and switching devices. If the redundant components are continuously in an operating state, and are employed in performing the system function, the redundancy is called parallel redundancy. If the redundant components do not perform any function, unless the primary component fails, the redundancy is called *standby redundancy*. When a switching , or standby redundancy is employed, it is necessary to have a device, capable of detecting the failure and switching to the redundant component. A schematic representation of a system with standby redundancies is shown in Figure 2.3. It is regrettably necessary, for mathematical reasons, to assume that the sensing of failure is perfect, and replacement of the failed unit is made instantaneously. Also, independence is assumed between the components, and the components are assumed not to impede or interfere with one another.

While dealing with reliability engineering, it is important to know the relations and differences between the terms Failure Distribution Function, Reliability Function, Hazard Function, and Cumulative Hazard Function.

Failure Distribution Function F(t): Failure distribution function is defined as the probability of failure of an element or component during the time interval [0,t]. Mathematically, probability of failure as a function of time can be represented as

$$P(0 \leq \mathit{t} \leq t) = F(t), \qquad t \geq 0.$$

where *t* is a random variable denoting the failure time.

Reliability Function R(t): Reliability is defined as the probability that the system will perform its intended function during the time interval [0,t]. Mathematically represented as,

$$R(t) = 1 - F(t) = P(\mathit{t} \geq t \geq 0).$$

If the time to failure random variable *t* has a density function *f(t)*, then:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)\,dt = \int_t^\infty f(t)\,dt \qquad (1)$$

Hazard Rate h(t): The hazard rate is the conditional failure rate of the component which is usually expressed in failure per unit time. That is, if *t* represents the time to failure of a component, **h**(t) *dt* is the probability that a component that has survived up to time *t* will fail in the next time interval *dt*. The function **h**(t) can be defined by

$$h(t) = \frac{f(t)}{1 - P(t)} = \frac{f(t)}{R(t)} \tag{2}$$

Considering the above relationship, a general formula of reliability function in term of hazard rate can be expressed by (Dhillon, 1982).

$$R(t) = \exp\left(-\int_0^t h(t)\, dt\right) \tag{3}$$

USEFUL STATISTICAL DISTRIBUTIONS

A number of statistical distributions have been used to model failure characteristics. Table 2.1 summarises most of the more widely used distributions including those which are applied more often in mechanical reliability assessment. The associated reliability and failure functions, hazard rate, and the range of parameters variation are also listed.

Type of distribution	Probability density Function f(t)	Cumulative Distribution Function F(t)	Reliability Function R(t)	Hazard Rate h(t)
Normal	$\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right]$ $-\infty<t<\infty$	$\int_0^t f(t)\,dt$	$\int_t^\infty f(t)\,dt$	$\frac{f(t)}{R(t)}$
Lognormal	$\frac{1}{t\sigma\sqrt{2\pi}}\exp\left[-\frac{(\log t-\mu)^2}{2\sigma^2}\right]$ $0<t<\infty$	$\int_0^t f(t)\,dt$	$\int_t^\infty f(t)\,dt$	$\frac{f(t)}{R(t)}$
Weibull two-parameter	$\frac{\beta t^{\beta-1}}{\lambda^\beta}\exp\left[-\left(\frac{t}{\lambda}\right)^\beta\right]$ $t\geq 0,\ \lambda>0,\ \beta>0$	$1-\exp\left[-\left(\frac{t}{\lambda}\right)^\beta\right]$	$\exp\left[-\left(\frac{t}{\lambda}\right)^\beta\right]$	$\frac{\beta t^{\beta-1}}{\lambda^\beta}$
Exponential	$\lambda\exp(-t\lambda)$ $t\geq 0$	$1-\exp(-t\lambda)$	$\exp(-\lambda t)$	λ
Gamma	$\frac{\lambda^\eta}{\Gamma(\eta)}t^{\eta-1}\exp(-t\lambda)$ $t\geq 0,\ \eta>0$	$\sum_{k=\eta}^{\infty}\frac{(\lambda t)^k\exp[-\lambda t]}{k!}$	$\sum_{k=0}^{\eta-1}\frac{(\lambda t)^k\exp[-\lambda t]}{k!}$	$\frac{f(t)}{R(t)}$
Special Erlangian	$\frac{t}{\alpha^2}\exp\left(-\frac{t}{\alpha}\right)$ $t\geq 0$	$1-\left(1+\frac{t}{\alpha}\right)\exp\left(-\frac{t}{\alpha}\right)$	$\left(1+\frac{t}{\alpha}\right)\exp\left(-\frac{t}{\alpha}\right)$	$\frac{t}{\alpha(t+\alpha)}$

Table 2.1 : Some Statistical Distributions Useful in Reliability Engineering.

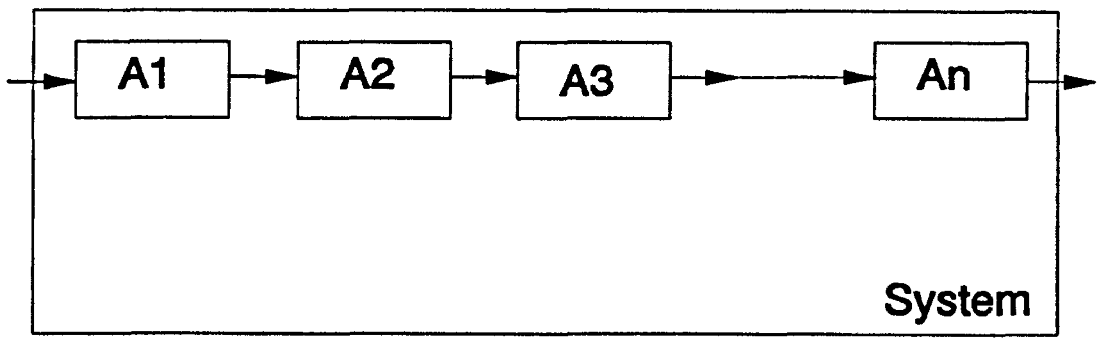


Figure 2.1 : Representation of a Series System

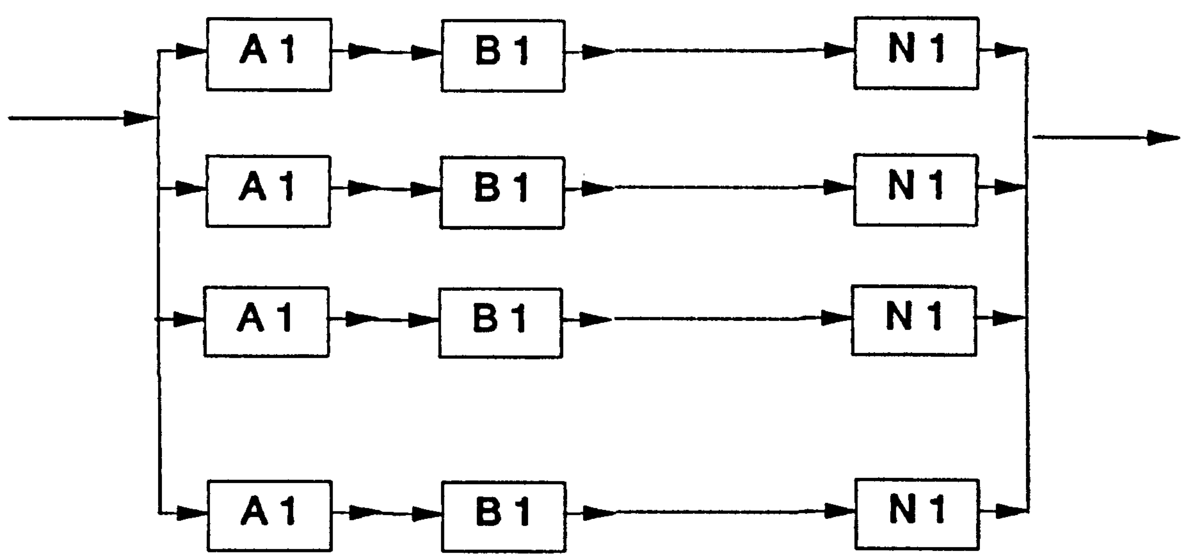


Figure 2.2 : Representation of a Parallel System

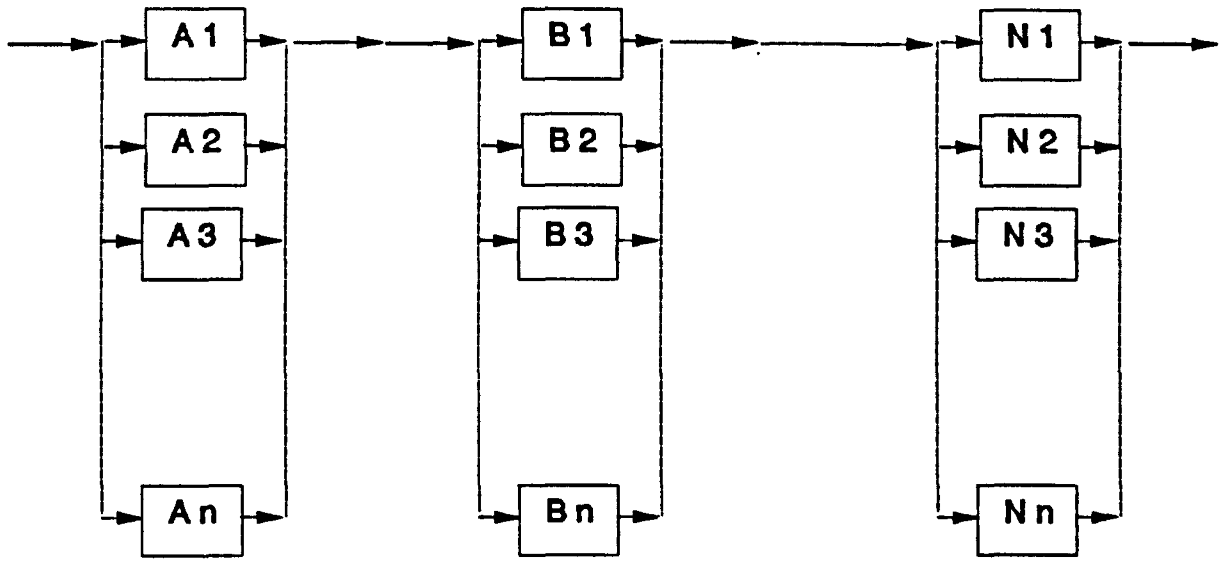


Figure 2.3 : Series System with Standby Redundancies

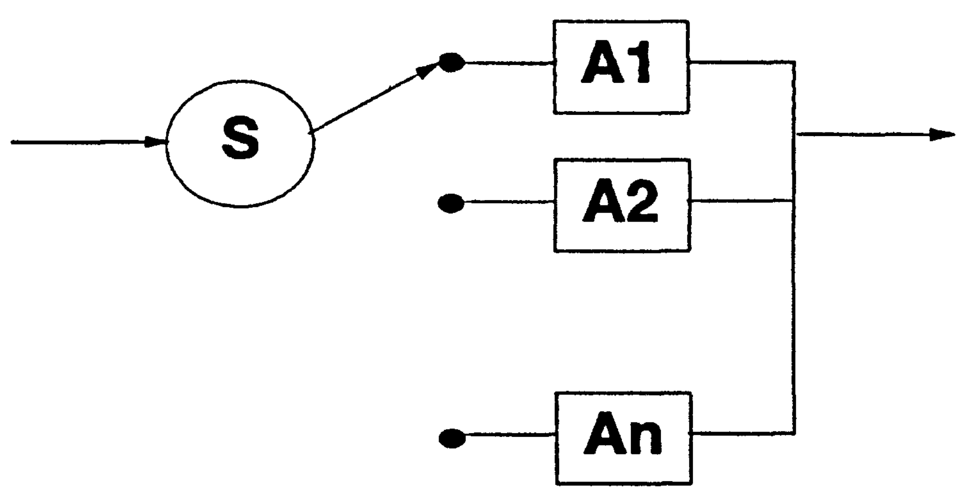


Figure 2.4 : Standby Redundancy with Switching Device

CHAPTER 3

LITERATURE SURVEY

The basic objective of the FMS concept is to achieve the efficiency and utilization of mass production, while retaining the flexibility of a job shop - (ideally). To achieve this goal, the production has to be well planned for an optimal run. Machine loading and tool allocation is considered as the lowest level of production planning problem. Both mathematical programming models and simulations are employed to solve loading problems in FMS. A detailed study of the literature on flexible manufacturing system as a whole was done before concentrating on the problem. This literature review can be divided into five groups, namely tool life, tool management, loading models, analogous systems, and reliability evaluations.

3.1 Tool Life :

To model a loading problem, it is important to assess the life of a cutting tool during which the quality of the workpiece is acceptable. The ability to effectively assess the 'useful life' of a tool would result in diminished inventory costs, optimal replenishing policies, fewer machine stoppages for tool changes, and reduced workpiece rejects. A tool is considered 'failed' when it either will not cut, or cuts in a manner grossly different from a sharp tool. The failure may be caused due to a 'single-injury' or due to a 'gradual wear'. In the manufacturing shops a tool has to be removed from service when it produces unsatisfactory jobs, or routinely removed prior to this point, if its 'economic tool life' is reached.

Gradual tool wear can be of various types, like flank wear, notch wear, crater wear, edge rounding, etc. There has been no universally acceptable physical explanation for tool failures. An empirical study assumes that even though various wear mechanisms come into play, gradual wear is produced by temperature-dependent mechanisms, and temperatures are greatly affected by cutting speeds. Taylor (1907), developed the relationship between average tool life and cutting velocity, through an empirical study of tool wear. His tool life equation is :

$$VT^n = k \qquad or \qquad T = \left(\frac{k}{V}\right)^{\frac{1}{n}} \tag{3}$$

Where:

T actual tool life of the cutting time between resharpening (minutes);

V cutting speed (feet/minute);

n,k empirical constant;

Heat generation increases with the increase in undeformed chip thickness and the chip width. Cook (1973) provided an extension to the above relationship relating the feed, speed, and depth of cut for a given tool life value, given as :

$$V_t = \frac{k}{d^x f^y} \tag{4}$$

Where

V_t equivalent cutting speed (feet/minute) for a given tool life;

f feed per revolution (inches);

d depth of cut (inches);

x, y, k empirical constants;

These equations provide the expected values for a gradual wear. Tool life however, depends also on the arrival of 'single-injury' events. The underlying physics of tool wear being so complicated, for general purposes, a failure rate function is best developed from previous tool failure data.

Tool life being highly case sensitive, there have been extensive studies, under varied conditions addressing the problem. For a rational design of a flexible manufacturing system, the statistical variability of tool life would provide a better understanding of the system. The literature indicates that standard distributions such as Normal, Log-normal, Weibull, Exponential, and Gamma distributions as well as their combinations, can be justified and fitted to describe the life of a tool under varied machining conditions.

Wagner and Barash (1971) reported that for high-speed steel turning tools the tool life values are subjected to a statistical distribution which can be approximated by a normal distribution. Based on experimental investigation, Hitomi et al. (1979) have suggested that the log-normal distribution conform for the tool-wear distribution. Friedman and Zlatin (1974) studied the tool life variation for several metal and cutting tool-workpiece combinations. Jeng and Yang (1992) derived a tool replacement model that took a general modelling approach to accommodate wider applicability. The expected part dimension was assumed to be a nonlinear function which had its effect from the cutting tool wear. The uncertain effects were aggregated together and treated as a random error. The wear process was divided into three periods, the initial wear period, the steady or normal wear period, and the accelerated wear period. Optimal initial tool setting and the tool replacement cycle was determined.

A noteworthy contribution to the study of tool life was provided by Ramalingam and Watson in their three part publication. Ramalingam and Watson (1977), presented the results obtained in cases where the useful life of a tool is terminated by a single catastrophic injury. It was shown that for a time-independent degradation, the tool life distribution can be given as an exponential distribution, or in other words a Weibull distribution with shape parameter, $\beta=1$. In the case of time-dependent degradation, the distribution obtained was a general Weibull distribution. So in general, the tool life distribution for both time-dependent and time-independent failure hazards is given by a Weibull distribution, and β is an indication of the time-dependence of the degradation process. Ramalingam (1977) addressed the case where the tool is considered to deteriorate by a gradual wear and cumulative wear process. The tool reaches the end of its life when a specified volume of material is removed from a relevant surface (flank surface or rake face) of the tool. It was shown that in the linear wear regime, the approximation of the life distribution by a normal distribution is not, in most cases, unrealistic. In the non-linear case the distribution was more log-normal. Whereas the first and the second parts of the publication used an arbitrarily introduced hazard function to account for the distributed tool life, Ramalingam et al. (1978) showed that the hazard function has a physical basis and is determined by the interaction between the properties of the tool material and the characteristics of the loading environment in which the tool operates. The model addressed in the first part was revisited. With the new hazard function obtained now, the tool-life distribution for single injury tool failure was shown to be a Weibull distribution, thus showing the previous modelling to be physically meaningful and realistic.

3.2 Tool Management :

It has been seen that the productivity of a FMS can be severely limited, without an efficient and well maintained tool-management system. FMS being capable of performing a wider variety of operations, poses the problem of being supplied by a varied types of tools, at different times during the production run. Typically, the flexibility of an FMS is constrained by pallets availability and tool magazine capacity. An effective tool management policy should thus,

- ✓ provide sufficient redundant tools at the machine, to take care of tool breakages and/or tool wear.
- ✓ use preset tools to avoid larger and excessive tool inventory.
- ✓ maximize the variety of jobs that can be produced by the machine, under the given resource constrains
- ✓ minimize the movement of tools between machines, during a production run, thereby improving the machine utilization.

Hankins and Rovito (1984) compared two tool allocation and distribution strategies through a case study. It was seen that for the case in study, the tooling strategy affected the number of machines required, the level of manpower required, and the level of tooling inventory. The strategies compared were bulk exchange and tool migration at the completion of workpiece. As for the tool distribution, the bulk exchange strategy was matched with manual loading and unloading of the machine matrix, while the migration strategy was matched with automated loading and unloading. The comparison study was done, using a Simulation. The data used as the input was the data gathered from metal working industries using this kind of systems.

Kiran and Karson (1988) noted that even after flexible manufacturing systems became operational, tool management studies were not given sufficient attention. After some financial disasters, both the FMS users and the machine tool builders recognized that tooling can have a major effect on the performance of FMS. Usually an FMS is used in a medium variety / medium volume manufacturing environment. Tool management would be even more important and complicated, as the systems find their application in a low volume/high variety environments. The objective of an effective tool management system is to provide the required tools to every operations on the scheduled machine at the right time, so that the desired quantities of workpieces are processed, while maintaining acceptable utilization of assets.

Hedlund et al. (1990) used simulation to model the complex manufacturing operations and controlling algorithms of a flexible manufacturing cell. The study was done to compare the tool delivery system for an actual FMC being installed. Since parts to be machined included hardened steel, some tool lives were foreseen to be as small as 5 minutes, which in turn demands a very effective tool management. The system investigated consisted of seven CNC machines with a tool magazine of 50 or 68 tools. In addition, there were two carousels, each having a capacity of 140 tools. An overhead monorail robot was used for the tool transfers between the machines and/or carousal. In advance of parts being brought to a machine for processing, the first five tools were allocated, and the tool magazine was checked for those tools. Three delivery options were debated. To help in analyzing the behaviour of the system, multiple output statistic screens were developed to monitor the system during the simulation process. The simulation identified the bottlenecks in the system.

Kolahan (1993) emphasised the need for the reliability analysis of the tooling system in FMS. Reliability based models were developed to evaluate the tooling system by its performance under different tooling strategies. The models determined an optimal set of spares of required tools, so that the system attributes were optimized, with the objectives of minimizing the tooling cost and the occupancy of the tool magazine. Models were developed for both situations where tool sharing was restricted and permitted, thus quantifying the difference between the strategies, in terms of tooling costs. The non-linear reliability constraints were linearized to form a linearized 0/1 integer model. A machine in the system could perform all the operations assigned to the workpiece, as long as the required tools were available at the required time. A tool was considered to be within its useful life, as long as the cumulative hazard function of the tool was less than the threshold. The value of the required reliability of the system, and hence the threshold value of the cumulative hazard was considered as a management policy. Since the life time of the tools were less than the required operation time during a production period, sufficient redundancies would have to be carried. More so, because a workpiece could have only one process plan for its operations, or the best process plan would have to be selected outside the model. A part entering the system was loaded on a machine, where different tool types performed their operations, one after the other. Therefore the problem could be treated as a series system, with standby redundancies. A magazine was allowed to have a maximum of only five redundancies of a tool type, and the examples cited were suited to the assumption. However, the individual tools were allowed to have any of the three failure distributions. The research also included a model for reliability optimization. A search algorithm was developed, which minimizes the tooling cost by a criterion of getting maximum reliability improvement per unit cost. The procedure was repeated until the desired system reliability was obtained, or the system resources were exhausted.

