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Modeling of flexible manufacturing tooling system with reliability considerations.

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Modeling of Flexible Manufacturing Tooling System with Reliability Considerations

by

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case if a tool is not available on a particular tool magazine it can be borrowed from another magazine or from the tool crib. Two Genetic algorithms are developed and used to solve the two cases, the solutions are compared to solutions obtained by LINGO optimization software and conclusions are derived.

The research conducted in this thesis is aimed at developing cost minimization models for the part assignment and tool loading in flexible manufacturing systems with reliability considerations. The thesis of this research states that tooling system reliability can be integrated in FMS planning decisions, and that such models will complement some of the apparent limitations in the existing models. The models aim at assessing decision-maker to decide a minimum tooling system reliability and to optimize overall processing and tooling cost of the part assignment and tool loading of FMS. A solution methodology is also presented in this thesis. The solution takes into account part assignment and tool loading along with tooling system reliability of FMS under consideration.

DEDICATION

To my parents

ABSTRACT

In the planning process of flexible manufacturing Systems (FMS), an FMS must not be designed to fulfill its intended functions only, but also to perform the intended functions successfully. The latter requires the design of reliability into the system. The decisions involving the number of tools and tool redundancies need to be carried and executed in real time. This research discusses FMS tooling reliability in the context of the machine loading and part assignment problem. As manufacturing systems become more and more complex, competition and cost grow even more rapidly. Flexible manufacturing systems became the means to narrow the gap between the various different pressures. FMS promises more efficient and effective ways of utilizing resources, information and assets, due to its capability to carry a variety of different tools so that it can perform different operations required in the production of a variety of low to mid size part types.

Integer-programming models are developed. The formulations consider an objective function with a set of governing constraints. A reliability level is decided for the tooling system, the models then will return with optimum number of tools and tool copies for each tool type. The overall objective is cost minimization while achieving maximum desired tooling system for the FMS under consideration. Two distinct scenarios are studied, the first considers an FMS where tool sharing is not allowed which implies that each tool magazine will be required to carry the required tools and tool copies to achieve the reliability levels decided and to carry the required machining operations on the different parts assigned to it during each production period. The second scenario is where tool sharing is permitted; in this

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NOMENCLATURE

Indices Used

(i) Parts

$i = 1, 2, \ldots, I$

(ii) Operations

$j = 1, 2, \ldots, J$

(iii) Machine index

$k = 1, 2, \ldots, K$

(iv) Tool index

$s = 1, 2, \ldots, S$

(v) Spares index

$m_s = 0, 1, 2, \ldots, M_s$

Decision Variables

X_{ijks} = Number of part type 'i' for which operation 'j' is performed on machine 'k' using tool type 's'.

Y_{ksm_s} = 1 If m copies of tool type 's' are to be loaded on machine 'k' and 0 otherwise.

Y_{klsm_s} = 1 If m copies of tool type 's' are transported from machine 'k' to machine 'l' and 0 otherwise.

Parameters

C_{ijks} = Processing cost per unit time for performing the j^{th} operation of part type 'i' on machine k using tool 's'.

t_{ijks} = Processing time of the j^{th} operation of part type i on machine k using tool type 's'.

q_i = Demand of part type 'i' for each production period.

C_s = Cost of tool type 's'.

E_k = Magazine capacity of machine 'k'.

T_s = Average tool life of tool type 's'.

A_s = Maximum available tools of tool type 's'.

Z_s = Number of slots required by tool type 's'.

R_{ks} = Reliability of the s^{th} tool on machine 'k'.

R_{kRq} = Minimum required tooling system reliability for each machine type 'k' in the system.

R_{Rq} = Minimum required tooling system reliability for all tools in the system.

CHAPTER 1

INTRODUCTION

1.1 Overview

The difficulty of achieving high reliability in FMSs is due to the complexity and sophistication of the equipment and the requirement that large numbers of tools must work together without malfunctioning for long periods of time. In an attempt to improve a tool's reliability one could easily over design the tool by choosing tools with higher ratings and greater safety margins. This would increase the size, weight, and cost of the tool. Trade offs between size, cost, weight and reliability are necessary to reach a practical compromise. The reliability performance of an FMS under various different conditions is of utmost importance in the industrial world. As stated by Tillman et al (1980), the qualitative concepts of reliability are not new, its quantitative aspects have been developed over the past two decades. These developments were the result of the demand for highly reliable systems and components with more safety and less cost. There exist several methods to improve systems reliability. Some of these methods approach the problem by using large safety factors, reducing the complexity of the system, increasing the reliability of constituent components through a product improvement program, using structural redundancy, and/or practicing a planned maintenance and repair schedule. Figures 1.2, 1.3, 1.4 and 1.5 show a tooling system in series, a tooling system in parallel, a tooling system with standby redundancies and a standby tooling system with redundancy switch respectively.

When we study flexible manufacturing systems, we speak of highly sophisticated, technically complex and very expensive systems. FMSs are highly capital intensive and FMS users are concerned with achieving high system utilization, Lee (1998). An FMS is a system that is able to quickly respond to change and flexibility is the system's ability to respond effectively to that change. Change varies with the conditions and circumstances under which FMS performs under, these circumstance can be internal such as machine breakdowns, variations in processing times and quality issues. The external disturbances include, design changes, demand fluctuations and product mix. The ability of the system to survive internal problems can be made possible through the introduction of redundancy in the system, whereas the ability of the system to cope with external changes requires the system to be versatile and capable of producing a wide variety of part types with minimal changeover times and costs to switch from one type of product to another. These systems are prone to failure and as stated in the literature FMS tooling accounts for approximately 30% of the overall cost of the system (Ayres 1988). This is true since an FMS contains a fairly large number of expensive and specialized tools. When a tool failure occurs the system is halted and eventually a tool replacement takes place, a cost is associated with this event. The idle time is certainly unwelcome because of the different sequence of events related to it, these involve lost production, disturbances to end product volumes and the like.

In order to minimize such failures, tools can be better designed to last longer, this however, results in higher tool costs. Over and above the high cost associated with better designed tools, the fact remains that beyond a certain tool quality, improvements become very expensive. In trying to prolong tool life, designers frequently resorted to the practice of extensive design, resulting in excessively bulky and costly tools. When the demand for extensive minimization and high weight tools is added to the equation, the problems are multiplied and so as the cost.

At some point in time the FMS tooling system's performance is evaluated and other ways of reliability improvements are considered. One of the techniques that can reduce the hazard of high-failure-rate is redundancy. In standby redundant systems, the standby tool is not activated unless the online tool fails. This situation is illustrated in Figure 1.5 below. The switch represents a tool switching device equipped with a sensing device for any tool failure.

From the previous discussions, it is clear that reliability needs to be considered early in the planning process of FMS when changes are most easily and economically made. The concepts discussed are incorporated in the development of the FMS planning models in order to achieve high enough FMS tooling system reliability. This in turn will be part of the process of over all FMS system cost justification.

1.2 Reliability Testing

Reliability testing simulates real usage in a compressed timeframe and is performed to determine the probability of a component, or a tool meeting the functional and durability requirements. Testing considerations, which are important to ensure reliability, include:

- Accelerated Testing:

Accelerated testing involves testing the tool at higher than normal stresses and/or cycle speeds. The advantages of accelerated testing include shorter times required to complete testing and discovery of premature failure modes. The disadvantages associated with accelerated testing include the potential of inducing "unrealistic" failure modes and difficulty in translating the acceleration time back to standard time.

- Demonstration Testing:

Reliability demonstration testing is performed to specified plans and applicable standards. The basic objective of these tests is to verify that the specified reliability requirement has been achieved. The choice of a specific plan requires knowledge of the requirement being demonstrated, including the statistical parameters affecting the results. In addition, knowledge of statistics and sampling theory are necessary to choose or tailor the most appropriate plan. The result of this test is a decision upon whether the tool has met the requirement. If the requirement involves a pass-fail type of test, knowledge of statistics, and sampling is still necessary to select the most appropriate plan. Often, tests for reliability involve only pass-fail as the acceptance/rejection criteria. The elements that comprise a basic test plan include:

✓ A reliability requirement

✓ The level of confidence for minimum reliability

✓ The number of samples required

✓ The number of failures allowed

Reliability demonstration using pass-fail testing requires a higher number of samples than the other types of demonstration testing and yields less information. Therefore, pass-fail testing for reliability demonstration should not be used until the other test methods are explored.

1.3 Strategies for Improving Tool and Tooling System Reliability

The reliability of a tool (tooling system) may be improved during the design and development phase by utilizing a number of different strategies. The choice of any particular strategy or strategies is primarily determined by the specific tool/tooling system being developed. A major initiative in improving reliability is the implementation of robust design techniques. Robust designs are those designs whose performance parameters are insensitive to all sources of input variation. This variability may occur in usage, stresses, environment, materials, and manufacturing processes. Since the removal of all variability is impossible, designs must be developed that are less influenced by variability without necessarily trying to eliminate the causes of variability.

The techniques to achieve a robust design are many. The key is to apply the correct tools at the correct time to address the sources of variation and optimize the ability of the tool's performance parameters to be stable in the presence of the variations. Some specific methods of improving reliability through robust design are:

- Design simplification
- Design Capability Improvement
- Fault Tolerance
- Modeling and simulation techniques

- Probabilistic analysis
- Robust design

1.3.1 Design Simplification Techniques

Simplifying design can improve the reliability by reducing the opportunities for failure, and making the design easier to build. The basic approaches used in simplification include:

- Tool or tooling module design
- Tool integration or reduced number of tools

1.3.2 Design Capability Improvement

The improvement of design capability as it relates specifically to reliability may be accomplished by several methods. The general result from all the approaches effectively adds margin to the design. For mechanical systems, there are four basic approaches toward improving reliability utilizing stress-strength. These are:

- Reduce stress level
- Reduce stress variability
- Increase inherent strength
- Reduce strength variability

From a practical point of view, the first two approaches are difficult, if not impossible to achieve. This is primarily due to the fact that stresses are not often controlled or controllable. On the other hand, strength is a material and design issue and is much easier to have a direct effect upon. None of the approaches are free of potential adverse impacts on cost, weight or maintainability.

1.3.3 Fault Tolerance

Fault tolerance can be utilized to minimize or eliminate downtime. The objective is to enable the system to continue to operate after a failure has occurred without having to shut down. There are different approaches to fault tolerance, which are not always practical for larger mechanical systems. For electrical, hydraulic, pneumatic, and some mechanical applications, redundancy may be used. If redundancy is used, it can be active or standby:

- Active redundancy is a case where both units operate at the same time, with either being able to perform the function alone.
- Standby redundancy is where a second unit is held in reserve and only switched to when the primary fails.

In some applications, continued operation in a degraded/reduced mode (i.e., slower speed, feed, etc...) may be possible by sharing loads with alternative tools.

1.3.4 Modeling and Simulation

Simulation involves using computer modeling and graphics capabilities to model the processes of the FMS. It can be used to measure and optimize cycle time, part flow, buffering, bottlenecks work in process and machine movement.

1.3.5 Probabilistic Analysis

Probabilistic analysis is the analysis of a tool's stresses and strength parameters as random variables, to allow the effect of each variable on the final design to be quantified. Probabilistic analysis incorporates statistical data explicitly in the design algorithms and, therefore, points out areas where effort is required.

1.3.6 Robust Design

Robust design is to design a tool or tooling system that performs consistently as intended under a wide range of conditions through its life cycle, Figure 1.1 below.

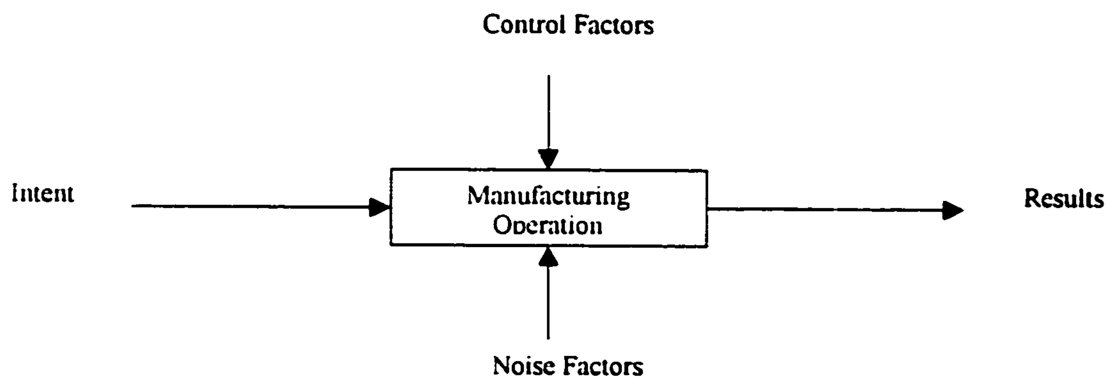

Figure 1.1 Input and Output for Tool/Tooling System

1.4 Tooling System Reliability and FMS

The term reliability has a dual meaning in the integrated manufacturing context. In general it refers to a wide range of issues relating to design, manufacture and assembly of the products which are required to work well. It is used at times to describe quality levels that would match customer satisfaction. In this research we mean the level at which the FMS tooling system performs. Firms and manufacturers in general look forward to maximum levels of reliability, however, there is a cost associated with higher reliability. In the case of FMS tooling system, reliability considerations are even more important for the sole purpose of justifying their initiation. An FMS can be defined as "an integrated, computer controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium sized volumes of a variety of part types", (Stecke, 1983). There are several methods to evaluate system's reliability these include:

- Fault tree analysis
- Fault model effect and criticality analysis
- Event tree analysis
- Block diagram analysis

In this dissertation, block diagram analysis is used to evaluate the tooling system reliability of FMS. Reliability calculations of each tool are done using probability techniques. The functional block diagram for a system represents the effect of subsystem failure on system performance. It is a black box analysis, which requires that complex systems be broken down into subsystems or components.

1.5 Systems Approach

An FMS tooling system consists of tools designed to operate in unison to achieve a desired goal; mainly the production of certain product at the end of the production period. The reliability requirements are given or decided in the systems specification and would usually limit downtime. The system planner distributes the required tools in the form of block diagram with interconnecting lines. A preliminary estimate of the reliability of the individual tools (subsystems) is prepared, to ascertain whether the system reliability requirements can be met. If they can't, trade offs are performed involving redundant tools.

1.5.1 Series Systems

In this type of configuration all tools must function successfully in order for the system to function. The block diagram is given in Figure 1.2 In this case redundancies can be added at the system level (high level) or at the (low level) individual components or subsystems, or to any single component of the system. These redundancies are termed parallel, if the primary tool and all redundancies associated with it are working at the same time. In the standby system, the standby tool is not activated unless the on-line tool fails; Figure 1.5. For the standby system's analysis it is assumed that tool failure's detection and switching to use a redundant tool is perfect.

1.5.2 Parallel Systems

A parallel system is a system that is not considered to have failed unless all components have failed. The use of components in parallel is a common practice, however, It is difficult to design a parallel system for a tooling system. It is also apparent that reliability gains are not significant beyond the fourth component as can be seen from Figure 1.6.

Other systems include parallel series systems and mixed parallel series systems depending on system requirements.

1.6 Tooling System Reliability

1.6.1 The Bath-Tub Curve

The Bath-Tub curve is perhaps the most basic model used in reliability engineering to model the various failure rates that occur during the life time of a product or tool. The Bath-Tub curve is divided into three distinct regions, each defined by different failure rates see Figure 1.7. The three regions are described below:

1) Infant mortality period; during this period the failure rate is high, owing to the presence of weak or substandard components, which may be due to manufacturing errors or improper design. As these components drop out one by one, the failure rate keeps decreasing until a relatively low constant level is obtained at time t_1.

2) At t_1, and as shown on the figure begins the useful life period or normal operating phase and is characterized by a constant hazard rate. In this region failures occur purely by chance and this is the only region in which the exponential distribution is valid. During this period no weak components are assumed to have remained from the infant mortality period. It is also assumed that no deterioration of the components during the useful life period takes place, and there are no wearout conditions present. The failures that do occur during this period are truly random, unpredictable, and cannot be prevented by additional testing or burn-in of the components. The reason for these failures is not fully understood, but they are thought to be at least partially due to abrupt changes in stress distribution in the components.

As long as the components that fail during the useful life period are replaced, so that the population of components remains intact, the same number of components will, on the average fail in any equal time period. It is during this period that mean time between failures (MTBF) concept applies. The MTBF represents the reciprocal of the constant failure rate present during the useful-life period. During the infant mortality period and the wearout period, which follows the useful life, the MTBF concept is not applicable.

3) The wearout period: this period begins at t_2 (as shown on Figure 1.7), and is characterized by a rapidly rising failure rate as more and more components break down.

The reliability R(t) of a tooling system is defined as the probability that, under certain operating conditions, the tooling system (or tools of the system) will perform well enough throughout a specified interval of time [0, t], producing quality jobs.

1.6.2 Failure Distribution Function

Failure distribution function F(t) is defined as the probability that a tool or a set of tools fail by time t, and the probability of failure is given by:

$$P\,(0 \le \mathit{t} \le t) = F\,(t), \qquad t \ge 0$$

Where t is a random variable representing failure time.

1.6.3 Reliability Function

The reliability function R(t) in the context of the FMS tooling system under consideration is defined as the probability that the tooling system will perform its function during the time interval [0, t]. The reliability function is given by:

$$R(t) = 1 - F(t) = P(t > t)$$

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

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

1.6.4 Hazard Rate

The hazard rate or the instantaneous failure rate h(t) of a tool or tooling system is expressed in terms of failures per unit time. If t denotes the time to failure of a tool (tooling system) then [h(t) dt] is the probability a tool has survived up to time t and will fail during time interval dt. Hazard rate function h(t) can be defined as:

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

1.7 Objectives of the Research

The objective of this research is to incorporate tool reliability considerations into the production planning framework of flexible manufacturing systems. The development of FMS resulted in various production planning problems as can be deduced from the massive literature on FMS. A flexible manufacturing system FMS is a combination of a group of stations in which different parts are routed via an automated handling system for a variety of operations. Different tools are utilized to conduct the various operations.

FMS combine the flexibility of job shops and the efficiency of transfer lines. The positive trend in moving towards FMS lies in the desire to achieve higher productivity, quality, reliability, efficiency, and reduced lead-time. The main hurdle that faces the justification of such systems lies in their high cost. The fact that FMSs can process several part types simultaneously, resulted in a complicated interaction between parts, different tool types, material handling system and other system components.

The short to medium term decisions involving part selection and loading decisions are made before production actually begins. One of the FMS major objectives is the minimization of operating cost. Once part selection and routing are made, the forecasted demand over the planned horizon (period) is divided between FMS and conventional production systems (or subcontracting). As the production level for each planning period is decided, the demand is broken into batches to meet the limited capabilities of the tool magazines. As tools get loaded, the different parts are routed to the various machines in the system for processing.

This research focuses on the maximization of FMS tooling reliability while minimizing the overall operating cost (namely, automatic part routing and tool machine loading). The constrained tool magazine capacity plays an important role in limiting the number of tools that can be mounted on a particular machine. Therefore, a procedure which takes into consideration the limited magazine capacity and returns with maximum possible tooling system reliability while minimizing the overall cost is pursued. The formulation takes into consideration the number of tool slots a tool occupies on a magazine and the fact that jobs are not splitable. To summarize the objectives of the research are as follows:

1) To develop mathematical model for the tool loading and part assignment problem of FMS subject to resource restrictions.

2) To extend the developed model in step (1) to cater for reliability calculations.

3) To use genetic algorithms in solving the FMS loading problem with tooling reliability requirements. These algorithms will also be used to solve the loading problem coupled with reliability considerations.

4) The models developed will be used in solving numerical examples with (LINGO) and genetic algorithms for optimum solutions and then results are analyzed.

1.8 Organization of the Research

This research is divided into the following stages. Chapter two discusses the relevant literature connected with the problem under investigation, including tool life, tool management in FMS, tool assignment and reliability optimization, genetic algorithms, heuristics, and simulation. FMS planning models are discussed in chapter three. Chapter three is dedicated to the development of models and required algorithms to solve them. Chapter four discusses the genetic algorithm approach used to solve developed models. Chapter five gives application examples of the proposed models and results for the given system are presented. Conclusions and further work are then discussed in chapter six.