3.3 Loading :

Stecke (1984) partitioned the FMS problems as Design, Planning, Scheduling, and Control problems. Planning problems appear after the FMS is implemented, and is in production. As a part of the planning problem, the part types have to be grouped together, and have to be assigned to the available machines, along with the required tools to process it, while ensuring that the resource constraints are not violated and that the returns are maximized. This subset of activities is termed as loading. Loading is an important component of the overall FMS operational problem. Therefore, loading has been the focal point of numerous research studies. Some of the salient literature has been cited below. The literature has been divided into three groups, based on the approach to the solution of the problem undertaken, i.e., analytical approach, heuristic approach, and simulation approach.

3.3.1 Analytical Approach :

Stecke (1983) defined five production planning problems that have to be solved for efficient use of an FMS. The problems being part type selection, machine grouping, production ratio, resource allocation, and loading. The paper addressed the problems of machine grouping and loading. A 0/1 nonlinear mixed integer program was formulated, and linearization methods were presented. For common problem sizes, the problems were solved optimally, within a reasonable time.

Kusiak (1985) formulated a model that took into account the limitation of the tool magazine and the tool life of individual tools. A 0/1 mixed integer linear program was proposed. The model however did not consider the tool sharing between machines or machine and tool cribs during the batch production. The life of the individual tools was assumed to be constant, independent of the batches being processed.

Sarin et al. (1987) formulated a model addressing machine loading and tool allocation problem. Given a fixed number of parts, which are to be processed by a group of machines, which have tool magazines loaded with tools of limited life, the objective was to minimize the total machining cost. The costs included both the cost of tool wear, and the cost of machine usage. The model assigned the required tools to machines, which stayed there for the entire planning period. Tool sharing between the machines was not considered. The parts were to have a unique process plan, or the best process plan was selected outside the model. A tool was used by the system for the duration of its useful life. Useful life of a tool was a duration, determined by previous statistics. An assumption that many tools and machines are not compatible drastically reduced the number of binary integer variables in the formulation.

Liang (1991) pointed out that when part selection and machine loading problems are dealt with separately, and linked thereafter, they could contradict each other, and lead to less meaningful, and sometimes even infeasible solutions. His study was directed towards the concurrent part selection and machine loading decision problem. A model was developed for a situation where the demand could vary widely, and tool sharing was not possible between the machines or the tool crib. Individual tool life was assumed to be shorter than the batch production time, necessitating the need for standby redundancies within the machine's magazine.

3.3.2 Heuristic Approach :

Berrada and Stecke (1986) considered a loading problem of simultaneously assigning machine tools, operation, and cutting tools to the part types. An operation is assigned to only one machine. Since balancing the workload corresponded to maximising the production rate, the objective of the model was to balance the workload, constrained by the tool magazine, machine tool, and system capacities. A non-linear integer program was formulated, which was solved by a branch and bound algorithm.

O'Grady and Menon (1987) examined a master scheduling problem for an existing FMS in Scotland. A multiple criteria approach was used to choose a subset of orders for processing, subject to resource constraints and potentially conflicting objectives. SCICONIC/VM mathematical programming system, running on a VAX was used to solve the problem. The solution adopted a compromise philosophy. It was argued that this solution procedure avoided the computational limitations associated with the pursuit of a global optimality using a 0/1 integer model.

Ventura et al. (1988) developed two mathematical models to load tools to machines in a FMS environment. Two sets of heuristic algorithms for solving the models were presented. The objective functions were to minimize the time-span required to process all the parts in a batch, and to minimize the number of part movements required to process the overall batch of parts. Tool processing times were considered to be machine dependent in one case, and machine independent in the other. It was found that the effectiveness of these algorithms is very much dependent on the magazine tightness values.

Part and tool movement policies are among the basic approaches used in loading problems in flexible manufacturing systems. Han et al. (1989) addressed a problem of loading a set of tools to different machining centres, where each part visits only one machine for its entire processing. Every machine could process all the operations on all the part types, as long as the corresponding cutting tools are available. A tool required, but not available in the machine's tool magazine could be borrowed from other machines. When the required tools to process a part are not mounted in the tool magazine, either the part may be sent to another machining centre where those required tools are available or the required tools may be transported from another machining centre. Tool movement policy was seen advantageous. Since parts do not move, there is no need to reposition the workpiece or recalibrate the position of the tool head which results in higher cutting precision. Also, a part is processed by only one machining centre. So a part is delivered into the shop only when a machining centre becomes available, thereby resulting in less work-in-process. However, tool movement policy results in tool-move delay time, which will be higher when the tool to be borrowed is in use at the other machining centre. They proposed a non linear programming model for the loading of a set of tools to the different machining centres, where each part visits only one of the machining centres for its entire processing. The quadratic objective function is to minimize the amount of tool traffic among the machining centres and between a machining centre and tool crib. A heuristic solution method was suggested. Analytical and simulated solutions were compared to the solution from the algorithm.

3.3.3 Simulation Approach :

One of the earliest study on loading FMS was done by Kathryn Stecke and

James Solberg. Stecke and Solberg (1981) performed their study in a practical environment of 'Caterpillar Tractor Company'. The system consisted of eleven production machines and an inspection machine. The operating strategies considered involved policies for loading (i.e. allocating operations and tooling to machines) and real time flow control. A detailed simulation was employed to test alternatives. The results were different from those of classical job shop scheduling studies, showing the dependence of system performance on the loading and control strategies chosen to operate the flexible manufacturing system. A 0/1 non linear mixed integer model was developed, which was solved by linearizing thereafter. This model did not consider the finite life of the tools.

Carrie and Perera (1986) studied the effect of tool variety, product variety and product similarity on the frequency of tool changes due to product variety, and due to tool wear. They based their study on a particular FMS. It was found that the number of tool changes due to product variety is small compared to those due to tool wear. For the analytical study they used the model given by Menon and O'Gradey (1984), with some variations. They made a post-processor which reads a file of work flow data , and by referring to the part routing and tool requirement file, maintains a list of tools which would be present in the tool magazine. Thus, the occurrence of tool changes due to product variety was deduced.

Gyampah et al. (1992) compared four scheduling strategies in the presence of three part selection rules, through a simulation of a five-machine FMS tool handling system. The strategies compared were bulk exchange, tool migration, resident tooling, and tool sharing. Significantly different outcomes were seen between the different strategies. Resident tooling was favoured over other strategies. It was pointed out that the study used long cycle times of parts, and the results could be different when parts with relatively shorter cycles were to be processed.

3.4 Analogous Literature :

Damodaran et al. (1992) developed models for production planning and cell design in cellular manufacturing systems. Parts were allowed to have more than one process plan, and the operation on the part could be performed on more than one machine. Cells had an upper limit to the number of machines it could accommodate. A model was developed to simultaneously form machine groups and to assign part-operations to the selected groups. Penalty costs were imposed on inter-cell movements. The non-linear constrain was linearized using the method suggested by Glover and Woolsey (1973). The models developed were mixed integer linear models.

Rajamani (1991) analyzed the influence of alternative process plans on the resource utilization, when part families and machine groups are formed simultaneously. A part could have more than more than one process plan and each operation could be performed on alternative machines. Integer programming models were developed, considering budget, floor space and capacity of machines to study the effect of alternative process plans and simultaneous formation of part families and machine groups on resource utilization. The non-linear constrain was linearized using the method suggested by Glover and Woolsey (1973). In another case a model was developed, that rearranged an existing manufacturing facility to Cellular manufacturing.

Atmani et al. (1995) introduced a 0/1 integer programming model for simultaneous solution of cell formation and operation allocation problem in cellular manufacturing. A part is assumed to have more than one process plan, and each operation could be performed on more than one machine. The objective of the model was to simultaneously form machine groups and allocate operations of the part types, so as to minimize the sum of operation, refixturing and transportation costs. Precedence relations among the machines and machine duplications were not considered. The model was used to solve large numerical examples . The model optimized these problems quite quickly.

3.5 Reliability Studies :

It is possible to improve the reliability of a system by improving the quality of its components. However, beyond a certain point, the improvement of reliability per unit cost may not be economical any more. Multiple copies may be beneficial or even necessary if these components are used very often. Reliability could then be improved by providing parallel paths, or standby redundancies. Predicting the number of spares of each component needed for a required operation time is of vital importance in designing a new system. Optimizing the reliability of a system, by providing redundancies has been the topic of many researches. Complex systems may contain some components which fail more often. Determining the location and the number of redundancies in the system is one of the issues discussed in this research.

Bellman and Dreyfus (1958) were among the first who applied dynamic programming to the solution of the optimal redundancy problem. Their formulation considered only two types of constraints: cost and weight. Messinger and Shooman (1970) conducted a tutorial review that evaluated and compared several techniques to allocate the number of spares of each part type, to maximize the system reliability. For an N-stage series system, Tillman et al. (1980) treated the problem of allocating redundancy to each of the components, so that the system reliability is maximized. The extension of this problem can be stated as finding the optimum number of redundancies which maximizes the system reliability subject to cost constraints (Rao, 1992). Tillman (1969) applied integer programming techniques to maximize the reliability or minimize the cost, subject to several constraints and the components may have different modes of failures. This required a bulky formulation that restricts the size of the system. Hwang et al. (1971) applied a zero-one integer programming to minimize the weight of sub-systems of a life support system, subject to several nonlinear constraints while maintaining an acceptable level of system reliability. Ghare and Taylor (1969) determined the optimum number of redundant components in order to maximize the reliability of series system subject to multiple resource restrictions. Solving the associated zero-one programming model by a branch-and-bound procedure, they showed that the optimal solution to the associated problem is equivalent to the optimal solution for the optimal redundancy problem.

Pan et al. (1986) derived a mathematical model to predict the system reliability of an automatic tool changing system, with the various cutting tools subject to Weibull failures. The system was regarded as a series system with stand-by redundancies. A recursive algorithm was presented to calculate the system reliability. The algorithm permitted the use of any failure distribution. However, no specific model to select the suitable spares combination was proposed. It had to be done by sorting all the possible combinations. They also took a numerical approach to integrate the reliability function for each tool with different number of spares. Ghosh and Wells (1990) presented a heuristic algorithm to solve the spares allocation problem to remote machines, in which machines were subsystems of a series system that would be used only for a specified period of time. They assumed that all spares must be assigned at the beginning of the system's mission. The algorithm determines number of spares for each subsystem (machines) that maximizes the minimum probability of each machine consuming its spares before the useful life of system is completed. To increase mean time between failures and to improve system reliability, Sears (1990) proposed a top-down technique to calculate required number of standby redundancies.

Kolahan (1993) in his thesis, emphasized the need for reliability studies on the performance of an FMS. Tool sharing between the machines was taken into consideration while modelling the problem. Also, a heuristic was developed to find the optimum reliability for a given system. For reliability evaluations, the machining centres were visualized as a series system, where the reliability of the system is the product of all the sub-components (cutting tools) in the system.

There has been no literature that deals with a full loading problem, with reliability considerations. It can be seen that ultimately a manufacturer requires that the production be carried out without interruptions, and without rejects of the work in progress. This research aims at solving the loading problem, with reliability considerations, thereby giving the production planner a comparison between the reliability of processing the demand, versus the total cost of processing the demand.

CHAPTER 4

MODELS

This chapter presents a few models with various objectives, that would optimize a typical loading problem in a FMS environment. The nomenclature and assumptions used are defined. The layout of an FMS in consideration is shown. The analytical model was run on packages LINGO® and LINDO®. The results obtained were verified by comparing against the simulations done on GPSS/H® and WITNESS®. The mathematical models were run on IBM® compatible PCs and SUN® workstation. The simulations were run on IBM mainframe.

4.1 System Configuration :

The layout of the system configured is shown in Figure 4.1. The system although hypothetical, is based on an existing system at Rock Island Arsenal, and presented by Hedlund et al. (1990). The system consists of a number of machining centres (4 in the diagram shown). Parts enter the shop if the local queue of the scheduled machine has the capacity to accommodate the batch to be processed. Parts enter and leave the system by the common gangway. It is assumed that, in general, all the operations required to be performed on a part can be done by a single CNC machines in the flexible manufacturing system, as long as the required tools are available. The models, however, can accommodate the need of restricting a particular tool or operation to specific machines. Each machine has a tool magazine of a limited tool capacity. While the tools are interchangeable between the machines, the tool magazines are fixed to the machine. The tools are assembled in the collet and tool holders, in a tool room, and enter the system through the tool transporter, or by a bulk exchange of the tool carousal. Since the 'useful life' of a tool is less than the production period, tool magazines would have to carry sufficient redundancies to process the entire demand without interruptions. The tool transporter shown in Figure 4.1 is applicable to the models where tool sharing is permitted. Tool transporter moves along a fixed path, as shown. Tool magazines of all the machines are accessible to this transporter, during the production run. There can also be a tool carousel within the system, which carries a larger number of tools, and is accessible to the tool transporter, during the production run. This would permit the system to hold more standbys of faster wearing tools, thereby allowing longer production runs. Without any modifications to itself, the loading models developed with tool change permitted, can accommodate the tool carousel. The total tool transport time is the sum of the times to pull the tool out of the donor machine, the time to transport the tool to the recipient machine, the time to insert the tool into the recipient machine's tool magazine, and the time to carry the worn out tool away. Worn out tools will be removed from the machine's tool magazine during the production run, and placed on the designated section of the tool carousal, as long as there is available space in the carousal. In other words, the number of tools in the tool magazine of the individual machine will be maximum at the beginning of the production run, and thereby decreases continually as the production proceeds.

4.2 Nomenclature :

Indices :

i	: part type index,	$i = 1,2,....,I$
j	: machine index, (to)	$j = 1,2,....,J$
k	: machine index, (from)	$k = 1,2,....,J$
l	: tool type index,	$l = 1,2,....,L$
m	: spares index,	$m = 0,1,....,M_{jl}$
p	: process plan index	$p = 1,2,....,P_i$

For the models where tool sharing is permitted, index k denotes the machine from which the tool is being borrowed, and index j denotes the machine to which the tool is transported. For the models where tool sharing is restricted, index k is not used, and the index j refers to the machine in context.

Decision Variables :

X_{ijp} Fraction of demand of part 'i', processed on machine 'j', using process plan 'p'.

Y_{ijp} $\begin{cases} 1 & \text{if part '}i\text{' is processed on machine '}j\text{' using process plan '}p\text{'.} \\ 0 & \text{otherwise.} \end{cases}$

$$Z_{jl} \begin{cases} 1 & \text{if machine 'j' has to be loaded with tool 'l'.} \\ 0 & \text{otherwise.} \end{cases}$$

$$Z_{jlm} \begin{cases} 1 & \text{if machine 'j' has to be loaded by 'm' spares of tool 'l'.} \\ 0 & \text{otherwise.} \end{cases}$$

N_{jkl} Number of tools of type 'l' transported to machine 'j' from 'k'.

N_{jl} Number of tools of type 'l' mounted originally on machine 'j'.

H_{jl} Number of tools of type 'l' transferred from other machines to machine 'j'.

Parameters :

$$\alpha_{ijp} \begin{cases} 1 & \text{if part 'i' can be processed on machine 'j' using process plan 'p'.} \\ 0 & \text{otherwise.} \end{cases}$$

$$\beta_{ilp} \begin{cases} 1 & \text{if part 'i' can be processed using tool 'l' and process 'p'.} \\ 0 & \text{otherwise.} \end{cases}$$

λ Hazard rate of the tool with an exponential failure distribution.

C_l Unit cost of tool 'l'.

E_j Tool magazine capacity available at machine 'j'.

M_{jl} Maximum number of tools of type 'l' that can be put on machine 'j'.

d_i Demand for part 'i'.

t_{ilp} Machining time for part 'i' using tool 'l', and process 'p'.

T_{lj} Useful tool life available from each spare of tool 'l' on machine 'j'.

t_{ljk} Time to remove a tool from machine 'k', for use on machine 'j'.

t_{2jk} Time to insert a tool from machine '*k*', for use on machine '*j*'.

Q_t Tool transporter time available during the production period.

B_j Machine time available, on machine '*j*', during the production period.

R_{jlm} Reliability of tool type '*l*' on machine '*j*' with '*m*' redundancies.

R_{ijp} Obtained reliability for part '*i*', on machine '*j*' using plan '*p*'.

R_l Reliability of tool type '*l*'.

U_{jl} Cumulative hazard factor of tool type '*l*', on machine '*j*'.

U_l Cumulative hazard factor of tool type '*l*' in the system.

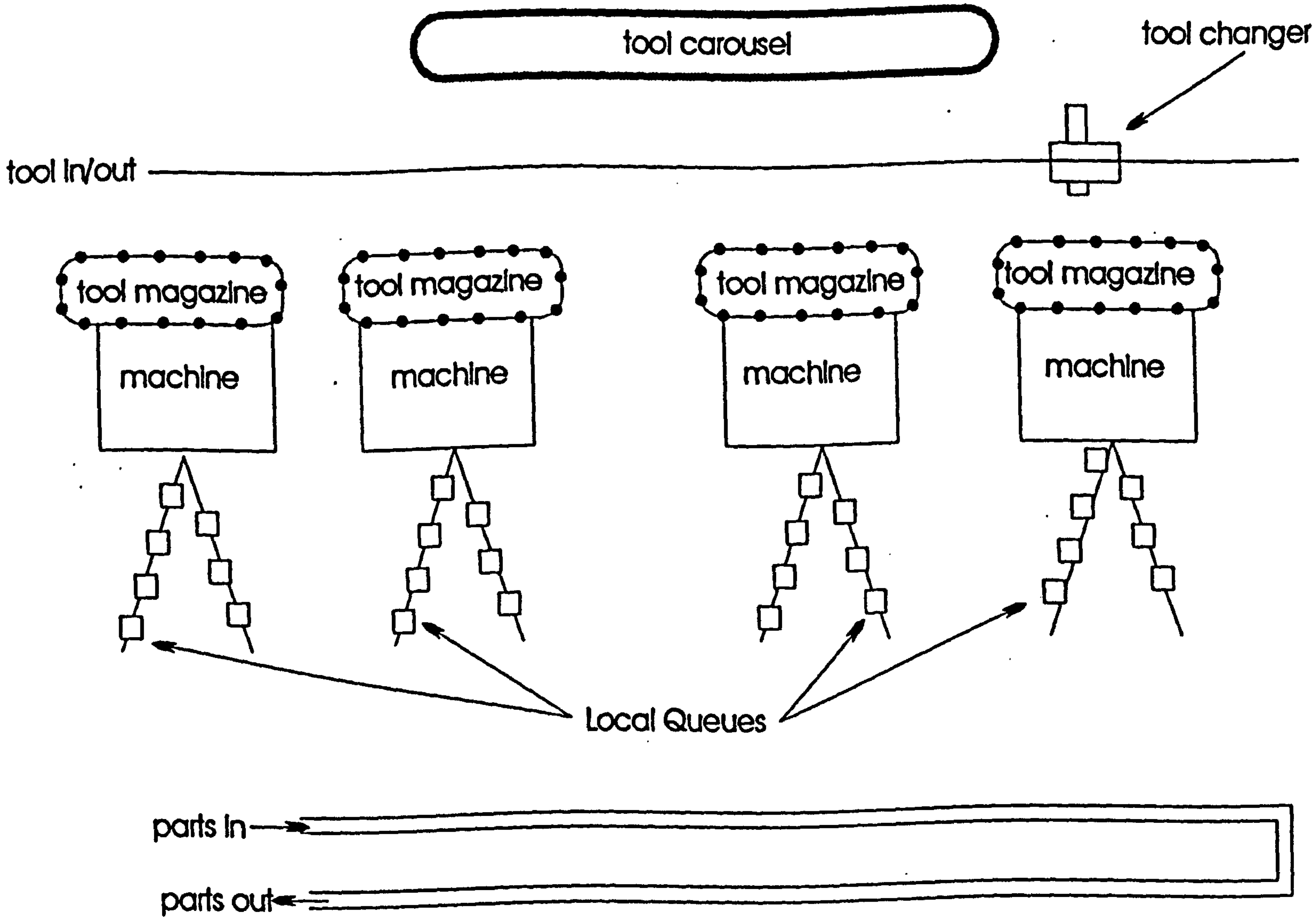


Figure 4.1 : Typical Configuration of the System.