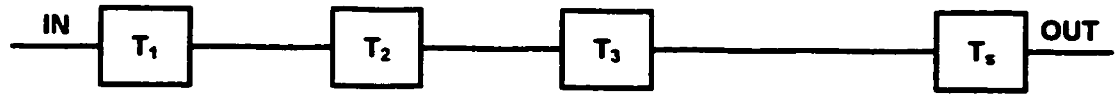

Figure 1.2 A Tooling System in Series

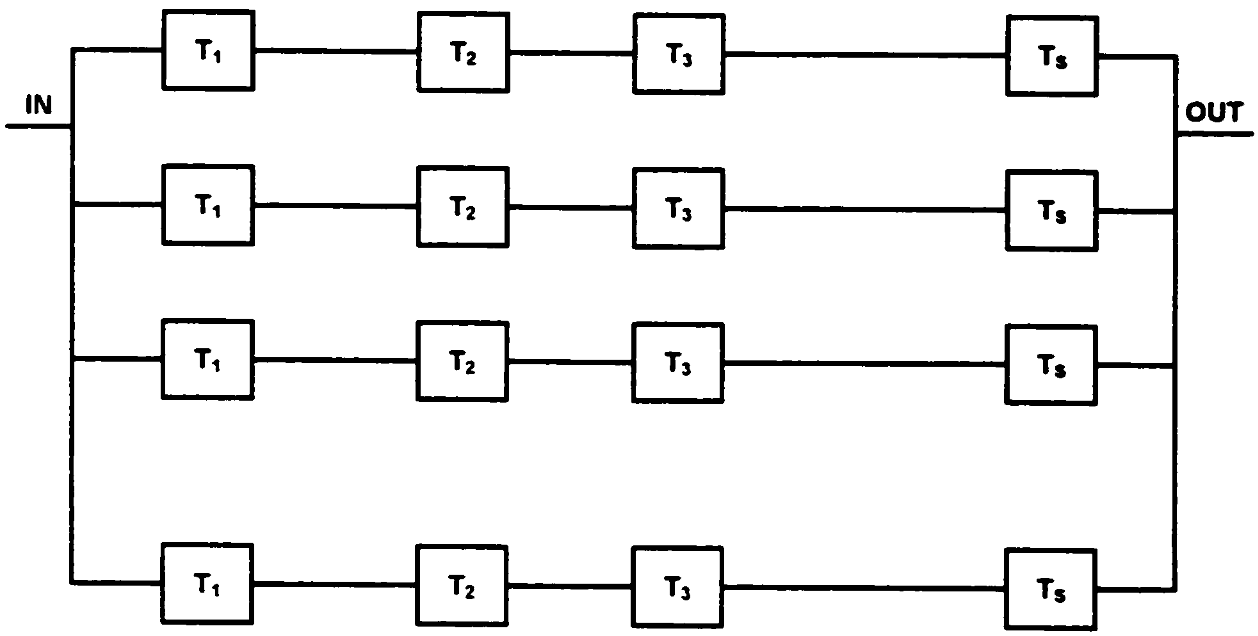

Figure 1.3 A Tooling System in Parallel

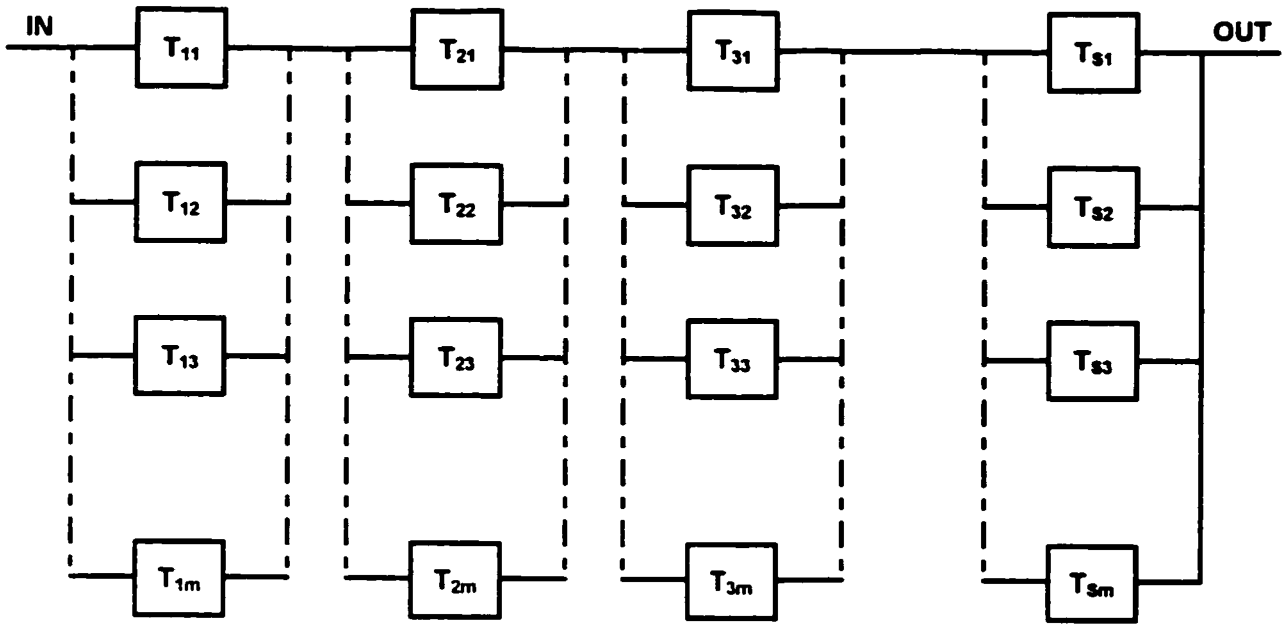

Figure 1.4 A Tooling System with Standby Redundancies

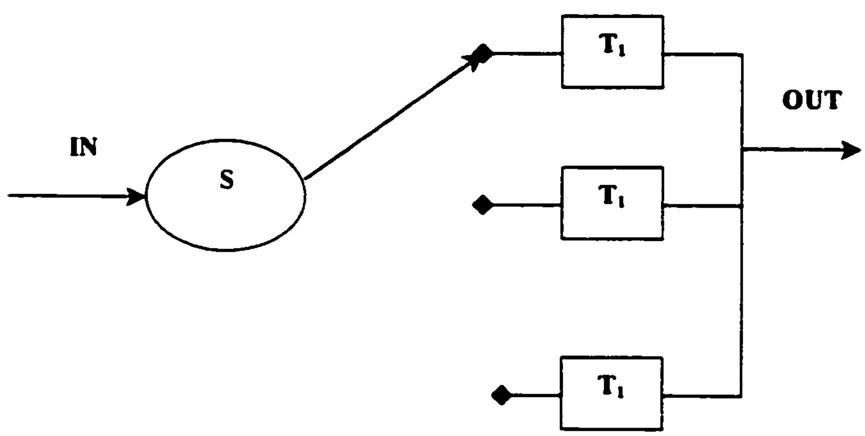

Figure 1.5 A Standby Tooling System with Redundancy Switch

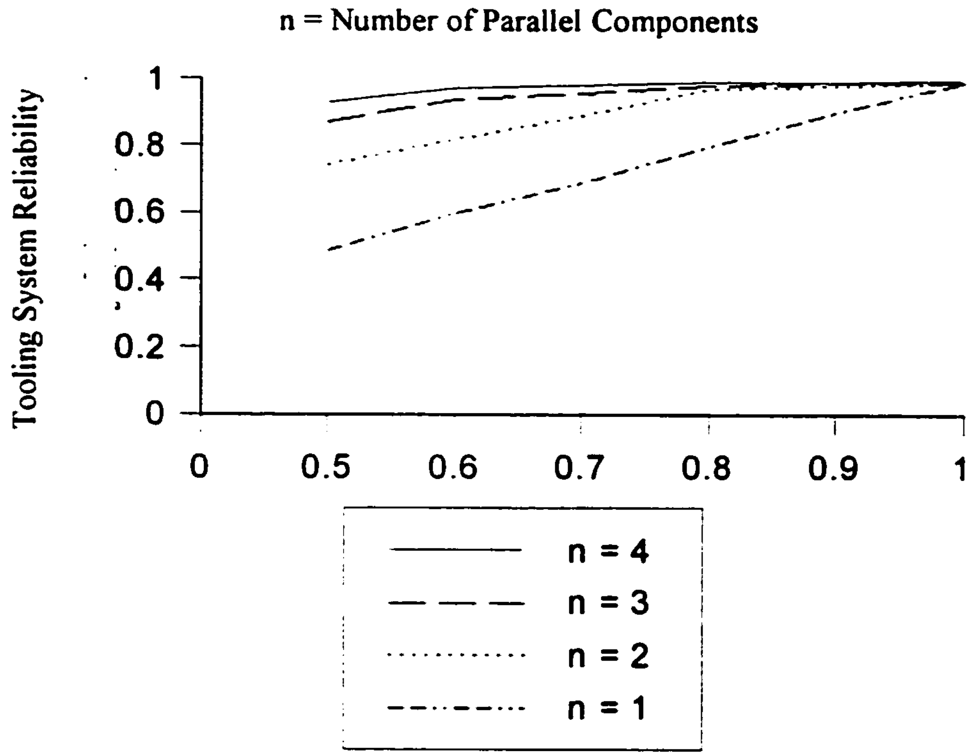

Figure 1.6 Reliability Improvement by n Parallel Components

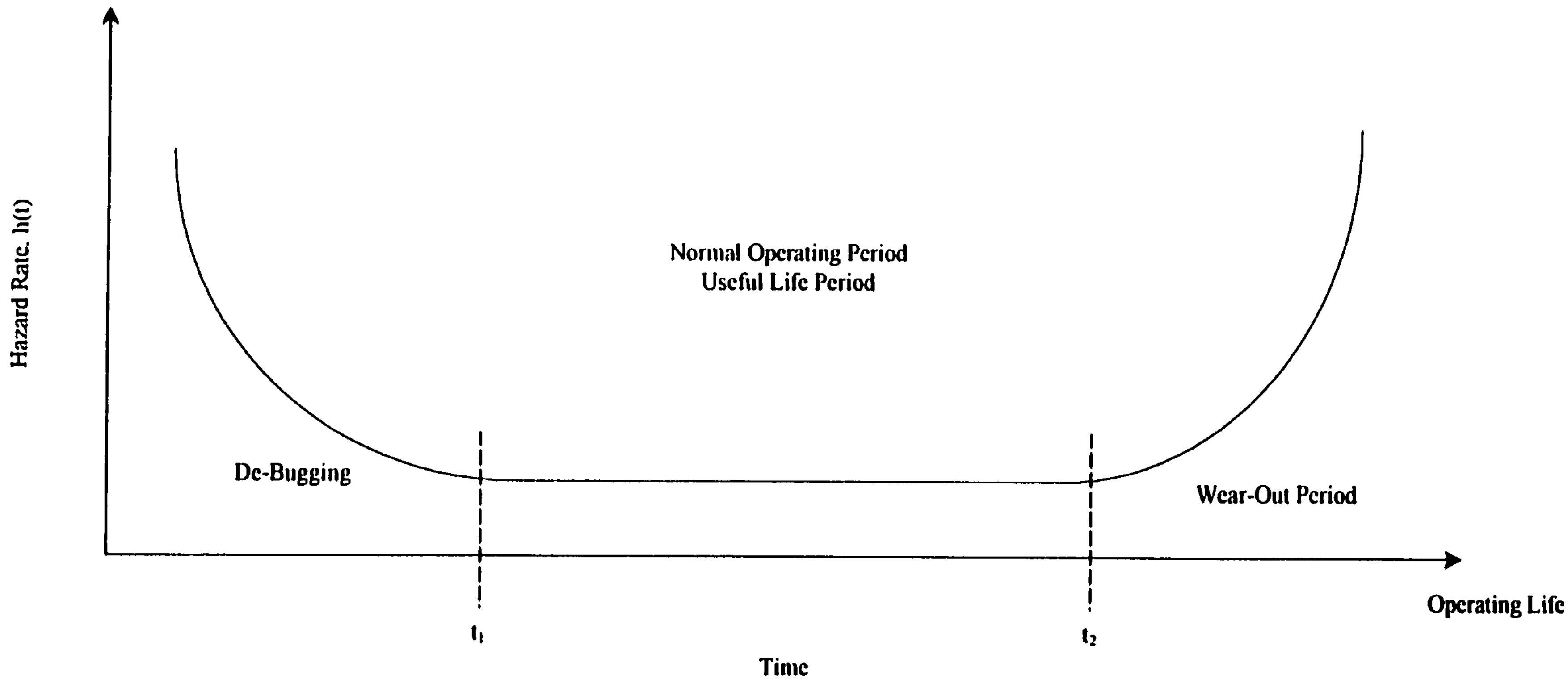

Figure 1.7 The Path-Tub Curve (Hazard Function Over Tool Life)

CHAPTER 2

LITERATURE REVIEW

In this chapter, a review of the relevant literature is presented. Genetic algorithms, heuristics, simulation analysis, tool management in FMS, tool assignment strategies, tool life, and optimization of systems reliability are presented in sections 1, 2, 3, 4, 5, 6 and 7 respectively. The thesis consists of three parts, which were studied by different researchers in the FMS literature, namely production planning and tool management in FMS, tool system reliability and cost, and the different techniques used to address and solve tool loading and part assignment of FMS. The production-planning portion includes tool loading and part assignment. Optimum tool system reliability is enhanced through the use of redundant tools, however, this is done with the objective of achieving minimum overall tooling system cost.

2.1 Genetic Algorithm

Genetic algorithms are search algorithms, which resemble the process of natural selection in search for better characteristics within a changing population. That is GA's are used as efficient optimizers and employ the concept 'survival of the fittest' among string structures along with random exchange of information. This is done interactively by randomly choosing two strings, and applying genetic operators in order to produce new strings with better-fit values. Hence, every generation created contains pieces of the fittest of the old generation. Fitness is a measure of profit, utility, or main direction towards which effort is directed, such as maximizing or minimizing etc.

Holland (1975), is one of the pioneers in the area of genetic algorithms, their uses and the would be research in this area. Goldberg (1989), gave an excellent basic introduction to the subject and highlighted hidden values and potential uses of GAs, their power and ease of understanding and application to various different applications. The central theme of research on GAs has been robustness, that is the balance between efficiency and efficacy necessary for survival in many different environments. GAs are based on the mechanics of natural selection. They are designed to mimic the process observed in natural evolution, Champbell et al. (1995) and Davis (1991):

- Evolution is a process that operates on chromosomes rather than on the living beings they encode.
- Natural selection is the link between chromosomes and the performance of their decoded structures. Processes of natural selection cause those chromosomes that encode successful structures to reproduce more often than those that do not.
- The process uses payoff function not derivatives or auxiliary knowledge.

Holland (1975), used GAs to solve difficult problems. He developed algorithms that manipulated strings of binary digits 0's and 1's, which were called chromosomes. The algorithms developed resembled the natural process in that they knew nothing about the problem they were solving. This was done through the evaluation of each chromosome (i.e. chromosomes with best evaluation were inclined to reproduce more frequently than those with lower evaluation or fitness). Evaluation function is the link between genetic algorithms and the problem it is solving.

Reeves (1995), used GAs for finding the minimum makespan of n-job m-machine permutation flow shop sequencing. The resultant algorithm out was then compared to neighborhood search techniques and it was suggested according to the study that the use of sophisticated procedures is not worth while for simple optimization problems, especially where simple neighborhood algorithms are proven to be sufficient. The GA, however, outperformed a proven simulated annealing algorithm.

Dereli and Filiz (2000) presented an optimization technique for the determination of optimal index positioning of cutting tools on machine tool magazines. Position selection is performed using a genetic algorithm which rankes a list of cutting tools assigned to certain machining operations together with total number of index positions available on machine magazine. A fitness function is used to evaluate the goodness of each solution in terms of total tool indexing time. Tool indexing is described as the process of automatic tool positioning and or changing on machine magazine or tool exchanger.

Yang et al. (1999) applied genetic algorithms to the reliability allocation problem of typical pressurised water reactor. The GA was used to determine the reliability of reactor systems, subsystems and major components of the system. Various cases were analysed which show the genetic algorithm is suitable for solving complex reliability allocation problems.

2.2 Heuristics

Although many techniques were used to obtain the solution of optimization problems, however heuristic approaches are very useful in solving the redundancy allocation problems. Sharama and Venkateswaren (1971), developed an intuitive procedure for allocating redundancy among systems. The procedure is to add a redundancy at each iteration in the stage, which has the lowest reliability. The algorithm was used to solve multistage system problems, which were subject to multiple nonlinear constraints. Misra (1991), introduced an approach for solving a redundancy optimization problem with multiple linear constraints. In the solution process, the problem with r-constraints is decoupled into r-problems, each with one constraint. A desirability factor, which represents the ratio of the percentage increase in the system reliability to the percentage increase of the corresponding cost, was introduced to determine the stage to which a redundancy is to be added. Aggarwal et al. (1975), improved the Sharama and Venkateswaran approach for solving series system problems with multiple nonlinear constraints by introducing a relative increment in reliability versus decrement in the slack variables as a criterion in selecting the stage to which a redundancy is to be selected. Aggarawal (1976) then extended the approach to solve complex system problems.

It is well known that using redundancy can increase system reliability. Chu and Beasley (1997) proposed a GA based heuristic to solve the generalized assignment problem (i.e. n-jobs and m-agents such that one job is assigned to only one agent depending on the capacity of the available agent). The GA developed gives good results, however, when the heuristic operators are applied to it significant improvements in the cost and feasibility of the solution are realized.

A heuristic was presented by Chang-Young Song et al. (1995), for the problem of assigning parts and tools to machines under the tool movement policy with the objective of minimizing the number of tool transfers. The heuristic solution was compared with an optimal solution for small sized problems and with an available heuristic solution for medium to large sized problems. In their approach alternative operations were considered as to improve the system's flexibility, performance and to reduce bottleneck possibilities, however, this algorithm doesn't determine the optimal number of tool copies to be used.

Chang et al. (1995) studied the tool loading problem in FMS in which each part visits one machine for its entire process. If a machine is not carrying a certain tool required for processing a certain part, it can borrow the needed tools from other machine(s) or a tool crib or use alternative tools. The problem was solved with the objective to minimize the number of tool transfers among the machines. A heuristic solution was developed considering similarity among parts. The heuristic was compared with an optimal solution for small size problems and with an existing heuristic for medium to large size problems. Computational results showing effect of two tool redundancy policies using alternative tools using multiple tools for each tool type on system performance were presented.

Mukhopadhy and Sahu (1996) presented a heuristics for solving the problem of loading a set of tools to different machine centers with variable machining time considerations. In their model, priority to perform as many operations as may be possible on a particular machining center was investigated with the objective of minimizing part movement. They also considered the option of assigning more than one operation to one machine in order to achieve better real time flexibility. The advantage of the tool movement approach over the conventional part movement approach include, avoiding the repositioning and re-set up of parts which leads to considerably lower cost and time. Hence better precision in machining operations, avoiding of tool head calibration which results in higher machining precision, and finally work in process is reduced since parts are loaded to machines only when a machining center is available.

2.3 Simulation Approach

Simulation provides the capability to perform modeling and analysis of FMS. These models are written in the form of computer programs that incorporates a sequence of steps, which represent the overall operating system. Probabilistic events are described via sampling from distributions, which adequately describe and represent system behavior. Therefore, it is essential to run such simulation programs for reasonably long times in order for different events to occur a reasonable number of times during each simulation run. Different strategies can be simulated in a great deal of detail without perturbing the actual system. Stecke and Solberg (1981) provided a detailed simulation model for individual FMSs. Their conclusion stated that FMS performance depends on machine loading and control strategies used. Whitney (1985) stated that simulation is not adequate for real time FMS control mainly because the time required to obtain results is too large. Carrie and Perera (1986) analyzed effect of tool variety, product variety and product similarity on the number of tool changes due to product variety, and due to tool wear. Their study was based on a particular FMS. They reported that the number of tool changes due to tool wear was considerably higher than those due to product variety. The procedure made use of the analytical model developed earlier by Menon and O'Gradey (1984), with some variations. They developed 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. Gyamph et al. (1992) compared four scheduling strategies, which include three part selection rules for a FMS consisting of five machines. The strategies were compared based on long cycle times, the comparison included bulk exchange, resident tooling, tool migration, and tool sharing. The study indicated that resident tooling was superior over other strategies, however, the results may differ for relatively shorter cycles.

Liang and Amini (1995) presented a simulation model that analysis effect of tool configuration, tool replenishing and tool sharing in automated manufacturing systems while it simultaneously keeps track of tool usage. An example is solved to illustrate usage of developed model.

A simulation study of FMS was presented by Parakash and Mingyuan (1995). FMS considered for the study consists of six machining centers capable of performing a variety of tasks, an automated guided vehicle based material handling system and a single input, single output storage retrieval system, connected to the manufacturing system by conveyors. The model developed accounts for uncertainties such as stochastic part arrival patterns, variable machining times and machine breakdowns. Major basis f the study is based on number of automated guided vehicles available in the system to speedup the system and account for any machine breakdowns in the system and keep machines working at all times during production run. It was observed that as the number of automated guided vehicles increase, average time spent by parts in the system tends to decrease (in any production system parts spend a large amount of time waiting in the queues).

Makin (1986) discussed the use of various simulation models over a four year period, starting with initial specification, functional design and ending with production planning model to evaluate alternative operating strategies during the five year of FMS operation. Special emphasis was paid to the effect of simulation upon control system design decisions taken. The system consisted of five CNC machines, operated on stand-alone basis and interconnected by a material handling system. The system handles thirty parts but further parts can be added at one or two hours notice. The parts are aluminum cast iron. There were no restrictions on minimum batch size, however, all parts must be prismatic. The system was designed for twenty-four-hour operation, eight of which were unmanned. The five machine tools in the FMS had capacity of 160 tools each and the tools were loaded manually.

Amoako-Gyamph (1996), research describes three heuristics that can be used to allocate tools to an FMS. The three heuristic procedures are then evaluated, through a simulation study, for an FMS that processes a low part type mix and high part type mix. Results from research work indicates that a tool allocation approach that aims at full utilization of the tool magazine capacity produces better FMS performance than an approach that seeks to minimize the frequency of tool changes. It was also stated that an approach that aims at combining both minimal tool changes at the machines and greater tool magazine utilization will be even more beneficial, especially if the cost of tool changes is high relative to capacity utilization.

Simulation based approaches that examine system behavior, have been popular in contemporary FMS research. Examples of works that explicitly deal with reliability in flexible manufacturing systems by using simulation are numerous. A few examples are summarized below.

Chaharbaghi and Davies (1986) proposed a technique for assessing the reliability of flexible manufacturing systems. Lulu and Black (1986) investigated the impact of unreliability of a single production stage to an integrated manufacturing production system's performance. D'Angelo et al. (1988) developed an event driven algorithm for simulating a factory production line with limited buffers and machine failures and repairs. Pritsker (1987) described simulation modeling techniques and procedures in assessing the reliability of flexible manufacturing cells.

Koo and Tanchoco, (1999) presented a simulation approach to address operation/tool selection in a single stage multi machine manufacturing environment where the tools are dynamically shared among machines. A real time operation selection method was studied where operations and their corresponding tools are selected on a real time basis while the parts are being processed. The procedure uses a dynamic tool transfer mechanism where coordination of operations among several machines in terms of tool requirements is a critical problem because some common set of tools can be required by several machines. Research work assumes that the operation sequence and method can be selected in real time, however, it was reported that the improvement realized in system performance due to real time operation selection must be weighted against the possible developing and implementation costs.

The popularity of simulation as a modeling tool stems from the fact that it is capable of modeling large and complex systems with a large number of parameters. From the reliability standpoint, simulation is useful in identifying critical components whose failure would greatly affect the overall system performance; in discovering unforeseen system blockage, and assessing sensitivity of the system performance to variations in part mix, operation times, machine buffer sizes and failure and repair times of components. As a result, most of the drawbacks encountered in mathematical queuing models are circumvented, Pierreval and Paris (2000).

There are a number of concerns with the simulation approach. Development of a simulation model is expensive and time consuming. It calls for high caliper of talent on the part of the modeler that may not be readily available. The methodology also requires moderate computer memory and CPU time when it models large, complex systems, as in the case of FMSs. Once simulation models are successfully constructed, they are "run", not solved for obtaining the desired information or results. This is not to say, simulation models are unable to generate a solution by themselves as in the case of analytical models. The analyst has to try many different parameter value combinations and perform simulation runs for each in an attempt to identify acceptable FMS parameter settings for required FMS output levels. As the number of parameter increase so does the number of runs, thus the restrictions of computer resources and time become a limiting factor. Another disadvantage that surfaces following the construction of the simulation model has to do with parameter values. If a parameter's value changes, additional lengthy simulation runs are required to study the effects of this change to the overall system performance. In other words, the simulation approach does not construct a mathematical expression for the system it models. Hence, a simple parameter change cannot immediately be assessed by merely substituting the new value into the equation.

2.4 Tool Management in FMS

The feasibility of an FMS can be negatively impacted with inefficient well-maintained tool management system. A great number of tools are utilized in the processing of different operations on various parts in FMS. The degree of FMS flexibility is constrained by fixture pallet availability and tool storage capacity. The high investment related to the acquisition of flexible systems forces firms to a better utilization of machines. Different actions can be taken in order to avoid idle times, times dedicated to rapid movements, tool exchange, pallet exchange, etc. An effective tool management system must provide the following, Matt et al. (2000);

- Sufficient backup tools at the machine to address tool breakage and/or wear.
- Minimize tool movement between machines during each production run. Thus improving machine utilization.
- Maximize the number of different operations that can be done by each machine without violating system constraints.
- Make use of preset tools to minimize excess tool inventories.

The tool management problem has been studied by Bard (1994), Tang and Denardo (1988), Grama et al. (1994), Sodhi et al. (1994), Selcuk and Selim (1996) and Souza (1997), to minimize the number of tool switches due to a change in part mixes. The fore mentioned studies assumed constant processing times and tool lives, even though tool wear could significantly impact tool replacement frequency as stated by Gray et al. (1993) and Sarin and Chen (1987). Majority of studies in the literature consider tool management and tool management in FMS without tool sharing thereby ignoring tool sharing and their positive effects on FMS. Tool sharing could decrease both tooling requirements and the non-machining time components, hence total production cost Avci and Akturk (1996).

Various studies of tool management in FMS are present in the literature. Decisions regarding loading and batching are closely related to tool management, Cruver and Senninger (1990), Eversheim et al. (1991), and Gray and Stecke (1988). This means that a certain number of the right tools need to be supplied to the right machines at a specific time so as to process the assigned parts. However, complications arise due to the limited tool magazine capacities. Hwang and Shogan (1989) regarded tool magazine capacity as the at most critical constraint in FMS. Some tool management constraints are; tool life, tool assignment, tool cost, number of tool copies, tool sharing and tool duplication for routing flexibilities and increased reliability are present in the literature.

Tool management studies were not given sufficient emphasis until financial catastrophes were realized. This was the case since FMSs are currently being used in medium variety and medium volume manufacturing, but would become more complicated and of greater importance as FMSs break their way in the manufacture of low volume high variety products.

Mohamed and Bernardo (1997) studied the interface between tool planning and the FMS loading and routing decisions. It was shown that tool policy has a pronounced effect on the flexibility and the planned makespan of an FMS. A tool planning model was developed and integrated into an overall FMS detailed tool loading and part routing procedure. The presented model while considerably reduces the number of tools required by 55% matches the performance of a policy that equips each machine with all tools in terms of makespan, routing flexibility and tool productivity.

There exists few studies in the field of tool efficiency Sarin and Chen (1987), and few others take into consideration tool reliability in FMS Kolahan (1993) and Philpose (1995). Tool management studies in FMS take their direction and are governed by the tool assignment technique considered; namely static and dynamic tool management strategies.

- Static strategy: in this case tools are assigned to machines in batches and no tool change over is allowed within the batches.
- Dynamic strategy: in this strategy tools are transported to the machines as required via an automated tool management system. So as part mix changes are made, parts can be routed differently since tool requirements are easily met. This implies that batching will render to be unnecessary and that machine efficiency will not decline due to changes in production ratios and part mix fluctuations. A major drawback to this strategy is fact that remaining tool lives are not easily tracked, this makes it difficult and may be of a great deal of confusion as to which tool needs to be replaced on each machine in the system.