4.3 Assumptions :

While developing these models, the following assumptions were made to simplify the modelling.

- ☞ The demand for each of the part type is known in advance, and will not change during the production period.
- ☞ All the spares of a particular tool type are assembled to be identical.
- ☞ Tool failures are independent of each other. So, the failure of one tool does not affect the failure of another tool in the system.
- ☞ A machining centre can perform all the required operations of the assigned parts, as long as the required tools are available in the tool magazine.
- ☞ Machining parameters such as feed, spindle speed, depth of cut, etc are determined before the production run, and does not change during the production run.
- ☞ The life of the tool transporter is much larger than the production period. So the tool transporter has a constant reliability during this period.
- ☞ The tool life distribution of all cutting tools is exponential. But the mean would depend on the tool type.
- ☞ Stochastic, single catastrophic injuries to the tool are ignored.
- ☞ The detection of a tool failure is perfect.

4.4 Mathematical Modelling :

The purpose of the mathematical modelling is to optimize the loading problem in a typical FMS. Layout of the system considered has been presented above. Tool sharing, although economically advantageous for a large system, requires a more complicated and meticulous tool setting and tool management systems, and additional equipments. For a less flexible or a smaller system, the investment may not be worth the returns. Thus an FMS may or may not have tool sharing. Two sets of mathematical models have been developed. Each model considers two cases, one where tool sharing is permitted, and the other where tool sharing is restricted.

4.4.1 Model I :

The objective of this loading problem is to minimize the tooling cost of the system. Each tool type is given a fixed value of 'useful life'. This value may have been found from the statistical analysis of tool wear, in the past. The useful tool life is a fraction of the absolute tool life, for a given tool type. Each machine has a tool magazine, with a limited number of tool slots. Also, there is a limit on the machine availability time during the production period. A demand can be split into batches, and the different batches of a demand can be processed on different machines and different process plans. The optimal size of a batch is determined by the mathematical models.

4.4.1a Case 1, Tool Sharing Not Allowed :

When tool sharing is not allowed, each machine will have to carry all the tool types, and sufficient redundancies of each type to process all the batches scheduled for the production period. The total number of tools in the magazine of a machine remains constant throughout the production period. A tool type can be assigned to more than one machine. The number of tool slots and the available time could be different from machine to machine. A linear integer programming model developed, is presented below.

$$\textit{Minimize} \quad \sum_{j=1}^{J} \sum_{l=1}^{L} \sum_{m=0}^{M_{jl}} m \, C_l \, Z_{jlm} \qquad (4.1)$$

Subject to

$$\sum_{j=1}^{J} \sum_{p=1}^{P} \alpha_{ijp} \, X_{ijp} = d_i \qquad \forall \, i \qquad (4.2)$$

$$\sum_{l=1}^{L} \sum_{m=0}^{M} m \, Z_{jlm} \leq E_j \qquad \forall \, j \qquad (4.3)$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \beta_{ilp} X_{ijp} t_{ilp} \leq t_{lj} \sum_{m=0}^{M} m Z_{jlm} \qquad \forall\ l,j \qquad (4.4)$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{l=1}^{L} \beta_{ilp} X_{ijp} t_{ilp} \leq B_j \qquad \forall\ j \qquad (4.5)$$

$$\sum_{m=0}^{M} Z_{jlm} = 1 \qquad \forall\ j,l \qquad (4.6)$$

$$\sum_{m=0}^{M_{jl}} m Z_{jlm} = N_{jl} \qquad (4.7)$$

Integer	Z_{jlm}	$\forall\ j,l,m$
GIN	X_{ijp}	$\forall\ i,j,p$

Z_{jlm} is a 0/1 variable that indicates that a machine *j* has *m* spares of the tool type *l*. Thus mZ_{jlm} gives the number of spares of tool type *l*, on machine *j*. C_l is the cost of a tool of type *l*. The objective function therefore minimizes the total cost of the cutting tools. Constraint set 3.2 confirms that the sum of the fractions of demand, named batches, adds up to the total demand of each part type. Constraint set 3.3 ensures that the total number of spares, for all tool types assigned to a machine, is less than the capacity of the tool magazine, for each machine *j*. The demand d_i multiplied by the fraction X_{ijp} is the batch size of part i, designated to machine j to be processed by process plan p. β is one, for all ilp combinations possible, and zero otherwise. Thus constraint set 3.4 ensures that the usage of a tool of lj combination is less than the available capacity. Constraint set 3.5 ensures that the available capacity of the machining centres is not exceeded. For a machine j and tool type l, as m varies from 0 to M_j, there can be only one Z_{jlm}, that can be 1. So, constraint set 3.6 sets a unique number of spares for each tool type for all machines. Finally, Z_{jlm} has been defined as a 0/1 integer variable.

4.4.1b Case 2, Tool Sharing is Permitted :

When tool sharing is permitted, all the tools within the system is available to every machine in the system. However, the transport of tools from other machines involves lost production time, for both the donor and the recipient machines. This effect is quantified as a penalty cost of borrowing, and is included in the objective function, which the program minimizes. This new configuration involves another facility, the tool transporter. Along with the other capacity constraints mentioned in the above model, this model also has to ensure that the available capacity, in terms of time, of the tool transporter is not violated. Every time a required tool is brought in from another machine, the tool transporter also carries away the worn out tool into a specified section of the tool carousal. Thus, if the tool magazine capacities are not violated at the beginning of the production period, then they will not be exceeded during the production run. An extension to the model would be to move every worn out tool to the tool carousal. While modelling this situation, general integer variables were used in the model. Although this makes the model less tedious to input, the computing time is longer. The model developed is shown below.

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{l=1}^{L} C_l N_{jl} + C_q \sum_{j=1, j \neq k}^{J} \sum_{k=1}^{J} \sum_{l=1}^{L} N_{jkl} \tag{4.10}$$

Subject to

$$\sum_{j=1}^{J} \sum_{p=1}^{P} \alpha_{ijp} X_{ijp} = d_i \qquad \forall i \tag{4.11}$$

$$\sum_{j=1}^{J} \sum_{l=1}^{L} N_{jkl} \leq E_k \qquad \forall k \tag{4.12}$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \beta_{ilp} X_{ijp} t_{ilp} \leq t_{lj} \sum_{k=1}^{J} N_{jkl} \qquad \forall l,j \tag{4.13}$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{l=1}^{L} \beta_{ilp} X_{ijp} t_{ilp} + \sum_{k=1, k \neq j}^{J} t_{1jk} N_{jkl} + \sum_{k=1, k \neq j}^{J} t_{2jk} N_{jkl} \leq B_j \qquad \forall j, k \neq j \tag{4.14}$$

$$T_q \sum_{l=1}^{L} \sum_{j=1, j \neq k}^{J} \sum_{k=1}^{J} N_{jkl} \leq Q_q \tag{4.16}$$

$$\sum_{k=1}^{J} N_{kjl} = N_{jl} \qquad \forall\, j,l \tag{4.17}$$

$$GIN \quad N_{jkl} \qquad \forall\ j,k,l$$
$$GIN \quad N_{jl} \qquad \forall\ j,l$$

The first part of the objective function is the same as the previous case. The second part imposes a penalty cost for borrowing a tool from another machine. The sum of N_{kj} with k not equal to j gives the total number of tool transports during the production run. In the examples run on the model, the penalty cost of borrowing is less than the cost of a new tool. Thus there is a cost trade-off, while optimizing the model. Like in the previous case, constraint set 3.11 breaks up the total demand into optimal batches, assigning a machine and a process plan for each batch. Constraint sets 3.12, and 3.13 like in the earlier case, keeps the tool magazine, and the cutting tool life, from being exceeded. In this modelling, it is assumed that when a tool is borrowed from another machine, both the donor and the recipient machine incurs lost time, given by t_{1jk} and t_{2jk}. If the tool change occurs while the machine is running, either or both of the lost time variables can be set to zero. So the total time required from a machining centre is given by the right hand side of 3.14. T_q being the total tool transport time, for each tool transaction between the machines, constraint 3.16 ensures that the time capacity of the tool transporter is not exceeded. Equation 3.17 sums up the total tools of *jl* combination.

4.4.2 Model II :

A tool is said to have failed when the cut made by the tool is significantly different from that of a sharp tool. In most cases, such workpieces may not meet the quality requirements of the shop. In this research, the operation time of a tool, till it gets to this point is said to be the 'absolute life' of the tool. To avoid running into this undesirable situation, the practice is to use the tool for only its 'useful life' time period. The value of this time period is a statistical inference, qualified by a safety factor. This is done, hoping to achieve a certain degree of reliability for the cutting tool, and hence the system, that is processing the batch. In most cases, the value of the useful life is an under-estimate of the actual value, thus leading to higher operational costs. In the model derived below, the production planner gets to know the reliability with which the batches and the demand can be processed for a pre-determined value of the useful life of a cutting tool. By reducing the value of the useful life, and thus changing the tools more often, the reliability of processing the batch is improved, but the trade-off would be a higher tooling cost. Moreover, reliability being a non-linear function, the use of the model quickens and optimizes the loading decisions.

In the system considered, a part enters a machine, and then the cutting tools come one after the other to perform their operations on the part. For reliability considerations this system can be visualized as a series system, where the operations are performed in series, on a part clamped on the machine. To calculate the reliability of a tool type, the absolute life of the tool type should be known. The reciprocal of the absolute tool life would be 'λ', the hazard rate of the tool with an exponential failure distribution. The cumulative hazard function of such a tool would be 'λt', where t (for this context only) is the cumulative usage time of the component. The reliability R_l of such a component, in a series system, with m standby spares is given by,

$$R_l = \sum_{m=0}^{M_{jl}} \frac{(\lambda t)^m \, e^{-\lambda t}}{m!} \tag{4.19}$$

So, when $m=0$, i.e. when no spares are available, or in other words, when the component does not exist, it is mathematically equivalent to having that component in the system, with a reliability 1. Thus, it can be said that the reliability of the component is a non-linear function of number of standby redundancies, cumulative hazard function, and a variable indicating the presence of the component in the system. Thus,

$$R_l\ [(\beta_{ilp} \neq 0), N_{jl}, U_{jl}] \quad = \quad \sum_{m=0}^{N_{jl}} \frac{(U_{jl})^m\ e^{-U_{jl}}}{m!} \tag{4.20}$$

and,

$$\mathbf{R}_l[(\beta_{ilp} = 0)\ ,\ \mathbf{N}_{jl},\ \mathbf{U}_{jl}]\ =\ 1$$

4.4.2a Case 1, Tool Sharing Not Allowed :

First, we consider the case, where tool sharing is not applicable. The situation is the same as described in the first case of the previous model, except that the reliability constraint has to be included and linked to the said formulation. For a given value of the 'useful tool life' the model optimizes the loading problem, and computes the reliability achieved for each of the batches being processed, so as to minimize the tooling cost. The non-linear integer program can be formulated as,

$$\textit{Minimize} \quad \sum_{j=1}^{J} \sum_{l=1}^{L} C_l\ N_{jl} \tag{4.21}$$

Subject to

$$\sum_{j=1}^{J} \sum_{p=1}^{P} \alpha_{ijp} X_{ijp} = d_i \qquad \forall i \qquad (4.22)$$

$$\sum_{l=1}^{L} N_{jl} \leq E_j \qquad \forall j \qquad (4.23)$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{l=1}^{L} \beta_{ilp} X_{ijp} t_{ilp} \leq B_j \qquad \forall j \qquad (4.24)$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \beta_{ilp} X_{ijp} t_{ilp} \leq t_l N_{jl} \qquad \forall l,j \qquad (4.25)$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \beta_{ilp} X_{ijp} t_{ilp} = (1/\lambda_l) U_{jl} \qquad \forall l,j \qquad (4.26)$$

$$X_{i,j,p} \leq d_i Y_{i,j,p} \qquad \forall i,j,p \qquad (4.28)$$

$$Y_{ijp} \prod_{l=1}^{L} R_l(\beta_{ilp}, N_{jl}, U_{jl}) = R_{ijp} \qquad \forall i,j,p \qquad (4.29)$$

Integer	Y_{ijp}	$\forall\ i,j,p$
GIN	N_{jl}	$\forall\ j,l$
GIN	X_{ijp}	$\forall\ i,j,p$

Constraint sets 3.23, 3.24, and 3.25 limits the usage of the tool magazine, machining centre, and the cutting tools to its capacities. Constraint set 3.21 divides the demand into optimal batches. Constraint set 3.26 finds the cumulative hazard functions U_j, of the different tool types while processing on the different machines. Constraint set 3.28 sets a 0/1 variable Y_{ip}, which indicates whether the corresponding batch has been chosen as an optimal batch for processing. Finally, the constraint set 3.29 defines the reliability of processing the corresponding optimal batch in the system. As mentioned earlier in 3.20, the reliability of a tool type is a function of 'β', Z and U. The objective then is to minimize the tooling cost, under the given set production policies and capacity limitations.

4.4.2b Case 2, Tool Sharing is Permitted :

Like in the previous model, when tool sharing is permitted, all the tools are available for use on any machine in the system. However, a penalty cost is imposed for borrowing the tools from other machines. The reliability of processing a batch in the system is the product of the reliability of its constituent operations. The reliability of the operation in turn is the reliability of the corresponding cutting tool with the total number of standby redundancies of that tool type in the system. The cumulative hazard factor in this case depends on the duration of the tools usage for all parts, all process plans and all machines. The non-linear formulation derived is presented below.

$$\textit{Minimize} \quad \sum_{j=1}^{J} \sum_{k=1}^{J} \sum_{l=1}^{L} C_l N_{jkl} + C_q \sum_{j=1, j \neq k}^{J} \sum_{k=1}^{J} \sum_{l=1}^{L} N_{jkl} \tag{4.30}$$

Subject to

$$\sum_{j=1}^{J} \sum_{p=1}^{P} \alpha_{ijp} X_{ijp} = d_i \qquad \forall i \tag{4.31}$$

$$\sum_{j=1}^{J} \sum_{l=1}^{L} N_{kjl} \leq E_k \qquad \forall k \tag{4.32}$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \beta_{ilp} X_{ijp} t_{ilp} \leq t_{lj} \sum_{k=1}^{J} N_{jkl} \qquad \forall l,j \tag{4.33}$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{l=1}^{L} \beta_{ilp} X_{ijp} t_{ilp} + \sum_{k=1}^{J} t_{1jk} N_{jkl} + \sum_{k=1}^{J} t_{2jk} N_{jkl} \leq B_j \qquad \forall j \tag{4.34}$$

$$T_q \sum_{l=1}^{L} \sum_{j=1, j \neq k}^{J} \sum_{k=1}^{J} N_{jkl} \leq Q_q \tag{4.35}$$

$$\sum_{i=1}^{I} \sum_{p=1}^{P} \sum_{j=1}^{J} \beta_{ilp} d_i X_{ijp} t_{ilp} = (1/\lambda_l) U_l \qquad \forall l \tag{4.36}$$

$$\sum_{k=1, k \neq j}^{J} N_{kjl} = H_{jl} \qquad \forall j,l \tag{4.39}$$

$GIN \quad N_{jlm} \qquad \forall \; j,l,m$

$GIN \quad Z_l \qquad \forall \; l$

Due to the tool sharing during the production run, any tool in the system is accessible to any and every machine in the system. The reliability of the processing the part in the system therefore is now dependent on the number of standby redundancies Z_l of each tool type available in the system. This modification is done on the objective function from model 1, to arrive at the objective function, 3.30 . Constraint sets 3.31, 3.32, 3.33, 3.34 and 3.35 are the same as in the previous model. The cumulative hazard factor of a tool type is now dependent on the usage of a tool type by the entire system. Thus the hazard factor now depends on the usage of the tool type by the system to process all parts in all the selected process plans on all machines in the system, as given by the equation set 3.36 . Equation set 3.39 gives the number of spares of each tool type, borrowed from all the other machines in the system. The reliability of processing an individual batch can be now calculated as,

$$R_{ijp} = Y_{ijp} \prod_{l=1}^{L} R_l(\beta_{ilp}, N_{jl}, U_{jl}) \; R_q^{H_{jl}}$$

When a tool for a machine is not available in its own tool magazine, it borrows it from another machine. Every borrowed tool uses the tool transporter, which in turn has a reliability of R_q. So, the reliability of a tool type R_l, a function of Z_l and U_l has to be multiplied by R_q, N_{lkj} times for all borrowed tools, i.e., k not equal to j. Because of the penalty costs, the model will try to minimize this cost.

4.4.3 Model III :

The models discussed above took the entire loading problem into consideration. The mathematical models partitioned parts into optimal batches, assigned them to machines, assigned tool to the machines, and found the optimal number of spares to be carried by the system. This constitutes a complete loading problem. But when the reliability calculations were included, the models turned highly non-linear. Solving this requires a non-linear optimizing package. Besides, as the problem grows larger, the computational for an optimal solution would take a longer time. It is also seen in practice that even if the parts belong to the same part family, some may require a specialized kind of material handling. In such cases, the decision variables regarding assigning parts to machines may depend on variables that cannot be quantified into a mathematical model. The loading problem to be solved is then a partial loading problem. The loading problem remaining is to assign tools to machines, and to determine the optimal number of spares for each tool type. It may also be required to have a certain level of reliability, while processing a certain batch of parts. The model discussed now is formulated to assign tools to machines and to find the optimal number of spares to be carried by the system, so that the parts can be processed with a certain level of reliability. Equation 3.20 defines reliability as a function of a 0/1 variable β_{ilp}, number of spares N_j, and the hazard factor U_j. The decisions regarding assigning parts to the respective machines, and selecting process plans have to be made before running this model. The total processing time of each tool in the system is now a known quantity. So, the cumulative hazard rates of each tool-type is also known. This reduces the complexity of the equation, which can now be written as,

$$R_l\ [(\beta_{ilp} \neq 0), N_{jl}, U_{jl}] = \sum_{m=0}^{N_{jl}} U_l^m \frac{e^{-U_l}}{m!} \qquad (4.41)$$

With these variations to the system, the mathematical formulations are derived for both the cases, where tool sharing is permitted and is restricted.