An FMS is capable of handling a limited number of parts. This is true no matter how flexible FMS may be. It is so simple because of tool storage capacity and tool costs. In order to minimize tool capacity restrictions a careful chosen tool management is selected. According to Luggen (1991) the major problems incurred due to tool capacity restrictions and lack of tool management strategy are as follows:

1. Insufficient tool redundant backups at the machines in case of tool failures.
2. Inefficient usage of tools and the problem of excess tool storage.
3. Insufficient tool matrix capacity, which leads to limiting the number of parts,

handled by FMS.

4. Underutilized machine capacity or low production levels resulting from excessive tools and tool changes.

The importance of tool management in FMS lies in the intent of having to provide the right tool to the proper machine at the right time. Once that is accomplished, then the desired part mix and quantities to be manufactured are achieved.

2.5 Tool Assignment Strategies

According to Amoako-Gyampah et al. (1992) tool assignment strategies are classified into four categories:

- Bulk exchange: replacement of tools with a new set of tools on a magazine takes place at the end of the production period, tools are then replaced for the new part tooling requirements. In this case a part visits the machine that carries the tools suited for the operations required on it. It is also assumed that individual tool lives are longer than the production period. Tool sharing is recognized in this strategy which in turn leads to increased tool inventory. This strategy best applies to FMSs with high volume and low part variety.
- Resident tooling: this strategy is based on group technology. Tool requirements govern the formation of part families and tool clusters. In this strategy tools reside permanently on the specified tool magazine until replaced with a new set of tools, once their useful life is reached.
- Tool migration: the main distinction this strategy poses is that, tools can be replaced during the production period itself. As some operations on different parts

are completed, some tools may be removed from the tool magazines and replaced by different tools. This results in the ability for the system to process other new parts or work on other operations of parts that are currently being processed.

- Tool sharing: this is a combination of both resident and bulk exchange tooling strategies. As in the case of bulk exchange, tool magazines are assigned different tools at the beginning of each production run according to the usual grouping of parts into families. Tools that can be used on different parts are identified and shared among the various machines to process those part operations. This strategy eliminates use of duplicate tools, as is the case with bulk-exchange strategy.

Luggen (1991) compared tool migration and bulk exchange strategies at the completion of a work-piece showed that the tooling strategy used had a substantial effect on the number of machines required, level of manpower needed and tool level inventory.

Zavanella (1996) reviewed the parameters which influence the dimensioning of tool inventory, e.g. tool life, batch size and duration of machining jobs. The study also reviews different tool management strategies and compares them. Three tool management strategies were studied, these were called kit management, pool management and store management. The three are one form or another of the strategies presented earlier. A comparison of the presented tool strategies indicate that pooling and machine center tool stores offer best results, however cost opportunities need to be evaluated. Kit management offers a less expensive policy than other techniques.

2.6 Tool Life

Tool life is defined as the time during which a cutting tool produces acceptable parts in a machining operation Luggen (1991). A cutting tool has reached its useful life limit when, Xiaoli and Zhejun (1998):

- Inaccurate part dimensions are being produced due to wear or deflection.
- Unacceptable surface finishes as a result of wear, chatter or material buildup.
- Excessive torque requirements due to increased feed rates, speeds and heavy stock removal.
- Breakage of tool as a result of excessive wear or due to chipping.

Tool life is directly connected to the cost, efficiency, productivity and reliability of FMS. This is true, since the ability to predict the useful life of FMS cutting tools will directly enhance part quality and increase system productivity. In turn this results in lower inventory levels and costs, a more accurate replenishing strategy, reduced lead-time, and above all better capital investment and planning. Taylor (1907) described the relationship between tool life and cutting speed as:

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

Where:

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

V Cutting speed (feet/minute);

n, k Empirical constants;

n, shape of Taylor tool life curve with regard to machining speed, in general between 0 and 1, usually 0.1 ~ 0.4, and k, 1 minute tool life machining speed. Both factors depend on cutting tool type and material to be machined, with or without cutting fluids, machine tools used, other machining conditions, etc. It is clear from the relationship given above that a slightly lower speed results in a substantial tool life. This means higher tooling reliability and better quality through reducing the probability of tool breakage, production of defective parts, or the number of tool changes within each production run. Figure 2.1 shows Taylor's tool life curve.

Cook (1973), worked on an extension to the above relationship which relates speed, feed and depth of cut for a given tool life value:

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

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;

Liang (1994) presented a two stage approach to the joint problem of part selection, machine loading and machine speed selection problem. The first stage uses a mathematical model to solve the part selection and machine loading. In the second stage, optimal cutting speed for all job-tool-machine is determined.

Wagner and Barash (1971) noted that for high speed steel turning tools, tool life values follow a statistical distribution that can closely be approximated by normal distribution. Experimental studies made by Hitomi et al. (1979) revealed application of the log normal distribution to tool wear provided good results.

Ramalingam and Watson (1977), provided results of tool life study in the case where useful tool life was terminated by a single catastrophic event. They showed that for a time independent degradation, tool life distribution can be given as an exponential distribution, or a Weibull distribution with shape parameter, $\beta = 1$. In the case of a time dependent tool degradation, the distribution that applied was a general Weibull distribution. Therefore, in general, tool life distribution for both time dependent and time independent failures is represented by Weibull distribution where β is an indication of the time dependence of tool degradation. Ramalingam (1977), studied gradual wear and cumulative wear process,. In his study, a tool reaches the end of its useful life when a specified volume of material is removed from a specific surface, ie flank surface or rake surface. It was reported that in the case of linear wear, the approximation of tool life by normal distribution was applicable in most cases. However, in case of non linear wear, log normal was more suitable. Whereas the first and second studies used an arbitrarily hazard function for 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 provided in the first study was revisited and new hazard function applied, tool life distribution for single injury tool failure was shown to be a Weibull distribution, hence it made first studies to be meaningful and realistic.

Guerrero et al. (1999) presented a tool loading approach which focuses on the existence of alternative routes for each part type. Also, the optimal number of copies of each tool type to be loaded into each magazine is directly determined. The objective of their machine loading and part type selection model is to balance machine work loads.

The problem was modeled as a mixed integer linear program. Tool life was known in advance and is not allowed to vary.

Sodhi et al. (1999) used Taylors's tool life equation in conjunction with models which were developed for determining optimal processing speeds for a given set of parts on a set of machines with tool magazines of finite capacity, based on tool life considerations. The tool loading on individual machines was also obtained. Several heuristics for solving real world size problems were presented. Computational experiments were conducted to evaluate and validate solutions

Figure 2.1 Taylor's Tool Life Curve, Shows a Linear Relationship between Tool Life and Machining Speed on a Bilogrithmic Curve

2.6.1 Tool Monitoring and Fault Detection

Tool life is defined as defined earlier is the time frame during which a cutting tool is capable of producing to spec parts. As described in the previous section tools wear, break, deform and will for a reason or another produce unacceptable finished parts. It is, therefore, essential to monitor tool life and tool condition to be certain that tool is functioning during its useful life. An essential component of tool life monitoring is an accurate and reliable on line tool database. Tool suppliers provide preliminary tool life data based on material type, cutting speed, feed rate and laboratory test data. This database builds on and becomes more valuable as tools are put to work and the user has on the job experience with these tools.

As part mix changes happen in FMS and as reliability requirements vary, enough redundancies along with related components such as holders need to be allowed to meet tooling system requirements. This entails the following:

1 Ensure all tools including redundancies are present on machine magazine. The number of tools required stems from the tool life of each tool type, reliability of each tool and total processing time required for each work-piece.

2. Only one unique tool of each tool type needs to be active on each individual machine. Tool copies are allowed to be used only when tool life is expired or as a tool breakage occurs.

Tool monitoring deals with normal tool wear values relative to predetermined values, as such decisions regarding tool life can be deduced and action may be taken. As for tool breakage or catastrophes, these can be detected through tool torque at each tool spindle or via methods of sensing and detection.

Li and Venuvinod (2000) presented a hybrid learning method to map the relationship between the features of cutting vibration and the tool wear condition. Results show that it can be used effectively to monitor the tool wear in different machining operations. Tool life monitoring places heavy emphasis on copies of redundant tools. Enough cutting tools, related components, and holders need to be available to provide for constantly changing mix of parts to be machined. At all times there are tools available for use, which are redundancies for the prime reason of boosting tooling system reliability. Fault sensing and detection capabilities are designed to detect and provide recovery for major tool damage, failure, or breakage within a tool's active life cycle. Fault detection is generally provided by, Zhou et al. (2000) and Luggen (1991):

1. Adaptive or torque measurement and control.
2. Broken tool sensing.

Adaptive or torque measurement capability works through built in sensors that detect when certain tools begin to draw more than acceptable levels of horsepower. For small diameter tools for which horsepower values are too small for practical measurement, optical or length sensing devices may be used for verifying tool length. Out of tolerance tool lengths are considered broken by the system. Torque measurement and control are essential for FMS because of its ability to adapt feed rates under varying stock removal conditions, as well as sense broken or dull tools. Broken tool sensing has long been considered an important feature of FMS, however, detection alone without a versatile and automatic recovery strategy offers little value in FMS.

2.7 Optimization of FMS Tooling System Reliability

Importance of FMS tooling system reliability stems from the fact that these systems are highly technical and therefore are fairly expensive. FMS failures are highly significant and require analysing due to their economic effects, Ebeling (1997).

Optimization techniques have their inherent characteristics and specific superiority to solve general linear or non-linear programming problems, various optimization techniques are present in the literature:

- Maximize tooling system reliability by adding a redundant component to each subsystem, Misra (1972).
- Maximize tooling system reliability by choosing suitable stage reliability in each subsystem Misra (1991).
- Minimize the "Cost" of the tooling system while satisfying the minimum requirement of the systems reliability, Altumi and Taboun (2000), Kolahan (1993) and Philipose (1995).
- Minimize the cost of a multi-function tooling system while satisfying the minimum requirement of each individual tooling system (tool) reliability, Altumi and Taboun (1999).

"Cost" constraints of cost, machines, tools, tool copies or some combination of these factors are imposed on a system with series, parallel, or complex configuration.

Many studies were conducted in the field of reliability optimization with emphasis of redundancy utilization. The studies formulated the problem as a maximization or minimization function under specific systems' constraints. Since complex systems need to operate with some predefined reliability especially when cost and due dates are a set priority. Also, due to the failure of some components in a more frequent manner than other components in the system. The introduction of better quality components is evident and may constitute a partial answer to the problem, however, the system may still call for standby redundancies to overcome the probability of component failures. The number and location of such needed redundancies is the issue here.

Coit and Smith (1996), developed a GA to solve the general class of the redundancy allocation problem. The GA was demonstrated on two different problems and results were compared with other techniques. The GA was demonstrated to be flexible and few restrictions were needed on the form potential solutions.

Ghare and Taylor (1969) under took the number of redundancies required to achieve the maximum allowable reliability of a system in series subject to resource constraints. The research employed a branch and bound procedure to solve the zero one model. Federowicz and Mazudar (1968) to optimize redundancies for a system in series used a geometric programming model. The results showed that the non-integer solutions obtained were close to discrete optimal values. Fan et al. (1967) investigated the effect of overall optimum redundancy profits. Dynamic programming was employed by Bellman and Dreyfus (1958) to solve for the optimal redundancies of a system, the study included cost and weight constraints. Tillman (1969) applied integer-programming techniques, the objective was the maximization of reliability or the minimization of cost. Several constraints were imposed, however, different modes of component failures were considered.

Heuristic algorithms were used to solve the redundancy allocation problem. Bala and Aggarwal (1987) developed a two-phase heuristic algorithm for a system in parallel to optimize redundancies in complex networks. The components for which redundancies should be considered were identified. An algorithm to solve optimal redundancy problems with resource constraints in situations where the system could operate when a component fails was developed by Volkovich (1986).

A computational scheme to maximize reliability subject to cost constraints was used by Kettle (1962), the redundancy problem was solved for a system in series employing minimum cost criterion. The approach was based on the availability and cost of each component in the system.