4.4.3a Case 1, Tool Sharing is Not Permitted :

When tool sharing is not allowed, each machine has to carry all the tool types, and sufficient standbys of each type to process all the batches are assigned to the machine for a given planning period. In this case, an optimal tooling is calculated for each machine, such that each batch can be processed by the system with a certain level of reliability. The objective function being considered is to minimize the total cost of tooling. The reliability constraint is first modified to suit this model. The reliability of processing a part can be calculated as the product of the reliability of their constituent operations. Thus, when R_{ijp} is the reliability of processing a part, and R_l is the reliability of an individual tool type.

$$Y_{ijp} \prod_{l=1}^{L} R_l(\beta_{ilp}, N_{jl}, U_{jl}) = R_{ijp} \qquad \forall \; i,j,p \tag{4.42}$$

As the first step, this product form equation has to be linearized. This is done by taking a logarithm on both sides of the equation. Also, R_l is a function of a 0/1 co-efficient, β_{ilp}. When this co-efficient takes a value of zero, R_l should be one, otherwise the calculated value of R_l. So, when taking the logarithm, the log value of the reliability should be zero, when β is zero, and not otherwise. So the above equation can now be written as

$$\sum_{l=1}^{L} \beta_{ilp} \log[R_{jl}(N_{jl}, U_{jl})] = R_{ijp} \qquad \forall\, ijp \qquad (4.43)$$

To linearize this equation, the variable N_j has to be brought outside the log function. Using the equation 3.7, N_j can be replaced by mZ_{jlm}. Then since Z_{jlm} is a 0/1 variable, we have

$$\sum_{l=1}^{L} \sum_{m=1}^{M_{jl}} \beta_{ilp}\, Z_{jlm} \log[R_{jl}(m, U_{jl})] = R_{ijp} \qquad \forall\, ijp \qquad (4.44)$$

The log quantity is now a one dimensional variable, and can be computed by a small number crunching program, and the results can be sent into the optimizing program. The partial loading problem can now be modelled as,

$$\textit{Minimize} \quad \sum_{j=1}^{J} \sum_{l=1}^{L} \sum_{m=0}^{M_{jl}} m\, C_l\, Z_{jlm} \qquad (4.45)$$

Subject to

$$\sum_{l=1}^{L} \sum_{m=1}^{M_{jl}} \beta_{ilp}\, Z_{jlm} \log[R_{jl}(m, U_{jl})] \geq \log[R_{ijp}] \qquad \forall\, ijp \qquad (4.46)$$

$$\sum_{l=1}^{L} \sum_{m=0}^{M} m\, Z_{jlm} \leq E_j \qquad \forall\, j \qquad (4.47)$$

$$\sum_{m=0}^{M} Z_{jlm} = 1 \qquad \forall\, j,l \qquad (4.48)$$

$$\textit{Integer} \quad Z_{jlm} \qquad \forall\, j,l,m$$

The constraint set 3.47 ensures that the magazine capacity of the individual machines is not exceeded. Constraint set 3.48 ensures that there is a unique number of spares of each tool type loaded on each machine. The number of spares could also be zero.

4.4.3b Case 2, Tool Sharing is Permitted :

Once again, when tool sharing is permitted, all the tools in the system are available for use on any of the machines in the system. A tool transporter would transfer the tools from one machine to the other. The penalty cost accounts for the additional costs involved in maintaining the tool transporter, as well as the waiting time for the tool to be transferred from one machine to the other. The reliability of processing a batch in the system is the product of the reliability of its constituent operations. The reliability of the operation in turn is the reliability of the corresponding cutting tool, with the total number of standby redundancies in the system. The cumulative hazard factor in this case depends on the duration of the tools usage for all parts, all process plans, and all machines. A new variable used in this case, Z_{kjlm} is a 0/1 variable, which exists when m number of tools, of tool type l moves from machine k to machine j, and 0 otherwise. The linearized formulation derived is presented below.

$$Min \quad \sum_{k=1}^{J} \sum_{j=1}^{J} \sum_{l=1}^{L} C_l N_{kjl} + C_q \sum_{k=1}^{J} \sum_{k=1,k\neq j}^{J} \sum_{l=1}^{L} N_{kjl} \tag{4.49}$$

Subject to

$$\sum_{k=1}^{J} \sum_{l=1}^{L} \beta_{ilp} Z_{jlm} \log[R_{jl}(m,U_{jl})] \geq \log[R_{ijp}] \qquad \forall\ i,j,p \tag{4.50}$$

$$\sum_{m=0}^{M_{jl}} m Z_{jlm} = \sum_{k=1}^{J} N_{kjl} \qquad \forall\ j,l \tag{4.51}$$

$$\sum_{j=1}^{J} \sum_{l=1}^{L} \sum_{m=0}^{M_{jl}} m Z_{kjlm} \leq E_k \qquad \forall\ k \tag{4.52}$$

$$\sum_{m=0}^{M_{jl}} Z_{kjlm} = 1 \qquad \forall\ k,j,l \tag{4.53}$$

Integer Z_{jlm} $\forall\ j,l,m$

Gin N_{kjl} $\forall\ k,j,l$

The objective, as in the earlier cases, is to minimize the total tooling costs. The total costs, in this case, is the sum of the capital costs and the penalty cost incurred in sharing the tools between the machines. The constraint set 3.50 ensures that the reliability of processing each batch in the system is as good, or better, than the required level of reliability. Constraint set 3.52 limits the total number of tools on every machine to their respective magazine capacity. Constraint set 3.53 ensures that there is a unique number of spares of each tool type loaded on each machine in the system. Z_{kjlm} is a 0/1 integer variable.

CHAPTER 5

NUMERICAL EXAMPLES

The models developed in the previous chapter were applied to hypothetical, but realistic scenarios.

5.1 Model 1, Tool Sharing Not Permitted :

In the first example, a manufacturing shop with 2 machines, is being considered. One hundred and fifty parts, under 5 part types, are to be loaded on the system. While some parts can be processed using any of the two available process plans, the others have to be processed by a unique process plan. Both machines being identical, any machine can be used for any part. In all, there are 6 tool types required for the process. Each machine has to carry sufficient redundancies to process the entire demand. There is a limitation on the number of spare tools of a type available in the shop. In this example, it is assumed that the demand for a part type can be split into batches. Each batch can be processed on any of the two machines, using any process plan available. Any demand has to be fulfilled, only by the end of the planning period. The production has to be optimized, with the objective of minimizing the tooling cost. The numerical values of the various parameters and capacities are given in a tabular form.

When it is not desirable to divide the demand into batches, and to process on different machines, X_{iip} can be defined as an integer.

Table 5.1 Process Plans & Processing Times

Tool Type	Part 1		Part 2		Part 3	Part 4		Part 5
	Pr. 1	Pr. 2	Pr 1	Pr. 2	Pr. 1	Pr 1	Pr 2	Pr.1
1	5	4	2	2	-	-	-	-
2	1	2	-	2	1	2	1	-
3	3	1	2	-	-	-	-	-
4	-	2	2	2	1	2	1	2
5	-	-	-	-	1	1	2	3
6	-	-	-	-	1	1	1	-

Table 5.2 Machine Capacities.

MACHINE	MAGAZINE SLOTS	AVAILABLE TIME
Machine 1	20	480 min.
Machine 2	20	480 min.

Table 5.3 Tool Life and Costs

Tool Type	1	2	3	4	5	6
Useful Life	25	25	25	25	50	25
Unit Cost	10	12	15	20	11	14

5.1.1 Analysis Of Results :

The problem was solved using the model 3.3.1. The input file to LINDO is given in the appendix. The results of the run can be summarized as

Table 5.4 : Dividing Demand into Batches & Assigning to Machines

Part Type	M/c 1; Pr.1	M/c 1; Pr.2	M/c 2; Pr.1	M/c 2; Pr.2
1	7	-	13	10
2	-	20	9	1
3	30	-	-	-
4	-	16	-	14
5	7	-	23	-

Table 5.5 : Assigning Tools and Spares to Machines

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
3	5	4	2	1	3	4	4	2	2	2	1

Total Tooling Cost	=	458 units
Total Available Machine Time	=	480 min. (8 hours).
Usage of Machine 1	=	418 min.
Usage of Machine 2	=	452 min.
Tool Slots Used on Machine 1	=	16
Tool Slots Used on Machine 2	=	17

5.2 Model 1b, Tool Sharing Possible :

The model with tool sharing permitted was tested, using the same numerical values of the above example. The process plans, and the processing times for each tool under each process plan is given in Table 5.1. The machine capacities in terms of tool magazines and available times are given in Table 5.2. Table 5.3 gives the useful tool life and the unit cost of these cutting tools. A tool transporter has been included in this model. The capacity constraint of the tool transporter has been included. It is assumed that when a tool transfer occurs, both the tool donor machine and the tool recipient machine have to stop and service the tool transfer operation.

Table 5.6 : Dividing Demand into Batches & Assigning to Machines

Part Type	M/c 1; Pr.1	M/c 1; Pr.2	M/c 2; Pr.1	M/c 2; Pr.2
1	21	2	7	-
2	5	18	2	5
3	7	-	23	-
4	3	1	8	18
5	3	-	27	-

5.2.1 Analysis Of Results :

Total Available time on the machines	=	480 min. (8 hours).
Total Machine usage time of machine 1	=	473.25 min.
Total Machine usage time of machine 2	=	413 min.
Tool slots used on machine 1	=	23 slots
Tool slots used on machine 2	=	10 slots
Total tooling cost, including penalty costs	=	460 units.

Table 5.7 : Assigning Tools and Spares to Machines

Tool Type	Machine 1	Machine 2	M/c.1 >> M/c.2	M/c.2 >> M/c.1
1	7	-	2	-
2	3	3	-	-
3	3	-	1	-
4	3	5	-	-
5	1	1	2	-
6	-	1	1	-

5.3 Model 2a, Tool Sharing Not Possible :

The second model is a nonlinear formulation. The model was solved using the package LINGO. At this stage, a small model was solved. A manufacturing shop with 2 machines is being considered. 100 parts, under 2 part types are to be loaded on the system. Each of the two part types has 2 process plans. A demand is broken up into batches. A batch can be processed by any of the machines, and any of the process plans. The two machines are identical. Four tool types are used for the processing. It is assumed that a demand has to be fulfilled only by the end of the planning period, in this case, the end of the shift. The production is to be optimized with the objective of minimizing the tooling cost. The numerical values are given in a tabular form as

Table 5.8 Process Plans & Processing Times

Tool Type	Part 1		Part 2	
	Process 1	Process 2	Process 1	Process 2
1	2	2	2	2
2	3	-	-	4
3	2	8	3	3
4	1	-	4	-

Table 5.9 Machine Capacities.

MACHINE	MAGAZINE SLOTS	AVAILABLE TIME
Machine 1	25	480 min.
Machine 2	25	480 min.

Table 5.10 Tool Life & Unit Costs

Tool Type	1	2	3	4
Useful Life	20	20	20	20
Absolute Life	100	100	100	100
Unit Cost	10	12	15	18

5.3.1 Analysis Of Results :

The problem was solved using the model 3.3.1. The input file to LINGO is given in the appendix. The results of the run can be summarized as

Table 5.11 Tools & Spares Allotment

Tool Type 1		Tool Type 2		Tool Type 3		Tool Type 4	
M/c 1	M/c 2	M/c 1	M/c 2	M/c 1	M/c 2	M/c 1	M/c 2
5	5	8	10	5	8	3	-

The entire demand for Part Type 1 is one batch assigned to machine 1, to be processed by process plan 1.

The entire demand for Part Type 2 is one batch assigned to machine 2, to be processed by process plan 2.

The two machines were allowed to use 480 min. to process the demand.

Machine 1 was used for 400 min., and machine 2 was used for 450 min.

Part 1 is being processed with a reliability of 99.7%

Part 2 is being processed with a reliability of 99.4%.

The minimized tooling cost was found to be 585 units.

5.4 Model 2b, Tool Sharing Possible :

The model with tool sharing permitted was tested, using the same numerical values of the above example. The process plans, and the processing times for each tool under each process plan is given in Table 5.1. The machine capacities in terms of tool magazines and available times are given in Table 5.2. Table 5.3 gives the useful tool life and the unit cost of these cutting tools. A tool transporter has been included in this model. The capacity constraint of the tool transporter has been included. It is assumed that when a tool transfer occurs, both the tool donor machine and the tool recipient machine have to stop and service the tool transfer operation.

Table 5.12 : Dividing Demand into Batches & Assigning to Machines

Part Type	M/c 1; Pr.1	M/c 1; Pr.2	M/c 2; Pr.1	M/c 2; Pr.2
1	21	2	7	-
2	5	18	2	5
3	7	-	23	-
4	3	1	8	18
5	3	-	27	-

Table 5.13 : Reliability Achieved for various batches

M/c #	Part 1		Part 2		Part 3	Part 4		Part 5
	Pr. 1	Pr. 2	Pr. 1	Pr. 2	Pr. 1	Pr. 1	Pr.2	Pr. 1
1	.984	.976	.984	.984	.872	.962	.962	.878
2	.953	-	.967	.980	.979	.979	.979	.990

5.4.1 Analysis Of Results :

Total Available time on the machines	=	480 min. (8 hours).
Tool slots used on machine 1	=	23 slots
Tool slots used on machine 2	=	10 slots
Total tooling cost, including penalty costs	=	460 units.

5.5 Model 3a, Tool Sharing Not Possible :

The third model is a linearized formulation. The numerical example was solved using LINGO. A fairly large model was solved. The manufacturing facility is assumed to have 4 machines. Each machine has a tool magazine capacity of 50 tool slots. Three hundred parts, under 10 part types are to be loaded onto the system. Each part type could have up to 2 process plans. Sixteen different tool types were used to perform the various operations on the machines. As used in the previous cases, each tool was assumed to have an absolute tool life of 100 minutes. The planning period is assumed to be 1000 minutes. Since this model solves a partial loading problem, some decisions as breaking up demand into batches, and assigning process plans to the batches is done outside the model. This is a realistic assumption, since in many cases, even if the operations are similar, the demand may have to be grouped into batches, depending on the material handling equipment, material specification of the workpiece, accuracy of the machine, etc. The model then assigns tools to the machines, determines the number of redundancies, and balances the tool magazines of different machines, while minimizing the total tooling cost. The principal constraint of the model is nonlinear. The constraint was linearized, by taking a logarithm on both sides of the inequality. The logarithm part of the model was worked on by a program in C. The program in C calculated the reliability of a tool, to be used for a given duration, with m number of redundancies, m varying from zero to 20. The program delivered the logarithm values of the reliabilities. The results of the C program were sent into a file. The optimization package LINGO pulls up the required values from the file generated by the C program. The code for the C program is included in the appendix. Table 5.12 shows the cycle times of various operations, under different process plans.

5.5.1 Analysis Of Results :

The model was solved for various values of 'minimum required reliability'. The total cost of operation was observed for different values of minimum required reliability. Also, the number of tool slots in the machine, used up for the operation is observed. The results have been tabulated in Table 5.13 and plotted on graphs (Figures 5.14 and 5.15). Tables 5.16, 5.17, 5.18 and 5.19 show the number of tools of each tool type used on the machines, as the minimum required reliability for processing the parts increased. The minimum required reliability of all the batches in the demand was taken to be equal during the observations. However, the model can accept any level of reliability for any individual batch of demand.

Table 5.14 : Cycle-time Of Operations In The System

Tool #	Pt. 1		Pt. 2		Pt. 3	Pt. 4		Pt. 5	Pt. 6		Pt. 7		Pt. 8	Pt. 9	Pt. 10
	Pr. 1	Pr. 2	Pr. 1	Pr. 2	Pr. 1	Pr. 1	Pr. 2	Pr. 1	Pr. 1	Pr. 2	Pr. 1	Pr. 2	Pr. 1	Pr. 1	Pr. 1
1	2.0	1.0	2.0	2.0	1.0	2.0	2.0	1.0	1.0	1.0	3.0	2.0	1.0	1.0	3.0
2	1.0	2.0	2.0	1.0	2.0	2.0	1.0	0.0	1.0	1.0	2.0	2.0	1.0	2.0	1.0
3	1.0	1.0	2.0	2.0	3.0	1.0	2.0	3.0	2.0	1.0	1.0	2.0	1.0	0.0	1.0
4	2.0	2.0	2.0	2.0	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.0	2.0	1.0	1.0
5	3.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	0.0	0.0	0.0
6	2.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	0.0	0.0	0.0
7	3.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	3.0	2.0	0.0	0.0	0.0	0.0
8	0.0	0.0	1.0	0.0	0.0	0.0	3.0	0.0	4.0	0.0	0.0	0.0	3.0	0.0	0.0
9	0.0	0.0	3.0	0.0	0.0	0.0	2.0	0.0	3.0	0.0	0.0	0.0	2.0	0.0	0.0
10	0.0	0.0	2.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0	0.0	0.0	1.0	0.0	0.0
11	0.0	1.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
12	0.0	3.0	0.0	2.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
13	0.0	2.0	0.0	1.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
14	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	1.0
15	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0
16	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	4.0

Table 5.15 Effect of the Required Reliability, on Magazine Occupancy and Total Cost

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/c 1	M/c 2	M/c 3	M/c 4	
74.9894 %	29	29	29	29	$1848
79.98 %	31	30	31	30	$1940
89.95 %	34	34	34	34	$2179
93.325%	36	36	36	36	$2304
95.5%	38	38	38	38	$2421
96.605%	40	39	39	39	$2509
97.724%	41	41	41	41	$2629
98.175%	42	42	42	42	$2687
98.86 %	45	44	44	44	$2831
99.083%	46	45	45	45	$2885
99.495%	47	46	48	47	$3026
99.7%	50	50	50	50	$3182

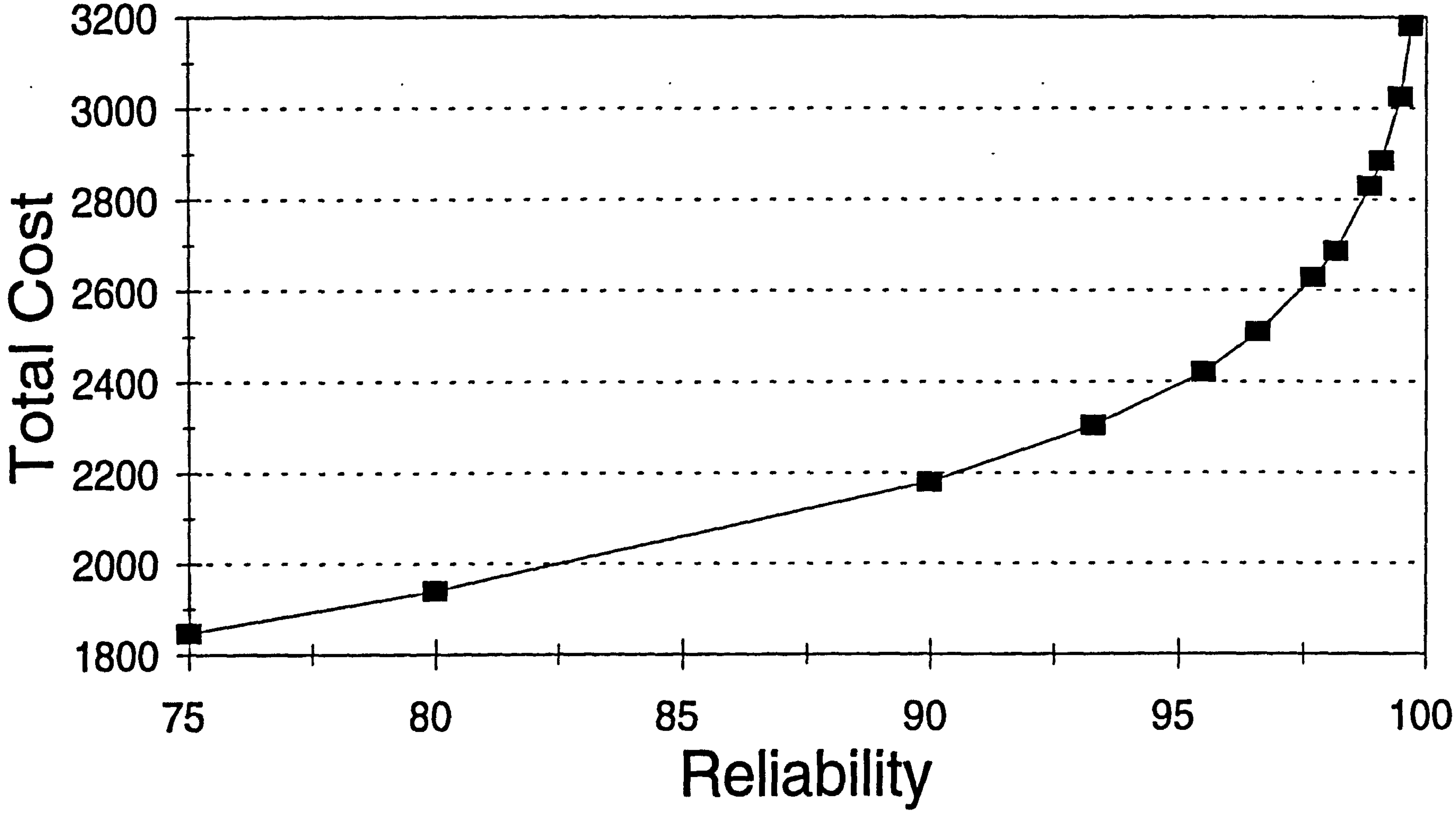


Figure 5.1 : Effect of Reliability on Total Cost of Tooling.