Ramachandran, (1997), proposed a genetics based algorithm to solve the redundancy optimization problem for maximizing the system reliability subject to the cost constraint. A systematic representation of the problem has been given in steps such that genetic algorithms can be applied. A series-parallel configuration has been considered to illustrate the genetics based technique. The results and the computing time have been compared with the existing techniques.

Painton and Campbell (1995), came up with a procedure for improvements made to components of a system, to upgrade system performance; for example, when designing a later version or release. The paper presents an optimization model that identifies the types of component improvements and the level of effort spent on those improvements to maximize one or more performance measures (e.g. system reliability or availability) subject to constraints (e.g. cost) in the presence of uncertainty about the component failure rates. For each component failure mode, some possible improvements are identified along with their cost and the resulting improvement in failure rates for that failure mode. The objective function is defined as a stochastic function of the performance measure of interest - in this case, 5th percentile of the mean time-between-failure distribution (MTBF). The problem formulation is combinatorial & stochastic. Genetic algorithms are used as the solution method. The approach was demonstrated on a case study of a personal computer system. Results and comparison with enumeration of the configuration space show that genetic algorithms perform very favorably in the face of noise in the output: they are able to find the optimum over a complicated, high dimensional, nonlinear space in a tiny fraction of the time required for enumeration. The integration of genetic algorithm optimization capabilities with reliability analysis can provide a robust, powerful design-for-reliability tool.

Braglia, and Zavanella, (1999) presented a model that aims at optimizing tool requirements in FMS. The model determines the best tool spectrum, ie the number of duplicates for each tool type to be provided considering different layouts of the tool management area (tool rooms).

CHAPTER 3

MODEL DEVELOPMENT

This chapter investigates the production planning tool allocation and part assignment models in flexible manufacturing systems. 0/1 integer programming models are developed for part routing and tool allocation of different tool types along with tooling system reliability requirements. The models include tooling reliability constraints along with the conventional problem of resource allocations. The details of the system under investigation are discussed in section 3.2. Different problems are selected and solved to test the performance of the developed models. The results show the ability of the developed models to find optimum or near optimal solutions for all problems.

3.1 System Definition

FMS is an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium sized volumes of a variety of part types Stecke (1986). FMSs are designed to attain a trade-off between the efficiency of transfer lines and the flexibility of job shops. FMSs are able to accomplish this trade off largely due to their ability to eliminate the setup times between consecutive operations. An FMS possess the following characteristics:

- Is designed for simultaneous manufacture of several different parts in a given production mix.

- Utilizes sophisticated flexible machines, this means that each machine is capable of processing different operations on parts with negligible tool change over times (batch processing is not required).
- A computer-controlled material handling system carries part movement through the system and between machines. Parts are mounted on pallets, which eases part movement and facilitates accurate positioning.

It is usually the case in FMS that parts assigned to a particular machining center would have to visit with a number of tools before completing their journey. This means that, the function of the system depends solely on the proper function of all tools. As stated previously, the reliability of the tooling system is considered as the probability of successful performance of all required machining operations of the parts assigned to the tooling system. The main components of an FMS are; numerically controlled machining centers, automated material handling system and real time computer control, Stecke (1983).

3.2 Problem Definition and Model Formulation

An FMS consisting of several machines and an automated material handling system is considered. The machining centers are not necessarily identical and are assumed to be controlled by a central computer unit. All parts programs can be downloaded to the different machines in real time. The automated material handling unit takes care of the load and unload of the different parts, it is assumed that this unit constitutes no limitations over the system. Each individual machine has a limited and finite tool magazine capacity. For any production period, there exist a number of parts to be assigned to the different machines for processing. Each part requires a finite number of operations to be executed over the production period. Each operation requires a certain tool which, will be loaded on one or more machines present in the system. For each operation, the processing time using a particular tool on any of the given machines is known beforehand. An operation is an elemental task, which can be performed by different tool types requiring different processing times on different machines. This research deals with the planning decisions made at the beginning of each manufacturing cycle, these include the assignment of part operations to the different machines and the allocation of tools and tool copies to machine tool magazines. Figure 3.1 below illustrates elements of the planning model. It is further assumed that part mix ratio and production requirements are known. The number of available tools and tool slot requirements for each tool type are available along with tool life distribution parameters for each tool type on different machines, tool reliability of each tool type on different machines is calculated using tool reliability parameters for different distributions.

3.2.1 Model Assumptions

The following assumptions were made when the model was developed:

- The demand for each part type is known and will not change during the production period. If the forecasted demand varies, proper adjustments are made.
- Tool failures are independent of one another. That is, the failure of one tool does not affect the failure of another tool in the system.
- Tool spares of each tool type are identical.
- Machining parameters including spindle speed, feed, depth of cut etc. are all

known before the production period, and will not change during the production run.

- Each machine has a limited tool magazine capacity, and hence only a limited number of copies of each tool type can be loaded on each machine.
- The changeover time on machine spindles is considered to be negligible, this is so due to its relative shortness when compared with the processing time of the different operations.
- The detection of tool failures is immediate and perfect.
- Tool magazines are replenished after each production period.
- Switch and tool exchange device reliability is 100%.

3.2.2 Notations Used

i : parts	$i = 1, 2, \ldots, I$
j : operations	$j = 1, 2, \ldots, J$
k : machine index	$k = 1, 2, \ldots, K$
s : tool index	$s = 1, 2, \ldots, S$
m_s : spares index	$m_s = 0, 1, 2, \ldots, M_s$

3.2.3 Decision Variables

X_{ijks} = Number of part type 'i' for which operation 'j' is performed on machine 'k' using tool type 's'.

Y_{ksm_s} = 1 If m copies of tool type 's' are to be loaded on machine 'k' and 0 otherwise.

Y_{klsms} = 1 If m copies of tool type 's' are transported from machine 'k' to machine 'l' and 0 otherwise.

3.2.4 Parameters

C_{ijks} = Processing cost per unit time for performing the j^{th} operation of part type 'i' on machine k using tool 's'.

t_{ijks} = Processing time of the j^{th} operation of part type i on machine k using tool type 's'.

q_i = Demand of part type 'i' for each production period.

C_s = Cost of tool type 's'.

E_k = Magazine capacity of machine 'k'.

T_s = Average tool life of tool type 's'.

A_s = Maximum available tools of tool type 's'.

Z_s = Number of slots required by tool type 's'.

R_{ks} = Reliability of the s^{th} tool on machine 'k'.

R_{kRq} = Minimum required tooling system reliability for each machine type 'k' in the system.

R_{Rq} = Minimum required tooling system reliability for all tools in the system.

3.3 Basic Models

In this section, integer-programming models are developed for part assignment and tool loading simultaneously. The problem is formulated as a tool machine formulation, where s different tools are assigned to k machines. The objective is to minimize the overall cost while maintaining preset overall tooling system reliability. Major constraints are, tool magazine capacity, processing times of tools on different machines may be different and the fact that some tools may require more than one slot for mounting. It is to be taken into consideration that same tools perform at different reliability levels on different machines due to various operating conditions.

3.4 Model I; Cost Minimization, No Tool Sharing

In this section, the part assignment-routing model of Leung and Maheshwari (1992), which examined part assignment and tool loading in FMS with material handling considerations, is incorporated into the tool allocation model to form a single cost optimization model which takes into consideration tool reliability.

An FMS with k machines with a material handling system to transport different parts between load/unload station and different machines in order that all operation requirements of different machines get done. Operation times of different parts processed on different machines by different tool types are known. Here, an operation is defined as an elemental task. This is needed to formulate the situations whereby alternate tool types requiring different tool types and generating different tool reliabilities on different machines may process an elemental task. Hence, higher FMS tooling system flexibility. Moreover, machine as well as tool requirements of each operation are known before hand. The number of available tools and tool slot requirements for each tool type is available to the system analyst. Machines/cutting tools compatibility is also known.

The objective of this model is to minimize total tooling cost while achieving a predetermined tooling system's reliability. As the reliability constraint gets added to the set of constraints governing the model, a trade off is pursued. This is done in order to reach a certain level of tooling system reliability while maintaining optimal or near optimal overall tooling system cost. This is accomplished through the introduction of additional tool copies to the system in the form of redundancies while optimizing total FMS tooling cost. The basic model is given below:

Minimize

$$\sum_{i=1}^{J}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S} C_{ijks} \,.\, t_{ijks} \,.\, X_{ijks} \;+\; \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{m_s=0}^{M_s} C_s \,.\, m_s \,.\, Y_{ksm_s}$$

Subject to

Tool life requirements

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{m_s=0}^{M_s} t_{ijks} \,.\, X_{ijks} \;\leq\; T_s \,.\, m_s \,.\, Y_{ksm_s} \qquad \forall\; k,\, s \qquad (3.1)$$

Upper limit of tools available

$$\sum_{k=1}^{K}\sum_{m_s=0}^{M_s} m_s \,.\, Y_{ksm_s} \;\leq\; A_s \qquad \forall\; s \qquad (3.2)$$

Magazine capacity

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m_s=0}^{M_s} Z_s \,.\, m_s \,.\, Y_{ksm_s} \;\leq\; E_k \qquad \forall\; k \qquad (3.3)$$

Out put requirements of each part type for a given production period

$$\sum_{k=1}^{K}\sum_{s=1}^{S} X_{ijks} \;=\; q_i \qquad \forall\; i,\, j \qquad (3.4)$$

Spare Tool Requirements

$$\sum_{m_s=0}^{M_s} Y_{ksm_s} = 1 \qquad \forall k, s \qquad (3.5)$$

Minimum Tooling System Reliability Requirements

$$\prod_{s=1}^{S} \prod_{m_s=0}^{M_s} R_{ksm_s} \cdot Y_{ksm_s} \geq R_{kRq} \qquad \forall K \qquad (3.6)$$

The linearized form of equation (3.6) is;

$$\sum_{s=1}^{S} \sum_{m_s=0}^{M_s} \log R_{ksm_s} \cdot Y_{ksm_s} \geq \log R_{kRq} \qquad \forall K \qquad (3.7)$$

Where, X_{ijks} are integers and Y_{ksm_s} is a 0/1 variable which indicate that a machine k has m_s spares of tool type s. Thus ($m_s \cdot Y_{ksm_s}$) gives the number of spares of tool type s, on machine k.

3.5 Tool Life Restrictions

Constraint set (3.1) guarantees that the total time required by the various different operations to be performed on a single machine by employing a particular tool does not exceed that tool's life. Tool life is a function of many different variables including, but not limited to, cutting parameters, part and tool material and the requirements of the cutting operation. This combination produces a stochastic tool life. A random failure of any of the different tools can critically cause disruption of the operation of the system, that in turn affects productivity, quality and profitability of FMS. The time between these failures is called tool life (MTBF). To reduce the impact of random tool failures in FMS, a tool is used only for a fraction of its expected tool life, as was pointed out by Talavage and Hannam (1987) as well as Braglia et al. (1999). Therefore, at the production planning stage, the useful life of a tool can be assumed to be deterministic. Each assigned operation of a part consumes a fraction of the tool life.

3.6 Tool and Tool Copies Availability

Different tools and tool copies will be required to perform the various operations on different part types, for higher levels of tooling system reliability even more copies will be needed. Therefore, the number of tool slots required by a specific machine must not exceed the number of slots available on that particular machine. This restriction may be relaxed by the introduction of a tool carousel, which carries the extra-required tools. These tools will be in a state of standby until called in for a task, then an exchange takes place between a tool or a group of tools on the machine tool magazine and the tool(s) on the carousel via an automatic tool exchanger. Constraint set (3.2) restricts the allocation of tool type, s, to an inventory limit, A_s, of that tool type.

3.7 Tool Magazine Capacity

The number of tool slots on the tool magazine restricts the capacity of each machine. Different tools may require different number of tool slots depending upon the size and shape of each individual tool. This dictate that the number of tool slots required by the tools allocated to a machine be at most equal to the number of available slots on that specific tool magazine, constraint set (3.3). Stecke (1983); Shanker, Tzen (1987), Mahehwari (1992) and Braglia and Zavanella (1999), indicated that overall number of slots utilized by a group of tools assigned to a tool magazine may vary according to the way tools are placed in the tool magazine. In this research it is assumed that only integer number of slots is required to accommodate each tool on any specific tool magazine regardless of location (one for slender tools, two for left handed tools and three for fat tools).

3.8 Machine Capacity

Any machine present in the system can perform a certain number of operations in any given cycle depending upon individual operation times. This implies that the sum of operations assigned to a particular machine may not exceed the manufacturing cycle time available to each individual machine in the system. The cycle time may be defined as an hour, a shift, a day, or a week depending on the planning horizon. Therefore, the total processing time required by the various different part types assigned to a particular machine (Z_s m_s . Y_{ksm_s}) must be less than or equal to the time allowed for each manufacturing cycle as indicated by constraint set (3.3). Constraint set (3.3) sets a limit on the workload of each machine.

3.9 Production Requirements

The output requirement of a part type is determined by the stream production requirements of the final product or the subassembly. Constraint set (3.4) defines the output requirements of each operation of part type. This set ensures that operations of each part type are assigned to a specific machine in the system. It is assumed that the final product or the subassembly requirements determine the production requirements as well as the production ratios.

Constraint (3.5) 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. The objective function of this model is to minimize the total cost while maintaining a certain level of tooling system reliability which is insured through constraint set (3.6).

3.10 Minimum Tooling System Reliability

Tooling system reliability is governed by constraint (3.6), which merely says that the reliability of all tools mounted on each machine need to satisfy the required preset reliability. Minimum tooling system reliability is decided in advance by the decision-maker and is given by; R_{kR_q}. The reliability of all tools type s mounted on machine type k with m spares is given by the following equation:

$$R^{m_s}(t) = \prod_{s=1}^{S} \left\{ \sum_{m_s=0}^{M_s-1} \frac{\left(\int_0^t \lambda(t)_s \, dt \right)^{m_s} \exp\left[-\int_0^t \lambda(t)_s \, dt \right]}{m_s!} \right\} \quad \forall k \qquad (3.8)$$

Where $\lambda(t)_s$ is the failure rate of tool type s on machine k in FMS tooling system.

3.11 Relationship between Sets of Decision Variables

Part assignment variables, X_{ijk_s}, depict the assignment of each part type, 'i', whose specific operation, 'j', is to be processed on a machine, 'k' and using a specific tool type, 's'. The tool allocation variable Y_{ksm_s}, represents the number of spares 'm_s' of tool type 's', allocated to machine, 'k'.

The two variables are closely related to one another. A part is assigned to a specific machine for a specific operation employing a given tool type along with a number of spares for each tool type only if that particular tool can be allocated to that machine. Constraint set (3.1) ensures that if a part is assigned, then the required tool is also available on that machine. By the same talking, if the parts assigned to a machine do not require a particular tool, then that tool type is not allocated to that machine. The objective function ensures that such a tool allocation is not possible.

3.12 Illustrative Examples

In this section, 8 problems of different sizes and structures are considered to illustrate the developed models. All problems were solved using LINGO optimization software on a Pentium 120 MHz personal computer. The following paragraphs discuss the results obtained from applying the mathematical model to each of these problems.

Eight example problems of different sizes are in part taken from Leung and Maheshwari (1992). Information about demand, production run lengths, processing times and cost, tool life parameters and tool cost are taken from literature, Leung and Maheshwari (1992) published research work.

The stochastic nature of tool life must be taken into account in order to predict the reliability of each tool type during a production period. This makes it possible to determine the number of required spares in order to have an uninterrupted production run with a certain probability. In this research, two types of failure distributions are considered for the proposed system. The general formula to calculate the reliability of a tool with standby redundancy is given by equation (3.8) of section 3.7.2 of this chapter.

In case where tool life of all tools follow exponential distribution, reliability of each tool with standby redundancy becomes:

$$R^{m_s}(t) = \frac{e^{-\lambda t} \sum_{m_s=0}^{M_s-1} \lambda(t)_s\, m_s}{m_s!} \tag{3.9}$$

To calculate the integral $\lambda(t)_s$ dt for the above mentioned distribution in the interval [0,t] in the above equation (3.8), the results are as follows:

For Weibull distribution;

$$\int_0^t \lambda(t)_s\, dt = \left(\frac{t}{\beta}\right)^b \tag{3.10}$$

Where β is scale and b is shape parameter of Weibull distribution.

For exponential distribution;

$$\int_0^t \lambda(t)_s\, dt = \lambda t \tag{3.11}$$

Where λ is constant failure rate for exponential distribution.

The part-operation decisions are made on the values of X_{ijks} and those for tool-machine allocation and spare requirements are Y_{ksm_s}. For example, X_{1247} indicates that operation 2 of part type 1 is assigned to machine 4 using tool 7, and Y_{473} indicates that 3 tools of tool type 7 are to be assigned to machine 4.

3.13 Example Problem 1

For illustration purposes, this example problem is analyzed in detail. Problem in part taken from Leung and Maheshwari (1992), consists of four different part types. Each part type requires four operations. The production requirements of the four part types are

60, 60, 40, 40 respectively. Each machining center carries a tool magazine of size 50. There are 20 different types of tools. Table 3.1 provides part-operation-tool compatibility matrix. Table 3.2 gives machine-tool compatibility matrix and number of tools available for each tool type. Processing times (minutes) and cost (dollars) of each operation of a part on a machine using different tools are shown in Table 3.3 and Table 3.4 respectively.

All example problems are solved using LINGO optimization software using a Pentium 120 MHz computer. The part operation and machine decisions are made based on the values of X_{ijks} and tool-tool copies and machine tool decisions are made based on Y_{ksm}. For example, X_{1234} indicates that operation 2 of part type 1 is processed using tool type 4 on machine 3, and Y_{345} means that 5 tools of tool type 4 are assigned to machine 3.