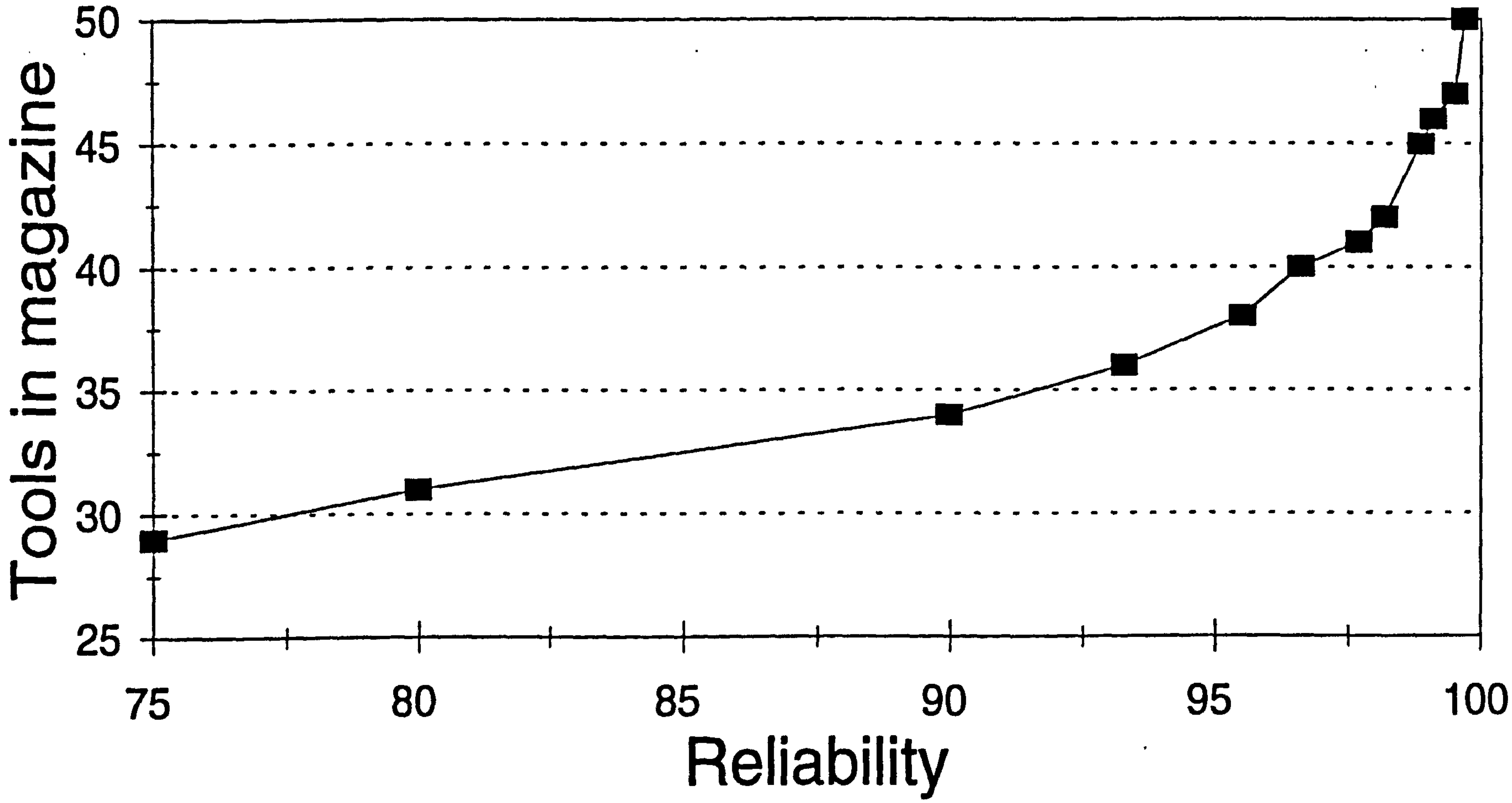


Figure 5.2 : Effect of Reliability on Tool Magazine Occupancy.

Table 5.16 : Redundancies Used, v/s Required Reliability, on M/c 1.

Tool #	79.98%	89.95%	95.5%	97.72%	98.86%	99.5%	99.7%
1	4	5	5	6	6	6	7
2	5	4	5	5	6	6	7
3	4	5	5	6	7	7	7
4	4	4	5	5	6	6	6
5	4	5	6	6	6	7	7
6	6	6	7	7	8	8	9
7	4	5	5	6	6	7	7

Table 5.17 : Redundancies Used, v/s Required Reliability, on M/c 2.

Tool #	79.98%	89.95%	95.5%	97.72%	98.86%	99.5%	99.7%
1	4	4	5	5	6	6	7
2	4	4	5	5	5	6	6
3	4	4	5	5	6	6	6
4	4	5	5	6	6	6	7
8	5	6	7	7	8	8	9
9	5	6	6	7	7	8	8
10	4	5	5	6	6	7	7

Table 5.18 : Redundancies Used, v/s Required Reliability, on M/c 3.

Tool #	79.98%	89.95%	95.5%	97.72%	98.86%	99.5%	99.7%
1	5	5	6	6	6	8	8
2	4	4	5	5	6	6	6
3	4	5	5	6	6	7	7
4	5	5	6	6	7	7	8
11	5	5	5	6	6	7	7
12	4	5	6	6	7	7	7
13	4	5	5	6	6	6	7

Table 5.19 : Redundancies Used, v/s Required Reliability, on M/c 4.

Tool #	79.98%	89.95%	95.5%	97.72%	98.86%	99.5%	99.7%
1	5	6	7	7	7	8	8
2	4	4	5	6	6	6	7
3	4	4	4	5	5	6	6
4	3	4	4	4	5	5	5
14	4	5	5	6	6	7	7
15	5	6	7	7	8	8	8
16	5	5	6	6	7	7	8

5.6 Model 3b, Tool Sharing Possible :

The model again is a linearized formulation. The numerical example has been solved using LINGO. A fairly large problem was used. The manufacturing facility in the above case was used for this case as well. So, the cycle times of the operations are the same as found in Table 5.12. Each machine has a tool magazine capacity of 50 tool slots. Three hundred parts, under 10 part types are to be loaded onto the system. Each part type could have up to 2 process plans. Sixteen different tool types were used to perform the various operations on the machines. A tool transporter is available, which could transfer the tools. If a particular tool required on a machine is not available on its tool magazine, the tool transporter could bring the tool from another machine, where a spare tool is available. The planning period is assumed to be 1000 minutes. This model being a partial loading problem, some decisions such as breaking up demand into batches, and assigning process plans to the batches is done outside the model. The model then assigns tools to the machines, determines the number of redundancies, and balances the tool magazines of different machines, while minimizing the total tooling cost. The principal constraint was linearized, by taking a logarithm on both sides of the inequality. The logarithm part of the model was worked on by a program in C. The results of the C program were sent into a file. The optimization package LINGO pulls up the required values from the file generated by the C program. The code for the C program is included in the appendix. The system, with cycle times of Table 5.12, is capable of achieving reliabilities upto 99.7% without tool sharing. To force tool sharing activity between machines, the absolute tool life of tools 5,6, and 7 were cut down to half. Thus tools 1,2,3,4,8,9,10,11,12,13, and 16 have an absolute tool life of 100 minutes, while tools 5,6,and 7 have an absolute life of only 50 minutes. To bring out the comparison between the two cases, model 1 was reworked on the modified problem, and the results compared.

Analysis Of Results :

The model was solved for various values of 'minimum required reliability'. The total cost of operation was observed for different values of minimum required reliability. Also, the number of the tool slots in the machine used up for the operation is observed. The results have been tabulated in Tables 5.21 and 5.22.

To force tool transfer in the system, the absolute life of tool number 5,6, and 7 on machine 1 was cut down to half the value, to 50 minutes. It is seen that as the required level of reliability rose to higher values, tool number 6 has to be located on machines where the tool is not being used, and brought into machine 1 by the tool transporter, when the tool was called for. Tools 1,2,3,4,8,9,10,11,12, and 13 have a tool life of 100 minutes, and so a failure rate of 0.01. Tools 5 and 6 have a life of 50 minutes, and so a failure rate of 0.02. Given the cycle times of each operation, the total usage of all the tools on every machine was found, and stored in a file 'totm2.dat'. The results of computation by the C program was sent to a file lgrel2.dat, which could be called up by the optimization program LINGO. The results obtained have been tabulated in Tables 5.21 and 5.22.

To bring out the comparison, the same problem was rerun for case1, where tool sharing is not possible. The results have been shown in Table 5.23. It can be seen that the batches being processed on machine 1 could not get a reliability, of more than 97.75%. For a realistic scenerio, this would be a low value. Further it can be seen that as the tool life of the tools go to lower values, the case 1 layout would tend to have lower planning periods, and or lower reliabilities. The illustrated example shows the use of 4 machines. However, as tools of lower tool life are put to use, there could be one or more tool carousals, which could stock a large number of redundancies. In such a case, tool sharing between machines could raise the the reliability of the tooling system to a very high value. In such situations, sytems without tool sharing cannot be employed.

Table : 5.21 Effect of the Required Reliability on Magazine Occupancy & Total Cost, Model 3 Case 2.

Minimum Reliability	Machine Number				Total Cost	Tool Movements
	M/c 1	M/c 2	M/c 3	M/c 4		
89.125%	42	34	34	34	2302	0
93.325%	45	36	36	36	2458	0
97.724%	50	41	41	41	2800	0
98.85%	50	48	44	44	3036	M/c 2 >> M/c 1 = 4 tools
99.3%	50	50	46	48	3187	M/c 2 >> M/c 1 = 4 tools M/c 4 >> M/c 1 = 2 tools
99.5%	50	50	49	50	3282	M/c 2 >> M/c 1 = 3 tools M/c 3 >> M/c 1 = 1 tool M/c 4 >> M/c 1 = 3 tools

Table : 5.22 Redundancies Used, v/s Required Reliability.

M/c #	Tool #	89.13%	93.33%	97.72%	98.85%	99.3%	99.5%
MACHINE 1	1	5	5	5	6	6	6
	2	5	5	6	6	6	6
	3	5	5	6	6	7	7
	4	4	5	5	6	6	6
	5	7	8	9	9	10	10
	6	9	10	10	8	6	5
	7	7	7	9	9	9	10
MACHINE 2	1	5	5	5	6	6	6
	2	4	4	5	5	6	6
	3	4	5	5	6	6	6
	4	5	5	6	6	6	6
	8	6	6	7	8	8	8
	9	5	6	7	7	7	8
	10	5	5	6	6	7	7
	6	0	0	0	4	4	3
MACHINE 3	1	5	5	6	6	7	8
	2	5	5	5	6	6	6
	3	5	5	6	6	7	7
	4	5	6	6	7	7	7
	11	5	5	6	6	6	7
	12	5	5	6	7	7	7
	13	4	5	6	6	6	6
	6	0	0	0	0	0	1

MACHINE 4	1	5	6	7	7	8	8
	2	4	5	6	6	6	6
	3	4	5	5	5	5	6
	4	4	4	4	5	5	5
	14	5	5	6	6	7	7
	15	7	6	7	8	8	8
	16	5	5	6	7	7	7
	6	0	0	0	0	2	3

Table 5.22 : Redundancies Used v/s Required Reliability (continued)

Table : 5.23 Magazine Occupancy & Total Cost Without Tool Sharing.

Minimum Reliability	Machine Number				Total Cost
	M/c 1	M/c 2	M/c 3	M/c 4	
89.125%	42	34	34	34	2302
93.325%	45	36	36	36	2458
97.724%	50	41	41	41	2800
98.85%	Maximum Feasibility Limited to 97.724 %	48	44	44	3033
99.3%		50	46	48	3187
99.5%		50	49	50	3282

5.7 Simulations On Witness :

The mathematical models optimized the system using average values for cycle times, absolute tool life, and inter-arrival times between the demand of various part types. In reality, however, these values could be stochastic in nature. To minimize the variation between the calculated values of the decision variables, it would be required to include the effect of the stochastic nature of the problem into the optimization of the decision variables.

Witness is a simulation package, receiving wide acceptance in today's industries. Compared to the other packages, this package is more user-friendly, and operates in Windows environment. The software simultaneously builds up the animation of the model as the model is being developed. Thus by running the simulation under a slower time scale, it is easy to watch the queues and facilities as the model runs. Witness also has a statistical analysis package along with it, giving it the capability of quick analysis of the simulated run.

In this research, simulation was used as a tool to verify the results obtained from the mathematical model, and to add the capability to include the stochastic nature of the real world problem. As far as possible, the model was designed so as to take the variations in the size of the problem. The limits, queue size, cycle times, and distributions were programmed to be variables and data files.

As the parts arrived into the system, they were given attributes, designating their part types, process plans and the machines on which they are to be processed. In this case, these values were attributed, as obtained from the mathematical model. However, they could be allowed to take up values based on a statistical distribution. The parts arriving in the system are thus sent to the respective machine's local queue, where they wait till they are pulled by the machine. On arriving at the machine, the parts will get processed, according to their attributed part types and process plans. As discussed in the mathematical modelling, the machining of the part can be seen as a series system, where tools perform their operations one after the other, to produce finished parts. On an actual machine, the tool magazine is attached to the machine itself. To give a better visualization during the animation, and also to provide the flexibility, the magazine was replaced by a source, having infinite number of tools of each tool type available. A variable matrix kept track of the number of tools of each tool type expired on each machine. Further, the matrix is displayed on the animation screen. Thus, as the simulation progresses, the number of tools expiring in the system will be displayed. A variable allows the user to put a variable limit on the maximum number of tools that could expire on a machine. This would give the effect of the number of tools available on a machine. Processed parts are sent out into the outgoing buffers. The effect of stochastic cycle times and catastrophic tool failures were programmed into simulation.

5.7.1 Tool Sharing Permitted :

In the first simulation, the system in consideration has 2 machines. 5 part types, with a maximum of 2 process plans were to be processed, using 6 different tool types. There was no tool sharing permitted between the machines. Cycle times for the operations were identical to the one used for model 1 case 1, in Table 5.1. The cycle times are deterministic. The useful life of the tools are the same as in Table 5.3. Parts were assigned to machines and process plans, as determined by the first mathematical model, case 1.

It is seen that the results of the simulation are identical to the results seen from the mathematical computation. The number of spares of each kind required was the same as the number determined by the mathematical models. The utilization of the machines were also found to be the same as earlier.

Table 5.23 Cycle Time for Operations in the System.

Tool Type	Part 1		Part 2		Part 3	Part 4		Part 5
	Pr. 1	Pr. 2	Pr 1	Pr. 2	Pr. 1	Pr 1	Pr 2	Pr.1
1	5	4	2	2	-	-	-	-
2	1	2	-	2	1	2	1	-
3	3	1	2	-	-	-	-	-
4	-	2	2	2	1	2	1	2
5	-	-	-	-	1	1	2	3
6	-	-	-	-	1	1	1	-

Table 5.24 Useful Tool Life

Tool Type	1	2	3	4	5	6
Useful Life	25	25	25	25	50	25

Table 5.25 : Demand Partitioned into Batches by Mathematical Model

Part Type	M/c 1; Pr.1	M/c 1; Pr.2	M/c 2; Pr.1	M/c 2; Pr.2
1	7	-	13	10
2	-	20	9	1
3	30	-	-	-
4	-	16	-	14
5	7	-	23	-

Table 5.26 : Spares Used for Determininistic Cycle times.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
3	5	4	2	1	3	4	4	2	2	2	1

Table 5.27 : Spares Used for Stochastic Cycle times.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
3	5	4	3	1	3	5	4	2	1	2	1

Table 5.28 : Spares Used with Stochastic Cycle times & Catastrophic Failures.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
3	5	4	3	2	3	5	4	2	2	2	1

5.7.2 Tool Sharing Permitted :

In the second case, tool sharing was permitted between the machines. The cycle times of operations were the same as those used in the previous case. As mentioned in the mathematical example, tool sharing was forced between machines, by changing the magazine capacity of the machines. The capacity of the magazine on machine 1 was limited to 10 slots. The machine and process plans were attributed to the incoming parts, in accordance to the solutions of the mathematical models given in Table 5.6. Like in the previous case, three cases were run, one with deterministic cycle times, one with exponential cycle times, and the third on with exponential cycle times, and catastrophic failures.

With the cycle times deterministic, the number of tools used by the system was found to be identical to that obtained from the mathematical model. As the stochastics were introduced the values were found to be almost the same as obtained from the mathematical model. Table 5.29 gives the results of simulation, with deterministic cycle times. Table 5.30 shows the case of exponential cycle times, and Table 5.31 includes catastrophic failures.

Table 5.29 : Spares Used for Determininistic Cycle times.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
9	-	3	3	4	-	3	5	3	1	1	1

Table 5.30 : Spares Used for Exponential Cycle times.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
9	-	4	3	4	-	4	5	3	1	2	1

Table 5.31 : Spares Used, Exp. Cycle Times & Catastrophic Failures.

Tool 1		Tool 2		Tool 3		Tool 4		Tool 5		Tool 6	
M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2	M 1	M 2
9	0	4	3	5	-	4	5	3	1	2	1

5.7.3 Discussion :

Whereas the mathematical models targeted optimization and generalization of problems, simulation deals with feasibility, comparisons and details of subjective cases. In this research, simulation is being used as a evaluation tool. It is used to verify that the system would perform all the required operations, given the decision variables of the problem scenario. In the mathematical models, we defined means and statistical distributions to describe and study the stochastic nature of real life randomness. The randomness is limited to a few distributions, which are easier to compute. While simulating, however, we can make the situation have a more complex randomness, so as to be similar to a previous observation or forecast. Details like utilization of resources, queues for facilities, makespan of batches, visual animation of the problem, etc are some of the other advantages of using simulation studies.

It is observed from the examples that the tool life and planning period are two variables that greatly influence the decision variables. As the tool life value decreases, or the planning period gets longer, the system would require more number of redundancies for functioning. Since the capacity of the tool magazine is limited, in the case of 'no tool sharing', as the number of spare tools increases, the production planner will be limited to lower values of 'minimum required reliability' or to a shorter production planning period. However in the case of tool sharing permitted, if the system be allowed to share with a tool carousel, one could still attain larger reliability values. To get even higher values of reliability, one could have carousels that are bulk exchangeable. In such cases, the capacity constraints of the tool transporter would play a more vital role. Simulation also provided the ability to include the effect of catastrophic failures on the decision variables. Since this is an added failure to the system, the effect of this failure was essentially more redundancies. Since most batches in the example required about eight operations to get a finished part, the utilization values of the individual tools were very low, in comparison to the machine itself.

To simulate the effect of reliability, the simulated model will have to be run a large number of times under stochastic conditions. Reliability can then be calculated, by tracking the number of times the decision variables were exceeded.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

With the advent of complex and expensive flexible manufacturing systems, production planning has become a critical factor that contributes to an efficient operation of the system. The main activity of the planning problem is the loading of the system. System reliability, and hence the reliability of the tooling system, is an important performance index to evaluate a system.

6.1 Conclusions :

In this research, three loading models were formulated that can be used to solve a loading problem in a FMS environment. Reliability of the tools were taken into consideration while optimizing the production system. It has also been shown that in terms of reliability assessment, the tooling system of FMS can be treated as a series system with standby redundancies. Two of the models dealt with, were 'full loading' problems, which assigned parts to machines, partitioned the demand into batches, assigned process plans to the batches, assigned tools to the machines. The third model was formulated for a 'partial loading' problem which assigned tools to machines, and determined the optimal spares for the production run. The models have been found to be giving optimal solutions to the hypothetical problems. The linear programs were solved, using the software package LINDO®, and the non-linear models were optimized, using LINGO®. The situations were simulated, using a popular simulation package, WITNESS®. The results were found to be in agreement with the values found from the mathematical models. Stochastic dimensions were added to the simulation model, by having the cycle times to be exponentially distributed, and also including the possibility of catastrophic tool failures.

6.2 Future Work :

It is for the first time, that the loading problem has been solved by giving reliability considerations to the components of the system. Therefore there are several possible recommendations for future work.

- Each cutting tool was assumed to be accommodated in one tool slot of the tool magazine. Models could be modified to accommodate tools that use more than one slot of the tool magazine.
- The models discussed were for a single production period. The study could be

extended to multiple periods.

☞ Material handling of the parts could be included into the loading problem.

☞ A heuristic modelling approach could be taken to handle very large loading problems.

☞ Tooling being the most wearing part in a typical machine shop, this research was concentrated on the reliability of cutting tools. This model could be extended to include the reliability of the machine tools as well.

☞ Simulations were done to verify the results from the mathematical models. The work could be extended by designing experiments, and running under various situations.

☞ A simulations program coupled with a pre-processor could be modelled to solve this problem.

REFERENCES

ASKIN, G. R., and STANDRIDGE, C. R., "Modelling and Analysis of Manufacturing Systems", *John Wiley and Sons, Inc.,* New York, 1993.

ATMANI, A., LASHKARI, R.S., and CARRON, J., "Mathematical Programming Approach in Joint Cell Formation and Operation Allocation in Cellular Manufacturing" *International Journal of Production Research*, Vol. 33 No. 1, 1995.

AYRES, R. U., "Future trends in Factory Automation", *Manufacturing Review,* Vol. 1, No. 2, pp. 93-103, 1988.

BELLMAN, R. E., and DREYFUS, S. E., "Dynamic Programming and Reliability of Multicomponent Devices", *Operations Research,* Vol. 6, pp. 200-206, 1958.

BERRADA, M., and STECKE, K. E., "A Branch and Bound Approach for Machine Load Balancing in Flexible Manufacturing System", *Management Science,* Vol. 32, pp. 1316-1335, 1986.

BILLATOS, S.B., and KENDALL, L.A., "A General Optimization Model for Multi-Tool Manufacturing System", *Journal of Engineering for Industry.*, Transaction of the ASME. Vol. 113 pp. 10-16, Feb. 1991.

CARRIE, A.S. and PERERA D.T.S., "Work Scheduling in FMS Under tool Availability Constraints", *International Journal of Production Research*, Vol. 24 No. 6., 1986.

CATUNEANU, V. M., MOLDOVAN, C., POPENTIU, F., and GHEORGHIU, M., "Optimum Allocation of Computer Spares for Three-Level Stocks", *Microelectronics and Reliability,* Vol. 27, No. 4, pp. 643-646, 1987.

CHANG, T., WYSK, R. A., DAVIS, R. P., and CHOI, B., "Milling parameter Optimization Through a Discrete Variable Transformation", *International Journal of Production Research*, Vol. 20, No. 4, pp. 507-516, 1982.

COOK, N. H., "Tool Wear and Tool Life", *ASME, Journal of Engineering for Industry,* pp. 931-938, Nov. 1973.

DAMODRAN, V., LASHKARI, R. S., and SINGH N., "A Production Planning Model for Cellular Manufacturing Systems with Refixturing Considerations" *International Journal of Production Research,* Vol. 30, No. 7, pp 1603-1615, 1992.

DHILLON, B.S., "Reliability Engineering in Systems Design and Operation", *Van Nostrand Reinhold Co.*, New York, 1982.

DHILLION, B.S., and SINGH, C., "Engineering Reliability : New Techniques and Applications", *John Wiely & Sons, Inc.*, 1981.

FAN, L. T., WANG, C. S., TILLMAN, F. A., and HWANG, C. L., "Optimization of System Reliability", *IEEE Transactions on Reliability*, Vol. R-16, pp. 81-86. 1967.

FRIEDMAN, M. Y., and ZLATIN, N., "Variability of tool Life as a Function of Mean Value", *Proceeding of the North American Metalworking Research Conference*, Madison, Wisc., pp. 128-138, 1974.

GHARE, P. M., and TAYLOR, R. E., "Optimum Redundancy for Reliability in Series System", *Operations Research*, Vol. 7, pp. 838-847, 1969.

GHOSH, J. B., and WELLS, C. E., "Determining Optimal Redundancy for Systems With Random Lifetimes", *IEEE Transactions on Reliability*, Vol. 39, No. 3, pp. 309-312, 1990.

GLOVER, F., and WOOLSEY, R. E., "Further Reduction of 0/1 Polynomial Programming Problem to 0/1 Linear Programming Problem", *Operations Research*, Vol. 21, pp. 156-161, 1979.

GROSH, D. L., "A Primer of Reliability Theory", *John Wiley & Sons, Inc.*, New York, 1989.

GROSS, D., MILLER, D. R., and SOLAND, R. M., "A Closed Queueeing Network Model for Multi-Echelon Repairable Item Provisioning", *IIE Transactions*, Vol. 15, NO. 3, pp. 344-352, 1983.

GYAMPAH, K. A., MEREDITH, J. R., and RATURI, A., "A Comparison of Tool Management Strategies and Part Selection Rules for A Flexible Manufacturing Systems", *International Journal of Production Research*, Vol. 30, No. 4, pp. 733-748, 1992.

HAN, M-H., NA, YOON K., and HOGG, G. L., Real-time Control and Job Dispatching in Flexible Manufacturing Systems, *International Journal of Production Research*, Vol. 27, No. 8, pp. 1257-1267, 1989.

HANKINS, S.L., and ROVITO, V.P., "A Comparison of Two Tool Allocation and Distribution Strategies for FMS", *Proceedings of the First ORSA/TIMS Conference on Flexible Manufacturing Systems*, pp. 272-277, Ann arbor, MI., 1984.

HEDLUND, E.P., DAVIS, W.J., and WEBSTER, P.L., "Using Computer Simulation to

Compare Tool Delivery Systems in an FMC", *Proceedings of 1990 Winter Simulation Conference,* pp. 641-645, 1990.

HITOMI, K., "Analysis of Production Models; Part 1. The Optimal Decision of Production Speeds", *AIIE Transactions,* Vol. 8, No.1, pp. 96-100, 1976.

HITOMI, K., NAKAMURA, N., and INOUE, S., "Reliability Analysis of Cutting Tools", *Journal of Engineering for Industry,* Vol. 101, No.1, pp. 185-190, 1979.

HWANG, C. L., FAN, L. T., TILLMAN, F.A., and KUMAR, S., "Optimization of Life Support System Reliability by an Integer Programming Method", *AIIE Transactions,* Vol. 3, No. 3, pp. 229-238, 1971.

JENG A. and YANG K., "Optimal Tool Replacement with Nondecreasing Tool Wear", *International Journal of Production Research,* Vol. 30, No. 2, pp. 299-314, 1992.

KIRAN, A.S., and KARSON, R.J., "Automating Tooling in a Flexible Manufacturing System", *Industrial Engineering,* April, Vol. 30, No. 2, pp. 52-57, 1988.

KOLAHAN, F., "The Effect of Tool Sharing on Reliability of Flexible Manufacturing Systems", *M.A.Sc Thesis, Ottawa-Carlton Institute for Mechanical and Aeronautical Engineering, University of Ottawa,* Ottawa, Ontario, Canada, 1993.

KOLAHAN, F., TABOUN, S., PHILIPOSE, A.M., "The Effect of Tool Sharing on Reliability of Flexible Manufacturing Systems", *Proceedings of the First World Automation Congress (WAC '94),* Hawaii, pp 111-114, 1994.

KUSIAK A., "Flexible Manufacturing Systems: A Structural Approach", *International Journal of Production Research,* Vol. 23, No. 6, pp. 1057-1073, 1985.

LIANG M., "The Combined Part Selection and Machine Loading Problems in Flexible Manufacturing Systems" *Ph. D Thesis, University of Windsor,* Windsor, 1991.

MACCARINI, G. C., ZAVANELLA, L. and BUGINI, A., "Production Cost and Tool Reliabilities: The Machining Cycle Influence in Flexible Plants", *International Journal of Machine Tools and Manufacture,* Vol. 31, No. 3, pp. 415-424, 1991.

MALEKI, R. A., "Flexible Manufacturins Systems The Technology and Management", *Printice Hall Inc.,* Englewood Cliffs, 1991.

MENON, U., and O'GRADY, P.J., "Loading a Flexible Manufacturing System", *International Journal of Production Research,* Vol. 22, No. 7, pp. 1053-1068, 1984.

MESSINGER, M. and SHOOMAN, M. L., "Techniques for Optimum Spares Allocation: A Tutorial Review", *IEEE Transactions on Reliability*, Vol. R-19, pp. 156-166, 1970.

O'GRADY, P.J. and MENON U., "Loading a Flexible Manufacturing System", *International Journal of Production Research*, Vol. 25, No. 7, pp. 1053-1068, 1987.

PAN, J.N., KOLARIK, W.J., and LAMBERT, B.K., "Mathematical Models to Predict the System Reliability of Tooling for Automated Machining Systems", *International Journal of Production Research*, Vol. 24, No. 3, pp. 493-501. 1986.

RAJAGOPALAN, S., "Formulation and Heuristic Solution for Parts Grouping and Tool Loading in Flexible Manufacturing Systems", *Proceeding of the second ORSA/TIMS* Conference on Flexible Manufacturing Systems: Operations Research Models and Applications, Elsevier Science Publishers, B.V., Amsterdam. 1986.

RAJAMANI, D., "Design of Cellular Manufacturing Systems" *Ph. D Thesis, University of Windsor*, Windsor, 1991.

RAMALINGAM, S., "Tool life Distribution. Part 2: Multiple-Injury Tool-life Model", *Journal of Engineering for Industry*, Vol. 99 No. 3, pp. 523-531. 1977.

RAMALINGAM, S. and WATSON, J.D., "Tool life Distribution. Part 1: Single-Injury Tool-life Model", *Journal of Engineering for Industry*, Vol. 99 No. 3, pp. 519-522. 1977.

RAMALINGAM, S., PENG, Y. I. and WATSON, J.D., "Tool life Distribution. Part 3: Mechanism of Single Injury Tool Failure and Tool Life Distribution in interrupted cutting", *Journal of Engineering for Industry*, Vol. 100, No. 1, pp. 193-200, 1978.

RAO, S.S., "Reliability - Based Design", *McGraw-Hill Inc*, 1992.

REZVANI, A.R., RAHNEIAT, H., and BERA, H., "Reliability Analysis of a Flexible Machining Cell", *The International Journal of Advanced Manufacturing Technology*, Vol. 1, No. 4, pp. 55-68, 1986.

ROVIITO, V.P., HANKINS, L., "Impact of Tooling in Flexible Manufacturing System", *Publised by IFS Publication Ltd*, Kempston, Engl & Springer-Verlag, Berlin, West Germany & New York, NY, U.S.A., pp. 249-271, 1986.

SARIN, S.C., and CHEN, C.S., "Machine Loading and Tool Allocation Problem in a Flexible Manufacturing System", *International Journal of Production Research*, Vol. 27, No. 7, pp. 1019-1034, 1987.

SASAKI, M., and KABURAKI, S., "System Availability and Optimum Spare Units", *IEEE Transactions on Reliability*, Vol. R-26, No. 3, pp. 182-188, 1977.

SCHRIBER, T.J., "Simulation Usung GPSS", *John Wiley and Sons,* New York, 1974.

SEARS, R. W. Jr., "Practical Models for Determining Standby Redundancy Levels", *Proceeding of the Annual Reliability and Maintainability Symposium*, Los Angeles, USA, Pub. by IEEE service centre, pp. 120-126, 1990.

SHAW, M.C., "Optimization of machine tool processes", *Technology of Machine Tools*, Vol. 2, 1980.

STECKE K. E., "Formulation and Solution of Non linear Integer Production Planning Problems for Flexible Manufacturing Systems", *Management Science*, Vol. 29, pp. 273-278, 1983.

STECKE K. E., and SOLBERG J.J., "Loading and Control Policies for a Flexible Manufacturing System ", *International Journal of Production Research*, Vol. 19, No. 5, pp. 481-489, 1981.

TANG, C. S., and DENARDO, E.V., "Models Arising from a Flexible Manufacturing Machine; Part I: Minimization of the Number of Tool Switches", *Operations Research*, Vol. 36, No. 5, Sept.- Oct. 1988.

TANG, C.S., "A Job scheduling Model for a Flexible Manufacturing Machine", 1986 *IEEE International Conference on Robotics and Automation*, Vol. 1, pp. 152-155, 1986.

TAYLOR, F. W., "On the Art of Cutting Metals", *ASME Transactions*, Vol. 28, pp. 310-350, 1907.

TILLMAN, F. A., HWANG, C. L., and KUO, W., "Optimization of Systems Reliability", *Marcel Dekker Inc.*, USA, 1980.

TILLMAN, F. A., "Optimization by Integer Programming of Constrained Reliability Problems with Several Modes of Failure", *IEEE Transactions on Reliability*, Vol. R-18, pp. 47-53, 1969.

TOMEK, P., "Tooling Strategies Related to FMS Management", *The FMS Magazine*, Vol. 4, pp. 102-107, April 1986.

VENTURA, J.A., CHEN, F. FRANK, LEONARDO, MICHAEL S., "Loading Tools to Machines in Flexible Manufacturing Systems", *Computer and Industrial Engineering*, Vol.

15, pp. 223-230, 1988.

WAGNER, J.G, and BARASH, MOSHE M., "Study of the Distribution of the life of HSS Tools", *Transactions of the ASME*, Nov. 1971.

ZAVANELLA, L., MACCARINI, G. C., and BUGINI, A., "Tool Supply in a Stochastic environment: Strategies and Related Reliabilities", *International Journal of Machine Tools and Manufacture*, Vol. 30, pp. 389-402, 1990.

ZELENOVIC, D. M., "Flexibility - A Condition for Effective Production Systems", *International Journal of Production Research*, Vol. 20, pp. 319-337, 1982.

APPENDIX 1

MODEL 1, CASE 1

```
! A NUMERICAL EXAMPLE  2 MACHINES, 5 PART-TYPES (3 WITH
! 2 PROCESS PLANS & 2 WITH 1 PROCESS PLAN), 6 TOOL TYPES,
! TOOL SHARING  R E S T R I C T E D
!
MINIMIZE
10N11+10N21+12N12+12N22+15N13+15N23
+20N14+20N24+11N15+11N25+14N16+14N26
!
!
SUBJECT TO
!
! DEMAND  BALANCE
X111+X112+X121+X122=1
X211+X212+X221+X222=1
X311+X321=1
X421+X422+X411+X412=1
X511+X521=1
!
! MAGAZINE  CAPACITY
N11+N12+N13+N14+N15+N16<=10
N21+N22+N23+N24+N25+N26<=10
!
! UNIQUE # OF TOOLS  &  TOOL QUANT. INDICATOR
Z110+Z111+Z112+Z113+Z114+Z115=1
Z111+2Z112+3Z113+4Z114+5Z115-N11=0
Z120+Z121+Z122+Z123+Z124+Z125=1
Z121+2Z122+3Z123+4Z124+5Z125-N12=0
Z130+Z131+Z132+Z133+Z134+Z135=1
Z131+2Z132+3Z133+4Z134+5Z135-N13=0
Z140+Z141+Z142+Z143+Z144+Z145=1
Z141+2Z142+3Z143+4Z144+5Z145-N14=0
```

```
Z150+Z151+Z152+Z153+Z154+Z155=1
Z151+2Z152+3Z153+4Z154+5Z155-N15=0
Z160+Z161+Z162+Z163+Z164+Z165=1
Z161+2Z162+3Z163+4Z164+5Z165-N16=0
Z210+Z211+Z212+Z213+Z214+Z215=1
Z211+2Z212+3Z213+4Z214+5Z215-N21=0
Z220+Z221+Z222+Z223+Z224+Z225=1
Z221+2Z222+3Z223+4Z224+5Z225-N22=0
Z230+Z231+Z232+Z233+Z234+Z235=1
Z231+2Z232+3Z233+4Z234+5Z235-N23=0
Z240+Z241+Z242+Z243+Z244+Z245=1
Z241+2Z242+3Z243+4Z244+5Z245-N24=0
Z250+Z251+Z252+Z253+Z254+Z255=1
Z251+2Z252+3Z253+4Z254+5Z255-N25=0
Z260+Z261+Z262+Z263+Z264+Z265=1
Z261+2Z262+3Z263+4Z264+5Z265-N26=0
!
! TOOL LIFE AVAILABLE
50X111+40X112+20X211+20X212-25N11<=0
50X121+40X122+20X221+20X222-25N21<=0
10X111+20X112+20X212+10X311+20X411+10X412-25N12<=0
10X121+20X122+20X222+10X321+20X421+10X422-25N22<=0
30X111+10X112+20X211-25N13<=0
30X121+10X122+20X221-25N23<=0
20X112+20X211+20X212+10X311+20X411+10X412+20X511
-25N14<=0
20X122+20X221+20X222+10X321+20X421+10X422+20X521
-25N24<=0
10X311+10X411+20X412+30X511-25N15<=0
10X321+10X421+20X422+30X521-25N25<=0
10X311+10X411+10X412-25N16<=0
10X321+10X421+10X422-25N26<=0
!
50X111+40X112+20X211+20X212+10X111+20X112+20X212
+10X311+20X411+10X412+30X111+10X112+20X211+20X112
+20X211+20X212+10X311+20X411+10X412+20X514+10X311
+10X411+20X412+30X511+10X311+10X411+10X412<=480
!
50X111+40X112+20X211+20X212+10X111+20X112+20X212
```

```
+10X311+20X411+10X412+30X111+10X112+20X211+20X112
+20X211+20X212+10X311+20X411+10X412+20X514+10X311
+10X411+20X412+30X511+10X311+10X411+10X412-B1<=0
!
!
50X121+40X122+20X221+20X222+10X121+20X122+20X222
+10X321+20X421+10X422+30X121+10X122+20X221+20X122
+20X221+20X222+10X321+20X421+10X422+20X524+10X321
+10X421+20X422+30X521+10X321+10X421+10X422<=480
!
50X121+40X122+20X221+20X222+10X121+20X122+20X222
+10X321+20X421+10X422+30X121+10X122+20X221+20X122
+20X221+20X222+10X321+20X421+10X422+20X524+10X321
+10X421+20X422+30X521+10X321+10X421+10X422-B2<=0
!
END
```

GIN N_{jl} $\forall$ j,l

INT Z_{jlm} $\forall$ j,l,m

MODEL 1, CASE 2

```
! A NUMERICAL EXAMPLE   2 MACHINES, 5 PART TYPES (3 WITH
! 2 PROCESS PLANS & 2 WITH 1 PROCESS PLAN), 6 TOOL TYPES,
! TOOL SHARING   P E R M I T T E D
!
 MODEL:
  ! STOTRAM ;
  ! E = TOOL MAGAZINE CAPACITY  B = MACHINE AVAILABILITY ;
  ! D = DEMAND  T = EXPECTED TOOLLIFE OF EACH TOOL ;
  ! N = No. OF REDANDANCIES OF EACH TOOL  ;
  SETS:
  MAC /1..2/ : E, B, MU ;
  FMC /1..2/ :  ;
  PT /1..5/ : D ;
  PR /1..2/ : ;
 TL /1..6/ : LF, C ;
 FMCTL (FMC,MAC, TL) : N ;
 PTPR (PT,PR) : V ;
 PTMCPR(PT,MAC,PR) : X ;
 PTTLPR(PT,TL,PR) : TM ;
 ENDSETS
 !
 ! The Objective ;
 MIN =
 @SUM( TL(L)  :
  @SUM (FMC(K) :
  @SUM (MAC(J) :
   C(L) * N(K,J,L)))) +
 @SUM( TL(L) :
  @SUM( FMC(K) :
  @SUM( MAC(J)  | K # NE # J :
   3 * N(K,J,L)))) ;
 !
 ! Sum Of Batches = Demand ;
 @FOR ( PT(I) :
 @SUM ( MAC(J):
 @SUM ( PR(P) | V(I,P) #EQ# 1:
```

```
 X(I,J,P))) = D(I));
!
! Magazine Capacity ;
@FOR( FMC(K) :
@SUM( MAC(J) :
@SUM( TL(L) :
  N(K,J,L))) < E(K));
!
! Machine Capacity ;
@FOR( MAC(J) :
@SUM( TL(L) :
@SUM( PT(I) :
@SUM( PR(P) : X(I,J,P) * TM(I,L,P)))) < B(J)) ;
!;
@FOR( MAC(J) :
@SUM( TL(L) :
@SUM( PT(I) :
@SUM( PR(P) : X(I,J,P) * TM(I,L,P)))) = MU(J)) ;
!;
@FOR( MAC(J) :
@FOR( TL(L) :
@SUM( PT(I) :
@SUM( PR(P) :
 X(I,J,P) * TM(I,L,P)))
 < LF(L) * @SUM (FMC(K) : N(K,J,L)))) ;
!
!
! RESTRICTING TO INTEGERS ;
@FOR( FMCTL : @GIN( N));
@FOR( PTMCPR : @GIN(X));
@FOR( FMCTL : @BND(0,N,10));
@FOR( PTMCPR : @BND(0,X,30));
!
! The Data ;
DATA :
E = 10,30 ;
B = 480,480 ;
C = 10,12,15,20,11,14 ;
```

```
D = 30,30,30,30,30 ;
LF = 25,25,25,25,50,25 ;
TM = 5,4,1,2,3,1,0,2,0,0,0,0,
   2,2,0,2,2,0,2,2,0,0,0,0,
   0,0,1,0,0,0,1,0,1,0,1,0,
   0,0,2,1,0,0,2,1,1,2,1,1,
   0,0,0,0,0,0,2,0,3,0,0,0 ;
V = 1,1,1,1,1,0,1,1,1,0 ;
ENDDATA

END
```

MODEL 2, CASE ~~1~~ 2

```
! A NUMERICAL EXAMPLE  2 MACHINES, 2 PART TYPES, 4 TOOL TYPES,
! TOOL SHARING  R E S T R I C T E D
!
MODEL:
! STOTRAM ;
! E = TOOL MAGAZINE CAPACITY   B = MACHINE AVAILABILITY ;
! D = DEMAND   LF = EXPECTED LIFE OF EACH TOOL ;
! N = No. OF REDUNDENCIES OF EACH TOOL ;
SETS:
MAC / 1 .. 2 / : E , B, MUTZ  ;
PT / 1 .. 2 / : D ;
PR / 1 .. 2 / :  ;
TL / 1 .. 4 / : LF , C ;
MCTL(MAC, TL) : N, UG ;
PTMCPR(PT, MAC, PR) : X, Y, R ;
PTTLPR(PT, TL, PR) : TM, ALPHA ;
ENDSETS
!
! The  Objective ;
MIN = @SUM( MAC(J) : @SUM ( TL(L): C(L) * N(J,L))
 + 10 * @SUM( PT(I) : @SUM(PR(P) :Y(I,J,P)))) ;
!
! Sum Of Batches  =  Demand ;
@FOR( PT(I) :
 @SUM( MAC(J) :@SUM( PR(P) : X(I,J,P))) = 1);
!
! Magazine  Capacity ;
@FOR( MAC(J):
 @SUM( TL(L): N(J,L)) <  E(J)) ;
!
! Machine Capacity  ;
@FOR( MAC(J):
 @SUM( TL(L) :
 @SUM( PT(I) :
 @SUM( PR(P) : D(I) * X(I,J,P) * TM(I,L,P)))) <  B(J)) ;
```

```
! ;
@FOR( MAC(J):
@SUM( TL(L) :
@SUM( PT(I) :
@SUM( PR(P) : D(I) * X(I,J,P) * TM(I,L,P)))) = MUTZ(J)) ;
! ;
@FOR( MAC(J):
@FOR( TL(L) :
@SUM( PT(I) :
@SUM( PR(P) : D(I) * X(I,J,P) * TM(I,L,P)))
< LF(L) * N(J,L))) ;
!
! Tool Usage ;
@FOR( MAC(J) :
 @FOR( TL(L) :
 @SUM( PT(I) :
 @SUM( PR(P) : D(I) * X(I,J,P) * TM(I,L,P)))
 = 100 * UG(J,L))) ;
!
! Provide Tools For The Selected Operations ;
@FOR( PT(I) :
 @FOR( MAC(J) :
 @FOR( PR(P) :
 @FOR( TL(L) : X(I,J,P) * ALPHA(I,L,P) < N(J,L))))) ;
@FOR( PT(I) :
 @FOR( MAC(J) :
 @FOR( PR(P) :
  X(I,J,P)  < 25 * Y(I,J,P)))) ;
!
! Reliability Constrains ;
@PPS( UG(1,1), N(1,1)) * @PPS( UG(1,2), N(1,2)) *
@PPS( UG(1,3), N(1,3)) * @PPS( UG(1,4), N(1,4)) *
Y(1,1,1) = R(1,1,1) ;
@PPS( UG(1,1), N(1,1))  * @PPS( UG(1,3), N(1,3)) *
Y(1,1,2) = R(1,1,2) ;
@PPS( UG(1,1), N(1,1)) * @PPS( UG(1,3), N(1,3)) *
@PPS( UG(1,4), N(1,4)) * Y(2,1,1) = R(2,1,1) ;
@PPS( UG(1,1), N(1,1)) * @PPS( UG(1,2), N(1,2)) *
@PPS( UG(1,3), N(1,3)) * Y(2,1,2) = R(2,1,2) ;
```

```
! ;
@PPS( UG(2,1), N(2,1)) * @PPS( UG(2,2), N(2,2)) *
@PPS( UG(2,3), N(2,3)) * @PPS( UG(2,4), N(2,4))
* Y(1,2,1) = R(1,2,1) ;
@PPS( UG(2,1), N(2,1))  * @PPS( UG(2,3), N(2,3))
*Y(1,2,2) = R(1,2,2) ;
@PPS( UG(2,1), N(2,1)) * @PPS( UG(2,3), N(2,3)) *
@PPS( UG(2,4), N(2,4)) * Y(2,2,1) = R(2,2,1) ;
@PPS( UG(2,1), N(2,1)) * @PPS( UG(2,2), N(2,2)) *
@PPS( UG(2,3), N(2,3)) * Y(2,2,2) = R(2,2,2) ;
!
! Restricting N to GIN ;
@FOR( MCTL : @GIN( N);) ;
@FOR( PTMCPR : @BIN( Y);) ;
!
!  The Data  ;
DATA:
E = 25 , 25 ;
B = 480, 480;
C = 10,12,15,18 ;
D = 50,50 ;
LF = 20,20,20,20 ;
TM = 2,2,3,0,2,8,1,0,
     2,2,0,4,3,3,4,0 ;
ALPHA = 1,1,1,0,1,1,1,0,
        1,1,0,1,1,1,1,0 ;
ENDDATA
END
TERS
```

Model 3, Case 1 :

```
MODEL:
! STOTRAM ;
! E = TOOL MAGAZINE CAPACITY ;
! M = NO. OF REDUNDENCIES OF EACH TOOL   C = COST OF EACH TOOL
;
SETS:
MC / 1 .. 4 / : E ;
PT / 1 .. 10 / : D ;
TL / 1 .. 16 / : C ;
RD / 1 .. 11/ :;
MCTLRD(MC, RD, TL) : Z,LGREL ;
PTPR(PT,MC) : V, REQR ;
ENDSETS
!
! The  Objective ;
MIN = @SUM ( MC(J) :
    @SUM ( TL(L) :
    @SUM ( RD(M) :
    (M-1) * C(L) * Z(J,M,L)))) ;
!
! Sum Of Batches  =  Demand ;
 @FOR( PT(I) :
 @FOR( MC(J) | V(I,J) #EQ# 1 :
 @SUM( TL(L) | LGREL(J,1,L) #NE# 0:
 @SUM( RD(M) :
 Z(J,M,L) * LGREL(J,M,L))) > REQR(I,J)));

! Magazine  Capacity ;
 @FOR( MC(J) :
 @SUM( TL(L) | LGREL(J,1,L) #NE# 0:
 @SUM( RD(M) :
 (M-1) * Z(J,M,L))) <  E(J)) ;
!
! Unique Number of Spares ;
 @FOR( MC(J) :
 @FOR( TL(L) | LGREL(J,1,L) #NE# 0:
 @SUM( RD(M) :
```

```
 Z(J,M,L)) = 1)) ;
!
! Restricting Z to Binary ;
@FOR( MCTLRD : @BIN( Z);) ;
!
! The Data  ;
DATA:
E = 50, 50, 50, 50 ;
C = 12,15,18,16,20,11,25,14,
   17,21,12,19,23,13,10,22;
V = 1,0,1,0,0,1,1,0,1,0,0,0,0,1,0,1,
   0,0,1,0,1,1,0,0,1,0,0,1,0,1,0,0
   0,0,1,0,0,0,0,1;
REQR = -0.01, 0, -0.01, 0, 0,
     -0.01,-0.01,0,-0.01,
     0,0,0,0,-0.01,0,-0.01,0,0,
     -0.01,0,-0.01,-0.01,0,
     0,-0.01,0,0,-0.01,0,-0.01,
     0,0,0,0,-0.01,0,0,0,0,-0.01;
LGREL = @FILE(LGREL.DAT);
ENDDATA
END
```

Model 3, Case 2 :

```
MODEL:
! STOTRAM ;
! E = TOOL MAGAZINE CAPACITY ;
! M = NO. OF REDUNDENCIES OF EACH TOOL   C = COST OF EACH TOOL
;
SETS:
MC / 1 .. 3 / : ;
FMC/ 1 .. 3 /: E ;
PT / 1 .. 8 / : D ;
TL / 1 .. 13 / : C ;
RD / 1 .. 15 /:;
MCTLRD(MC, RD, TL) : Z,LGREL ;
PTPR(PT,MC) : V, REQR ;
FMCMCTL(FMC,MC,TL) : N ;
ENDSETS
!
! The  Objective ;
MIN = @SUM (FMC(K) :
    @SUM ( MC(J) :
    @SUM ( TL(L) :
    C(L) * N(K,J,L))))
    +
    @SUM (FMC(K) :
    @SUM ( MC(J) :
    @SUM ( TL(L) | J #NE# K:
    C(L) * N(K,J,L)))) ;
!
! Sum Of Batches  =  Demand ;
 @FOR( PT(I) :
 @FOR( MC(J) | V(I,J) #EQ# 1 :
 @SUM( TL(L) | LGREL(J,1,L) #NE# 0:
 @SUM( RD(M) :
 Z(J,M,L) * LGREL(J,M,L))) > REQR(I,J)));

! Converting 0/1 integer to General integer ;
 @FOR( MC(J) :
 @FOR( TL(L) :
```

```
@SUM( RD(M) :
(M - 1) * Z(J,M,L)) -
@SUM(FMC(K) :
N(K,J,L)) = 0 ));

! Magazine  Capacity ;
@FOR(FMC(K) :
@SUM( MC(J) :
@SUM( TL(L) :
N(K,J,L))) <  E(K)) ;
!
! Unique Number of Spares ;
@FOR( MC(J) :
@FOR( TL(L) | LGREL(J,1,L) #NE# 0:
@SUM( RD(M) :
Z(J,M,L)) = 1)) ;
!
! Restricting Z to Binary ;
@FOR( MCTLRD : @BIN( Z);) ;

! Restricting N to General Integers ;
@FOR( FMCMCTL : @GIN( N);) ;

! The Data  ;
DATA:
E = 50, 50, 50 ;
C = 12,15,18,16,20,11,25,
   17,21,19,23,13,10;
V = 1,0,0,0,1,1,1,0,0,0,1,1,
   1,1,0,1,0,1,1,0,0,0,0,1;
REQR = -0.005,0,0,0,-0.005,-0.005,
     -0.005,0,0,0,-0.005,-0.005,
     -0.005,-0.005,0,-0.005,0,-
     0.005,-0.005,0,0,0,0,-0.005;
LGREL = @FILE(LGREL2.DAT);
ENDDATA
END
```

APPENDIX 2

LISTING OF THE SIMULATION :

```
! WITNESS MODEL: AUX7

  * Title  : PHILIPOSE
  * Author : ABI
  * Date   : Wed Apr 05 20:01:01 1995
  * Version: WIN-207 Release 6.0


DEFINE

  FILE: TULLF,Read;
  PART: block,Variable attributes;
  VARIABLE: LIF,1,7,Real;
  MACHINE: DRILL,3,General,150,0;
  VARIABLE: TLCT,2,7,2,Integer;
  LABOR: T1,5;
  LABOR: T2,5;
  LABOR: T3,5;
  BUFFER: OUTBF,1,1000;
  LABOR: ROBO,1;
  FILE: cycltm,Read;
  VARIABLE: CYTM,2,10,7,Real;
  ATTRIBUTE: PTYP,1,Integer,1;
  ATTRIBUTE: PROC,1,Integer,1;
  FUNCTION: PTP:Integer,0,;
  FILE: ABSLF,Read;
  VARIABLE: TL,1,1,Integer;
  ATTRIBUTE: TUL,1,Integer,1;
  ATTRIBUTE: MAC,1,Integer,1;
  VARIABLE: LOOP,1,1,Integer;
  VARIABLE: CATFL,2,7,2,Real;
  LABOR: T4,5;
  LABOR: T5,5;
  LABOR: T6,5;
  VARIABLE: tlusg,2,7,2,Real;
```

```
 VARIABLE: CTMN,1,7,Real;
 ATTRIBUTE: TUSE,1,Real,1;

END DEFINE


REPORT_MODE ON_SHIFT_TIME TEXT STANDARD

DISPLAY
 OPTIONS
  TIME_SCALE FACTOR : 1.00,Off;
  WALK TIME : Slow;
  TIME INCREMENT : 1;
  BATCH INCREMENT : 10;
 END OPTIONS

 DEFAULTS
  NAME COLOR: White;
  BACKGROUND COLOR: Black;
  TEXT SIZE: Standard;
  PART DISPLAY SIZE: 1;
  LABOR DISPLAY SIZE: 1;
  VEHICLE DISPLAY SIZE: 1;
  CONVEYOR: GAPS: 96,....;
  TRACK: GAPS: 16,....;
  MACHINE: GAPS: 45,....;
 END DEFAULTS

 KEY
 END KEY

 SCREEN 1
 END SCREEN

 SCREEN 2
 END SCREEN

 SCREEN 3
 END SCREEN
```

```
SCREEN 4
END SCREEN

SCREEN 5
END SCREEN

SCREEN 6
END SCREEN

SCREEN 7
END SCREEN

SCREEN 8
END SCREEN

SCREEN 9
END SCREEN

CLOCK
 UNIT : :;
 MULTIPLE : 1,Time ,60,0;
 MULTIPLE : 2,Day ,24,1;
 MULTIPLE : 3,Week ,7,1;
 RATIO : 1:1;
 DISPLAY : REGULAR;
END CLOCK

WINDOW_TITLES
 TITLE : 1,Window 1
 TITLE : 2,Window 2
 TITLE : 3,Window 3
 TITLE : 4,Window 4
 TITLE : 5,Window 5
 TITLE : 6,Window 6
 TITLE : 7,Window 7
 TITLE : 8,Window 8
 TITLE : 9,Designer Elements
 TITLE : 10,Designer Elements Display
END WINDOW_TITLES
```

```
LAYER_STATUS
 LAYER : 0,On,Simulation Layer
 LAYER : 1,On,Layer 1
 LAYER : 2,On,Layer 2
 LAYER : 3,On,Layer 3
 LAYER : 4,On,Layer 4
 LAYER : 5,On,Layer 5
 LAYER : 6,On,Layer 6
 LAYER : 7,On,Layer 7
 LAYER : 8,On,Layer 8
 LAYER : 9,On,Layer 9
END LAYER_STATUS

BAR_SELECTOR_POSITION : -16,54,28,629;

LIST_SELECTION_FORM_POSITION : 244,61;

SELECT

block

STYLE: Desc,3,bloc;

END block

LIF


END LIF

DRILL

MACHINE ICON: Status,78,256,112,2,2,0,0
             136,112,2,2,0,0
             24,112,2,2,0,0;
GAPS: 45,....;
PART: Up,White,0,8,1,All,280,152
              152,152
              40,152;
```

INPUT BUFFER: Count,White,0,8,3,All,280,184
160,184
48,184;
LABOR: Down,White,0,-8,1,All,296,144
176,144
64,144;

END DRILL

TLCT

VALUES: Standard,Green,4,352,88,32,16,1;

END TLCT

T1

NAME: Standard,White,8,24;
STYLE: Icon,15,80;
IDLE OPERATORS: Count,White,0,8,1,All,8,8;

END T1

T2

NAME: Standard,White,40,24;
STYLE: Icon,5,80;
IDLE OPERATORS: Count,White,0,8,1,All,40,8;

END T2

T3

NAME: Standard,White,72,24;
STYLE: Icon,10,80;
IDLE OPERATORS: Count,White,0,8,1,All,72,8;

END T3

OUTBF

NAME: Standard,White,328,264;
BUFFER ICON: Status,95,344,232,1,1,0,0;
PART: Count,White,0,8,3,All,352,224;

END OUTBF

ROBO

STYLE: Icon,6,77;
IDLE OPERATORS: Left,White,8,0,1,All,368,224;

END ROBO

CYTM

VALUES: Standard,White,4,1,336,8,24,8,1;

END CYTM

PTP

END PTP

TL

END TL

LOOP

END LOOP

CATFL

VALUES: Standard,Yellow,5,1,328,184,40,16,1;

END CATFL

T4

NAME: Standard,White,104,24;
STYLE: Icon,12,81;
IDLE OPERATORS: Count,White,0,8,1,All,104,8;

END T4

T5

NAME: Standard,White,136,24;
STYLE: Desc,12,T5;
IDLE OPERATORS: Count,White,0,8,1,All,136,8;

END T5

T6

NAME: Standard,White,168,24;
STYLE: Desc,7,T6;
IDLE OPERATORS: Count,White,0,8,1,All,168,8;

END T6

tlusg

VALUES: Standard,White,4,1,344,128,40,16,1;

END tlusg

CTMN

END CTMN

END SELECT

```
END DISPLAY

DETAIL
 OPTIONS
  BREAKDOWN MODEL: Actual;
  REPAIR MODEL: Actual;
  LABOR TO UNLOAD : No;
  WARMUP PERIOD : 0.00;
  OUTPUT INTERVAL : None;
  UNBLOCK BASIS : Priority;
  MONITOR STEP : Undefined;
  MIXTURE STEP : Undefined;
  MODULE ELEMENT NAMES : Use local preferences;
 END OPTIONS

SELECT

 PTP

 NAME OF FUNCTION: PTP;
 TYPE: Integer;
 PARAMETERS: 0
 ACTIONS, Execute
 Add
  RETURN 2 * (PTYP - 1) + PROC
 End Actions

 END PTP

 TULLF

 NAME OF FILE: TULLF;
 FILES ACTUAL NAME: TULLF.dat;
! TYPE: Read;
 RESTART: Yes;

 END TULLF

 block
```

```
NAME OF PART: block;
TYPE: Variable attributes;
GROUP NUMBER: 1;
MAXIMUM ARRIVALS: 150;
INTER ARRIVAL TIME: 0.0;
FIRST ARRIVAL AT: 0.0;
LOT SIZE: 150;
ACTIONS, Create
Add
 TUSE = 0
 TUL = 1
 IF M <= 7
  PTYP = 1
  PROC = 1
  MAC = 1
  GOTO CHQ
 ELSEIF M > 7 AND M <= 20
  PTYP = 1
  PROC = 1
  MAC = 2
  GOTO CHQ
 ELSEIF M > 20 AND M <= 30
  PTYP = 1
  PROC = 2
  MAC = 2
  GOTO CHQ
 ELSEIF M > 30 AND M <= 50
  PTYP = 2
  PROC = 2
  MAC = 1
  GOTO CHQ
 ELSEIF M > 50 AND M <= 59
  PTYP = 2
  PROC = 1
  MAC = 2
  GOTO CHQ
 ELSEIF M = 60
  PTYP = 2
  PROC = 2
```

```
 MAC = 2
 GOTO CHQ
ELSEIF M > 60 AND M <= 90
 PTYP = 3
 PROC = 1
 MAC = 1
 GOTO CHQ
ELSEIF M > 90 AND M <= 106
 PTYP = 4
 PROC = 2
 MAC = 1
 GOTO CHQ
ELSEIF M > 106 AND M <= 120
 PTYP = 4
 PROC = 2
 MAC = 2
 GOTO CHQ
ELSEIF M > 120 AND M <= 127
 PTYP = 5
 PROC = 1
 MAC = 1
 GOTO CHQ
ELSE
 PTYP = 5
 PROC = 1
 MAC = 2
 LABEL CHQ
 IF CYTM (PTP (),TUL) > 0
  GOTO DNE
 ELSE
  TUL = TUL + 1
  GOTO CHQ
 ENDIF
 LABEL DNE
ENDIF
End Actions
OUTPUT RULE: PUSH to DRILL(MAC);
PART ROUTE: None
REPORTING: Yes;
```

CONTAINS FLUIDS: No;
SHIFT: Undefined;

END block

LIF

NAME OF VARIABLE: LIF;
QUANTITY: 7;
REPORTING: Yes;

END LIF

DRILL

NAME OF MACHINE: DRILL;
QUANTITY: 3;
TYPE: General(Multi-Cycle);
PRIORITY: Undefined;
LABOR:
 Repair: None;
END
DISCRETE LINKS :
 Fill: None
END
DISCRETE LINKS :
 Empty: None
END
CYCLE_DETAIL
 Cycle number: 1
 * Cycle time: TUSE;
 * Input quantity: 1;
 * Finish quantity: 1;
 * Description: Cycle number 1
 ACTIONS, Start
 Add
 IF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - LIF (TUL) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)

```
 tlusg (TUL,MAC) = 0
ELSEIF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - CATFL (TUL,MAC) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ENDIF
TUSE = CYTM (PTP (),TUL)
End Actions
ACTIONS, Finish
Add
tlusg (TUL,MAC) = tlusg (TUL,MAC) + TUSE
IF TUL < 7
 TUL = TUL + 1
ENDIF
LABEL QWE
IF CYTM (PTP (),TUL) = 0 AND TUL < 7
 TUL = TUL + 1
 GOTO QWE
ENDIF
End Actions
LABOR:
 Cycle: IF TUL = 1
        T1#1
       ELSEIF TUL = 2
        T2#1
       ELSEIF TUL = 3
        T3#1
       ELSEIF TUL = 4
        T4#1
       ELSEIF TUL = 5
        T5#1
       ELSEIF TUL = 6
        T6#1
       ELSE
        NONE
       ENDIF;
 Pre-empt level: None;
END
Input rule: BUFFER  (150);
```

```
Cycle number: 2
* Cycle time: TUSE;
* Input quantity: 0;
* Finish quantity: 1;
* Description: Cycle number 2
ACTIONS, Start
Add
IF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - LIF (TUL) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ELSEIF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - CATFL (TUL,MAC) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ENDIF
TUSE = CYTM (PTP (),TUL)
End Actions
ACTIONS, Finish
Add
tlusg (TUL,MAC) = tlusg (TUL,MAC) + TUSE
IF TUL < 7
 TUL = TUL + 1
ENDIF
LABEL QWE
IF CYTM (PTP (),TUL) = 0 AND TUL < 7
 TUL = TUL + 1
 GOTO QWE
ENDIF
End Actions
LABOR:
 Cycle: IF TUL = 1
        T1#1
        ELSEIF TUL = 2
        T2#1
        ELSEIF TUL = 3
        T3#1
        ELSEIF TUL = 4
        T4#1
```

```
        ELSEIF TUL = 5
         T5#1
        ELSEIF TUL = 6
         T6#1
        ELSE
         NONE
        ENDIF;
  Pre-empt level: None;
END
Input rule: Wait;
Cycle number: 3
* Cycle time: TUSE;
* Input quantity: 0;
* Finish quantity: 1;
* Description: Cycle number 3
ACTIONS, Start
Add
IF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - LIF (TUL) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ELSEIF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - CATFL (TUL,MAC) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ENDIF
TUSE = CYTM (PTP (),TUL)
End Actions
ACTIONS, Finish
Add
tlusg (TUL,MAC) = tlusg (TUL,MAC) + TUSE
IF TUL < 7
 TUL = TUL + 1
ENDIF
LABEL QWE
IF CYTM (PTP (),TUL) = 0 AND TUL < 7
 TUL = TUL + 1
 GOTO QWE
ENDIF
```

```
End Actions
LABOR:
 Cycle: IF TUL = 1
        T1#1
       ELSEIF TUL = 2
        T2#1
       ELSEIF TUL = 3
        T3#1
       ELSEIF TUL = 4
        T4#1
       ELSEIF TUL = 5
        T5#1
       ELSEIF TUL = 6
        T6#1
       ELSE
        NONE
       ENDIF;
 Pre-empt level: None;
END
Input rule: Wait;
Cycle number: 4
* Cycle time: TUSE;
* Input quantity: 0;
* Finish quantity: 1;
* Description: Cycle number 4
ACTIONS, Start
Add
IF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - LIF (TUL) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ELSEIF CYTM (PTP (),TUL) + tlusg (TUL,MAC) - CATFL (TUL,MAC) > 0
 TLCT (TUL,MAC) = TLCT (TUL,MAC) + 1
 CATFL (TUL,MAC) = NEGEXP (CTMN (TUL),9)
 tlusg (TUL,MAC) = 0
ENDIF
TUSE = CYTM (PTP (),TUL)
End Actions
ACTIONS, Finish
```

```
Add
tlusg (TUL,MAC) = tlusg (TUL,MAC) + TUSE
IF TUL < 7
 TUL = TUL + 1
ENDIF
LABEL QWE
IF CYTM (PTP (),TUL) = 0 AND TUL < 7
 TUL = TUL + 1
 GOTO QWE
ENDIF
End Actions
LABOR:
  Cycle: IF TUL = 1
         T1#1
        ELSEIF TUL = 2
         T2#1
        ELSEIF TUL = 3
         T3#1
        ELSEIF TUL = 4
         T4#1
        ELSEIF TUL = 5
         T5#1
        ELSEIF TUL = 6
         T6#1
        ELSE
         NONE
        ENDIF;
  Pre-empt level: None;
END
Input rule: Wait;
Cycle number: 5
* Cycle time: 0.0;
* Input quantity: 0;
* Finish quantity: 1;
* Description: Cycle number 5
LABOR:
  Cycle: ROBO;
  Pre-empt level: None;
END
```

Input rule: Wait;
END CYCLE_DETAIL
BREAKDOWNS: No;
OUTPUT RULE: PUSH to OUTBF;
REPORTING: Individual;
SHIFT: Undefined,0,0;

END DRILL

TLCT

NAME OF VARIABLE: TLCT;
QUANTITY: 7,2;
REPORTING: Yes;

END TLCT

T1

NAME OF LABOR: T1;
QUANTITY no shift: 5;
REPORTING: Yes;

END T1

T2

NAME OF LABOR: T2;
QUANTITY no shift: 5;
REPORTING: Yes;

END T2

T3

NAME OF LABOR: T3;
QUANTITY no shift: 5;
REPORTING: Yes;

END T3

OUTBF

NAME OF BUFFER: OUTBF;
QUANTITY: 1;
CAPACITY: 1000;
DELAY TIME : Undefined;
INPUT POSITION: Rear;
OUTPUT SCAN FROM: Front;
* Select: First;
REPORTING: Individual;
SHIFT: Undefined,0;

END OUTBF

ROBO

NAME OF LABOR: ROBO;
QUANTITY no shift: 1;
REPORTING: Yes;

END ROBO

cycltm

NAME OF FILE: cycltm;
FILES ACTUAL NAME: cycltm2.dat;
! TYPE: Read;
RESTART: Yes;
ACTIONS, Close file
Add
 REWIND cycltm
End Actions

END cycltm

CYTM

NAME OF VARIABLE: CYTM;
QUANTITY: 10,7;
REPORTING: Yes;

END CYTM

PTYP

NAME OF ATTRIBUTE: PTYP;
QUANTITY: 1;

END PTYP

PROC

NAME OF ATTRIBUTE: PROC;
QUANTITY: 1;

END PROC

ABSLF

NAME OF FILE: ABSLF;
FILES ACTUAL NAME: ABSLF.dat;
! TYPE: Read;
RESTART: Yes;

END ABSLF

TL

NAME OF VARIABLE: TL;
QUANTITY: 1;
REPORTING: Yes;

END TL

TUL

NAME OF ATTRIBUTE: TUL;
QUANTITY: 1;

END TUL

MAC

NAME OF ATTRIBUTE: MAC;
QUANTITY: 1;

END MAC

LOOP

NAME OF VARIABLE: LOOP;
QUANTITY: 1;
REPORTING: Yes;

END LOOP

CATFL

NAME OF VARIABLE: CATFL;
QUANTITY: 7,2;
REPORTING: Yes;

END CATFL

T4

NAME OF LABOR: T4;
QUANTITY no shift: 5;
REPORTING: Yes;

END T4

T5

NAME OF LABOR: T5;

QUANTITY no shift: 5;
REPORTING: Yes;

END T5

T6

NAME OF LABOR: T6;
QUANTITY no shift: 5;
REPORTING: Yes;

END T6

tlusg

NAME OF VARIABLE: tlusg;
QUANTITY: 7,2;
REPORTING: Yes;

END tlusg

CTMN

NAME OF VARIABLE: CTMN;
QUANTITY: 7;
REPORTING: Yes;

END CTMN

TUSE

NAME OF ATTRIBUTE: TUSE;
QUANTITY: 1;

END TUSE

END SELECT

END DETAIL

```
INITIALISE
 Add
  FOR TL = 1 TO 7
   READ cycltm CYTM (1,TL),CYTM (2,TL),CYTM (3,TL),CYTM (4,TL);
   READ cycltm CYTM (5,TL),CYTM (6,TL),CYTM (7,TL),CYTM (8,TL);
   READ cycltm CYTM (9,TL),CYTM (10,TL)
  NEXT
  FOR TL = 1 TO 6
   READ TULLF LIF (TL)
  NEXT
  READ ABSLF CTMN (1),CTMN (2),CTMN (3),CTMN (4);
  READ ABSLF CTMN (5),CTMN (6),CTMN (7)
  FOR TL = 1 TO 2
   FOR LOOP = 1 TO 7
    CATFL (LOOP,TL) = NEGEXP (CTMN (LOOP),7)
   NEXT
  NEXT
 End Actions
END INITIALISE
```

APPENDIX 3

Model 3, Case 1 :

The following program was used to generate a file, 'rel.dat', with the values of the reliability of a tool 'l', with 'm' redundencies, given the tool life 'lif[]' and the duration of usage for a particular tool type. The duration of usage was fed in the form of a file 'totm.dat'.

```
# include <stdio.h>
# include <stdlib.h>
# include <conio.h>
# include <math.h>
# define TOOL 16
# define MAC 4
# define RED 10

main()
{
 float a,U[5][17],totm[5][17],rel[5][17][11],lgrel[5][17][11],
       exlda[5][17];
 int i,j,k,l,p;
 long fac[11];
 float lif[17] = {0,  0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01,
                 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01 };
 FILE *fp1,*fp2 ;
 clrscr() ;

  fp1=fopen("totm.dat","r");
  for(j= 1 ; j <= MAC ;  j++)
  for(l = 1; l <= TOOL ; l++)
   { fscanf(fp1,"%f", &a ) ;
    totm[j][l] = a ;
   }
  fclose(fp1);

  fac[0] = 1;
```

```
for(i=1; i <= RED; i++)
fac[i] = fac[(i-1)] * i;

for(j=1; j<=MAC; j++)
for(l=1; l<= TOOL; l++)
 { U[j][l] = totm[j][l] * lif[l];
  if(totm[j][l] >0)
  exlda[j][l] = exp(-U[j][l]) ;
  else
  exlda[j][l] = 0 ;

  rel[j][l][0] = 0;
  rel[j][l][1] = exlda[j][l] ;
  for(k=2; k<=RED; k++)
   {
    rel[j][l][k] =  pow ( U[j][l],(k-1)) *  exlda[j][l] / fac[(k-1)] ;
    rel[j][l][k] = rel[j][l][k] + rel[j][l][k-1] ;
    if (rel[j][l][k] > 1.000000000 )
    printf(" THERE IS A FAULT !!!!!!!!!!!");
   }
 }
 fp2=fopen("rel.dat","w");
 for(j=1; j<=MAC; j++)
 for(k=0; k<=RED; k++)
  { for(l=1; l<=TOOL; l++)
   {  if(U[j][l] > 0 && k == 0)
          lgrel[j][l][k] = -10;
         else if(U[j][l] > 0 && k > 0)
          lgrel[j][l][k] = log10(rel[j][l][k]) ;
         else
          lgrel[j][l][k] = 0 ;
         fprintf(fp2," %11.6f", lgrel[j][l][k]) ;
    }
   fprintf(fp2," \n");
  }
  fclose(fp2);
getch() ;
exit(0);
}
```

Model 3, Case 2 :

The following program was used to generate a file, 'rel2.dat', with the values of the reliability of a tool 'l', with 'm' redundencies, given the tool life 'lif[]' and the duration of usage for a particular tool type. The duration of usage was fed in the form of a file 'totm.dat'.

```
# include <stdio.h>
# include <stdlib.h>
# include <conio.h>
# include <math.h>
# define TOOL 13
# define MAC 3
# define RED 14

main()
{
 float a,U[4][14],totm[4][14],rel[4][14][15],lgrel[4][14][15],
       exlda[4][14], fac[15];
 int i,j,k,l,p;
 float lif[17] = {0, 0.01, 0.01, 0.01, 0.01, 0.015, 0.015,
                  0.018, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01 };
 FILE *fp1,*fp2,*fp3 ;
 clrscr() ;

  fp1=fopen("totm2.dat","r");
  for(j= 1 ; j <= MAC ;  j++)
  for(l = 1; l <= TOOL ; l++)
  { fscanf(fp1,"%f", &a ) ;
  totm[j][l] = a ;
  }
   fclose(fp1);

  fac[0] = 1;
  for(i=1; i <= RED; i++)
  fac[i] = fac[(i-1)] * i;

  for(j=1; j<=MAC; j++)
```

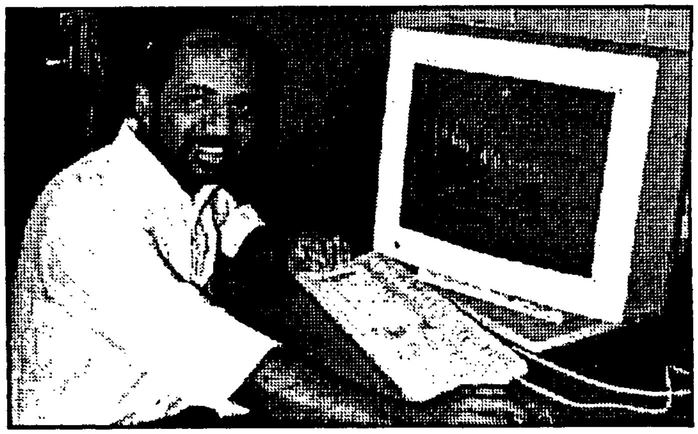
```
for(l=1; l<= TOOL; l++)
 { U[j][l] = totm[j][l] * lif[l];
  if(totm[j][l] >0)
  exlda[j][l] = exp(-U[j][l]) ;
  else
  exlda[j][l] = 0 ;

  rel[j][l][0] = 0;
  rel[j][l][1] = exlda[j][l] ;
 for(k=2; k<=RED; k++)
 {
 rel[j][l][k] =  pow ( U[j][l],(k-1)) *  exlda[j][l] / fac[(k-1)] ;
 rel[j][l][k] = rel[j][l][k] + rel[j][l][k-1] ;
 /* if (rel[j][l][k] > 1.000000000 )
      printf(" THERE IS A FAULT !!!!!!!!!!!!");  */
 }
 }

 fp2=fopen("rel2.dat","w");
 for(j=1; j<=MAC; j++)
 for(k=0; k<=RED; k++)
  { for(l=1; l<=TOOL; l++)
    {  if(U[j][l] > 0 && k == 0)
        lgrel[j][l][k] = -10;
        else if(U[j][l] > 0 && k > 0)
        lgrel[j][l][k] = log10(rel[j][l][k]) ;
        else
        lgrel[j][l][k] = 0 ;
        fprintf(fp2," %11.6f", lgrel[j][l][k]) ; }
   fprintf(fp2," \n"); }
   fclose(fp2);

getch() ;
exit(0);
}
```

Table 8.1 : Effect of Number of Redundancies on the Reliability of Tool Type.

M/c #	Spare	Tool Number												
		1	2	3	4	5	6	7	8	9	10	11	12	13
M/c 1	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1	0.273	0.301	0.301	0.301	0.165	0.123	0.407	0.000	0.000	0.000	0.000	0.000	0.000
	2	0.627	0.663	0.663	0.663	0.463	0.380	0.773	0.000	0.000	0.000	0.000	0.000	0.000
	3	0.857	0.880	0.880	0.880	0.731	0.650	0.937	0.000	0.000	0.000	0.000	0.000	0.000
	4	0.957	0.966	0.966	0.966	0.891	0.839	0.987	0.000	0.000	0.000	0.000	0.000	0.000
	5	0.989	0.992	0.992	0.992	0.964	0.939	0.998	0.000	0.000	0.000	0.000	0.000	0.000
	6	0.998	0.999	0.999	0.999	0.990	0.980	0.999	0.000	0.000	0.000	0.000	0.000	0.000
	7	0.999	0.999	0.999	0.999	0.999	0.994	1.000	0.000	0.000	0.000	0.000	0.000	0.000
	8	1.000	1.000	1.000	1.000	1.000	0.999	1.000	0.000	0.000	0.000	0.000	0.000	0.000
	9	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
	10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
M/c 2	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1	0.333	0.387	0.273	0.287	0.000	0.000	0.000	0.202	0.142	0.273	0.000	0.000	0.000
	2	0.699	0.754	0.627	0.645	0.000	0.000	0.000	0.525	0.420	0.627	0.000	0.000	0.000
	3	0.900	0.929	0.857	0.868	0.000	0.000	0.000	0.783	0.690	0.857	0.000	0.000	0.000

	4	0.974	0.984	0.957	0.962	0.000	0.000	0.000	0.921	0.866	0.957	0.000	0.000	0.000
	5	0.994	0.997	0.989	0.991	0.000	0.000	0.000	0.976	0.952	0.989	0.000	0.000	0.000
	6	0.999	0.999	0.998	0.998	0.000	0.000	0.000	0.994	0.985	0.998	0.000	0.000	0 000
	7	1.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	0.996	1.000	0.000	0.000	0.000
	8	1.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	0.999	1.000	0.000	0.000	0.000
	9	1.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	1.000	1.000	0.000	0.000	0.000
	10	1.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	1.000	1.000	0.000	0.000	0.000
M/c 3	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1	0.202	0.368	0.368	0.387	0.000	0.000	0.000	0.000	0.000	0.000	0.273	0.150	0.142
	2	0.525	0.736	0.736	0.754	0.000	0.000	0.000	0.000	0.000	0.000	0.627	0.434	0.420
	3	0.783	0.920	0.920	0.929	0.000	0.000	0.000	0.000	0.000	0.000	0.857	0.704	0.690
	4	0.921	0.981	0.981	0.984	0.000	0.000	0.000	0.000	0.000	0.000	0.957	0.875	0.866
	5	0.976	0.996	0.996	0.997	0.000	0.000	0.000	0.000	0.000	0.000	0.989	0.956	0.952
	6	0.994	0.999	0.999	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.998	0.987	0.985
	7	0.999	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.997	0.996
	8	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.999	0.999
	9	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	1.000
	10	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	1.000

Table 8.1 (cont) : Effect of Redundancies on the Reliability of Tool Type.



VITA AUCTORIS

Abi M. Philipose was born in Kerala, the paradise state of India, on 4th of January 1961. He attended Birla Institute of Technology, Ranchi, India, from 1977 to 1982 and graduated with a B.Sc. in Electrical Engineering. He worked as an Electrical Engineer at Tata Engineering and Locomotive Company (TELCO) from 1982 to 1985. Later, he worked at A.B.E. Electrical Installations, Bahrain from 1985 to 1987. From 1988 to 1992 he was a Service Engineer for Homag Machinenbau, at their Canadian branch at Mississuaga, Ontario. He has been studying towards a M.A.Sc. in Industrial and Manufacturing Systems Engineering at the University of Windsor since January 1993. He has been working for Okuma Machinery, as a Controls Engineer at GM's Windsor Transmission Plant since 1994.