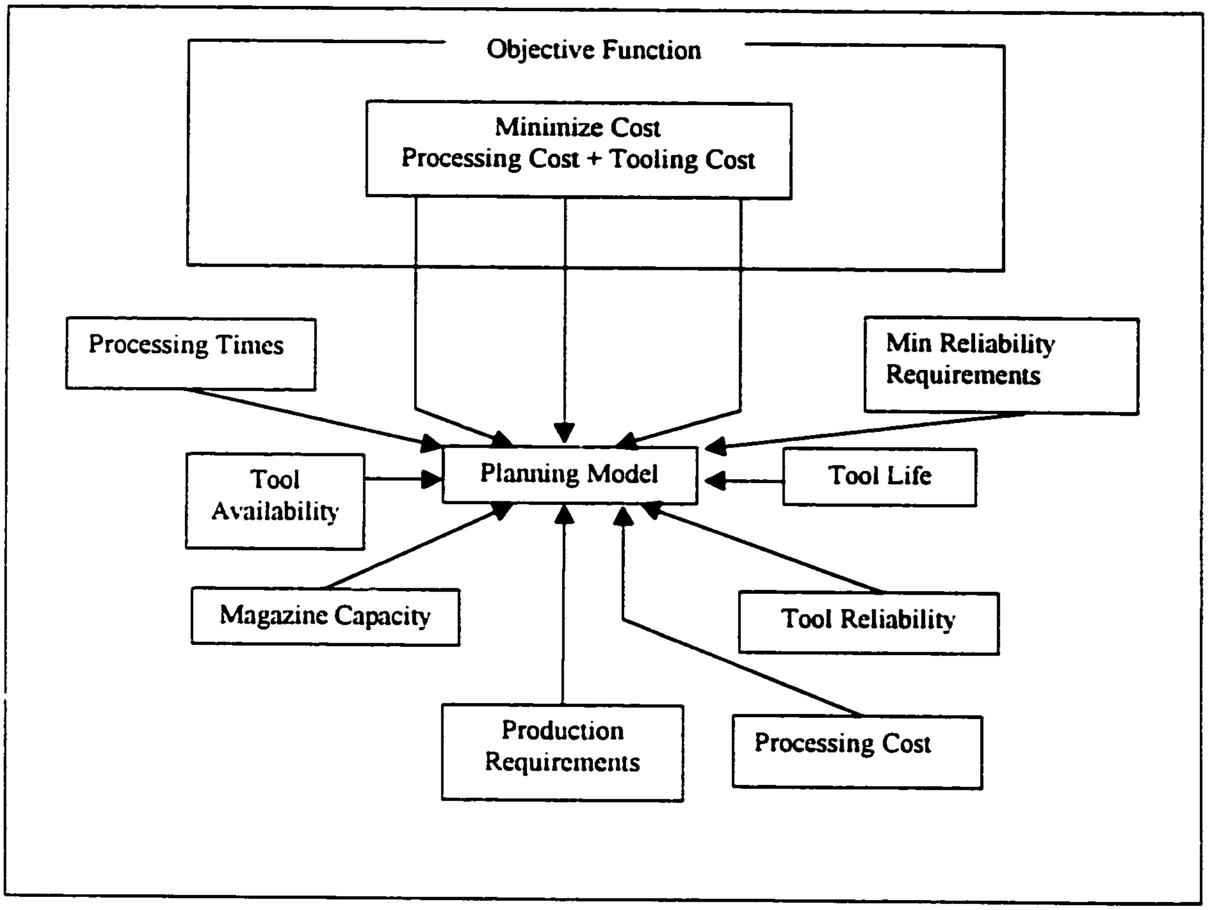

Figure 3.1 Planning Model Components

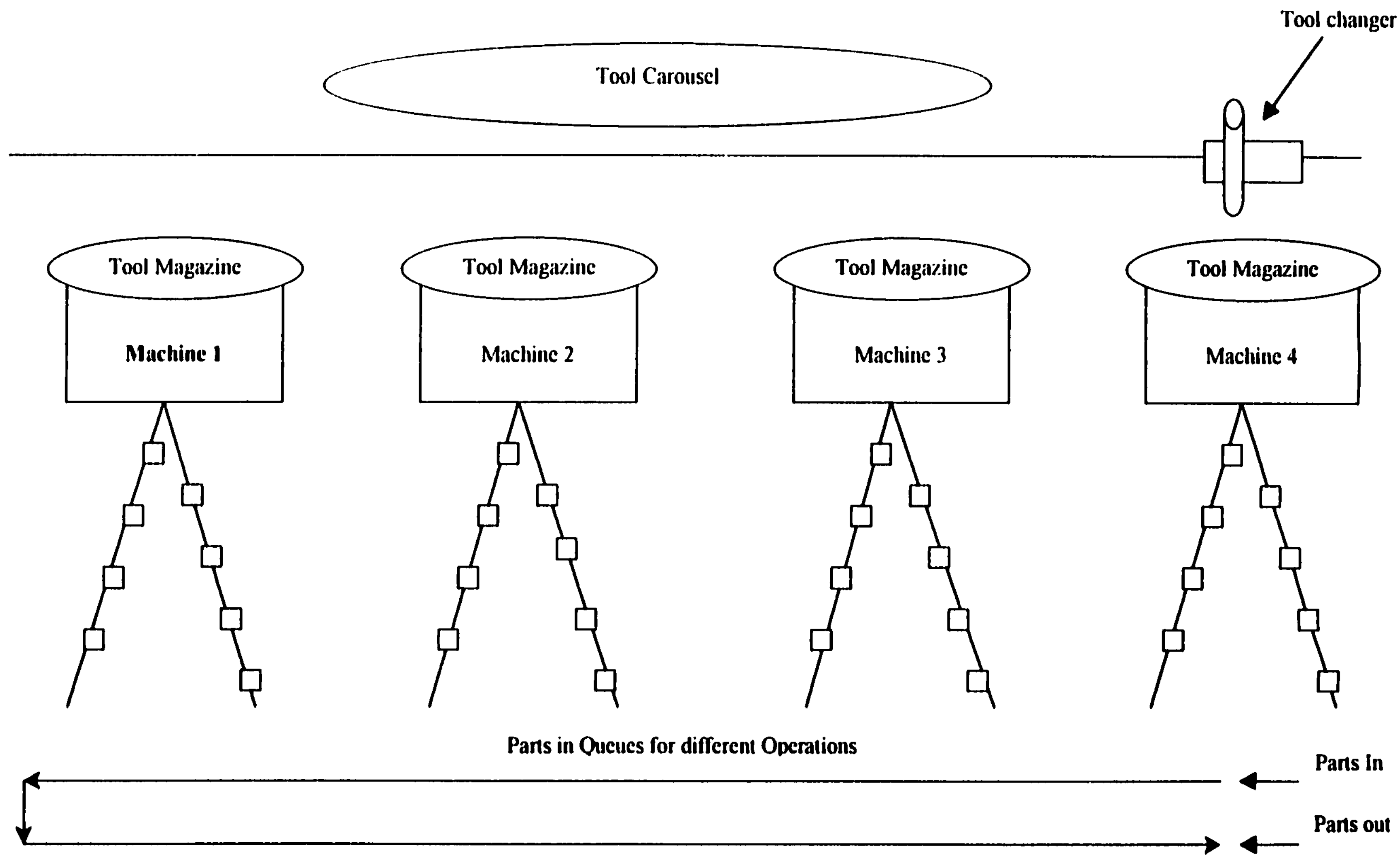

Figure 3.2 Typical Configuration of System

Table 3.1 Part-Operation-Tool Compatibility Matrix, Example Problem 1

Tool Type		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Part	**Operation**																				
1	1	1	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2	*	*	*	1	*	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*
	3	*	*	*	*	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	4	*	*	*	*	*	*	*	*	*	1	*	*	1	*	*	*	*	*	*	*
2	1	1	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2	*	*	*	*	*	*	1	*	*	*	*	*	*	*	*	1	*	*	*	*
	3	*	*	*	*	*	*	*	*	*	1	*	*	*	*	*	*	1	*	*	*
	4	*	*	*	1	*	*	*	*	*	*	*	1	*	*	*	*	*	*	*	*
3	1	*	*	*	*	*	*	*	*	*	*	*	1	*	*	1	*	*	*	*	*
	2	*	*	*	*	*	*	*	*	1	*	*	*	*	*	*	*	*	1	*	*
	3	*	*	*	*	*	*	*	*	*	*	1	*	*	*	*	*	*	*	1	*
	4	*	*	1	*	*	*	*	*	*	*	*	*	*	1	*	*	*	*	*	*
4	1	*	1	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2	*	*	*	*	1	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1
	3	*	*	*	*	*	*	*	*	*	*	*	*	1	1	*	*	*	*	*	*
	4	*	*	*	*	*	*	1	1	*	*	*	*	*	*	*	*	*	*	*	*

Table 3.2 Machine-Tool Compatibility Matrix and Tool Availability, Example Problem 1

Tool Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Machine																				
1	1	*	1	*	1	*	1	*	*	1	*	1	*	*	*	1	*	*	*	*
2	1	*	1	1	*	1	1	*	*	1	1	*	*	1	*	*	*	*	1	1
3	*	1	*	1	*	1	*	1	1	*	*	1	*	*	*	*	1	*	*	*
4	*	*	*	*	1	*	*	*	1	*	1	*	1	1	1	*	*	1	*	*

Table 3.3 Processing Times (min) of Each Operation of a Part on a Machine Using Different Tools, Example problem 1

Part Type	1							2								3								4							
Oper.	1		2		3	4		1		2		3		4		1		2		3		4		1		2		3		4	
Tool Type	1	2	4	7	6	10	13	1	3	8	16	10	17	4	12	12	15	9	18	11	19	3	14	2	4	5	20	13	14	7	8
Machine																															
1	7	*	*	4	*	3	*	6	6	*	3	6	*	*	7	4	*	*	*	*	*	3	*	*	*	9	*	*	*	4	*
2	6	*	7	8	6	3	*	8	7	*	*	4	*	7	*	*	*	*	*	7	5	9	6	*	6	*	4	*	7	5	*
3	*	7	6	*	7	*	*	*	*	7	*	*	6	6	3	7	*	8	*	*	*	*	*	9	5	*	*	*	*	*	8
4	*	*	*	*	*	*	7	*	*	*	*	*	*	*	*	*	8	7	4	8	*	*	*	*	*	7	*	9	7	*	*

Table 3.4 Machining Cost ($) of Each Operation of a Part on a Machine Using Different Tools, Example Problem 1

Part Type	1							2								3								4							
Operation	1		2		3	4		1		2		3		4		1		2		3		4		1		2		3		4	
Tool Type	1	2	4	7	6	10	13	1	3	8	16	10	17	4	12	12	15	9	18	11	19	3	14	2	4	5	20	13	14	7	8
Machine																															
1	12	*	*	7	*	11	*	11	14	*	22	13	*	*	8	5	*	*	*	*	*	4	*	*	*	18	*	*	*	6	*
2	11	*	17	14	12	17	*	17	10	*	*	9	*	7	*	*	*	*	*	8	13	8	9	*	15	*	19	*	20	4	*
3	*	7	15	*	15	*	*	*	*	16	*	*	21	12	17	15	*	17	*	*	*	*	*	11	18	*	*	*	*	*	12
4	*	*	*	*	*	*	10	*	*	*	*	*	*	*	*	*	7	12	20	11	*	*	*	*	*	14	*	9	15	*	*

3.13.1 Results of Example Problem 1

The results of the example problem are summarized in Table 3.5 through Table 10, which contain the part assignment and tool allocations, respectively. For example, the assignment for part type 1 with tooling system reliability considerations is:

- Operation 1, 15 units are processed on machine 2 and 45 units are processed on machine3.
- Operation 2, all 60 units are processed on machine 1.
- Operation 3, 40 units are processed on machine 2 and 20 units are processed on machine 3.
- Operation 4, 10 units are processed on machine 1, 39 units are processed on machine 2 and 11 units are processed on machine 4.

Tool allocation is given in Table 3.7 through Table 3.10 for reliability levels of 80%, 90%, 95%, 97%, 98.8%, 99.3% and 99.7% respectively. The total number of tools assigned to each machine type is given in Table 3.6 for different required tooling system reliability levels. A total cost value of 102042 was obtained in 23 seconds of CPU time for minimum tooling system reliability of 99.7%.

3.13.2 Effects of Tooling System Reliability Level, Example Problem 1

To examine the effects of tooling system reliability level for this example problem, the basic models are solved for various values of "minimum required tooling system reliability" and the cost of operation was observed. Also the number of tool slots in the machine used up for the operation is observed. The results are tabulated in Table 3.5 through Table 3.10. The following sections analyze and highlight these effects.

With higher tooling system reliability levels, part assignment is such that more parts are moved among machines for different operations. In this research, effect on part assignment is not studied due to the huge resultant combinations, which produces to many tables for analysis.

The increase in tooling system reliability level results in higher part movement which is done in order to utilize tools to their limit and introduce more tools into the system to fulfill such desired tooling system reliability levels. The total cost increased by $3475 when tooling system reliability is increased by 0.4% from 99.3% to 99.7%. The solution for 99.7% minimum tooling system reliability was obtained in 23 seconds.

Previous planning models on part assignment and tool allocation; for example Stecke (1981), Kusiak (1985), Sarin and Chen (1987), and Maheshwari (1992) did not consider tooling system reliability levels. However, results from this example problem, Table 3.6 through Table 3.10, show that the tooling system reliability level has significant impact on part assignment and tool allocation decisions in FMS. Therefore, disregarding tooling system reliability considerations at the planning level may result in unrealistic solutions.

Table 3.5 Example Problem 1, Part Routing of the Different Part Types and Required Operations, No Tool Sharing

	Part Type 1				Part Type 2				Part Type 3				Part Type 4			
	Operation number				Operation number				Operation number				Operation number			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Machine																
1	0	60	*	10	53	48	50	48	32	*	*	40	*	10	*	0
2	15	0	40	39	7	*	0	0	*	*	20	0	0	20	0	40
3	45	0	20	*	*	12	10	12	0	15	*	*	40	*	*	0
4	*	*	*	11	*	*	*	*	8	25	20	*	*	10	40	*

Table 3.6 Example Problem 1, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
80%	31	30	31	30	82567
90%	34	35	34	34	85292
95%	38	38	38	38	89367
97%	41	42	41	41	92342
98.8%	45	44	44	44	95542
99.3%	47	47	48	47	98567
99.7%	50	50	50	49	102042

Table 3.7 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
1	4	5	5	6	7	7	7
3	5	4	5	5	6	6	7
5	4	5	5	6	6	6	7
7	4	5	5	6	6	7	7
10	4	4	5	5	6	6	6
12	6	6	7	7	8	8	9
16	4	5	6	6	6	7	7

Table 3.8 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
1	4	5	5	6	6	7	7
6	5	6	7	7	8	8	8
7	5	6	6	7	7	7	8
10	4	5	5	6	6	6	7
11	4	4	5	5	5	6	6
19	4	4	5	5	6	6	7
20	4	5	5	6	6	7	7

Table 3.9 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
2	5	5	6	6	7	7	8
4	5	5	6	6	6	8	8
6	4	5	6	6	7	7	7
8	5	5	5	6	6	7	7
9	4	5	5	6	6	7	7
12	4	4	5	5	6	6	6
17	4	5	5	6	6	6	7

Table 3.10 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
5	4	5	5	6	6	7	7
9	4	4	5	6	6	6	7
11	5	6	7	7	7	8	8
13	5	5	6	6	7	7	8
14	5	6	7	7	8	8	8
15	4	4	4	5	5	6	6
18	3	4	4	4	5	5	5

3.14 Example Problem 2

This example problem and as can be seen from Table 1 in the appendix, consists of 5 part types (namely parts 2, 4, 13, 17 and 18). The demand for these 5 part types is 20, 18, 12, 20 and 22 respectively. Tool magazine capacity of each machine is limited to 50. Table 2 of the appendix, provides machine and cutting tool compatibility matrix as well as inventory for all tools available in the system. Table 3 and Table 4 of the appendix provide operation times (min) of parts on machines using different tools and operation cost ($) of parts on machines using different tools. Comparison of the results is presented in this chapter. Results were evaluated to show the impact of tooling system reliability levels on cost, number of tools required and parts and operations assignment. The results are then compared to those achieved using genetic algorithm model in chapter 5. This chapter also shows the utilization of presented models in forecasting overall number of tools required for a given system to satisfy tooling system reliability requirements and seek cost minimization.

3.14.1 Results of Example Problem 2

The problem was solved using LINGO software optimization package, the results are summarized in Table 3.11 through Table 3.16. Information regarding demand, cost of different tool types, tool life and tool failure parameters are taken from literature. For example, the assignment for part type 2 with minimum tooling system reliability considerations is:

- Operation 1, all 20 units are processed on machine 1 using tool number 16.
- Operation 2, all 20 units are processed on machine 1 using tool number 12.
- Operation 3, 12 units are processed on machine 1 using tool number 37 and 8 units are processed on machine 4 using tool number 37.
- Operation 4, 16 units are processed on machine 1 using tool number 7 and 4 units are processed on machine 1 using tool number 33.
- Operation 5, 10 units are processed on machine 1 using tool number 16 and 10 units are processed on machine 4 using tool number 16.

Tool allocation for various different tooling system reliability levels are given in Table 3.13 through Table 3.16. The model was solved for various values of minimum required tooling system reliability. The cost of operation was observed. Also the number of tool slots in the machine used up for the operation is observed, Table 3.12 through Table 3.16 show redundancies used vs required tooling system reliability on machines 1 through 4 respectively. Table 3.12 presents effect of tooling system reliability on magazine occupancy and total cost. In this example problem, none of the machine tool magazines was utilized fully. The solution for 90% minimum tooling system reliability was obtained in 53 seconds for a total cost of 145063.

Table 3.11 Example Problem 2, Part Assignments with Tooling System Reliability, No Tool Sharing

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	20	*	*	20	*	12	16	4	10	*		
	2	x	x	*	*	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	*	*	x	x	*	8	*	*	10	*		
	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	17			
Part 4	Mach.												
	1	*	*	x	x	x	x	18	x	x			
	2	x	x	12	*	*	*	x	15	3			
	3	x	x	6	*	18	*	x	*	*			
	4	18	*	x	x	x	x	*	x	x			
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	12	x	x	x	x	*				
	2	*	*	*	x	x	12	*	x				
	3	8	4	x	*	*	*	*	x				
	4	x	x	x	6	6	x	x	12				
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	8	x	x	x	x	x	x	x	x	13	*
	2	x	x	20	*	*	*	14	6	20	*	x	x
	3	x	x	*	*	10	10	*	*	*	*	x	x
	4	12	*	x	x	x	x	x	x	x	x	*	7
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	*	*	*	10	x	x	x		
	2	x	x	14	x	x	x	x	15	*	18		
	3	12	10	8	x	x	x	x	*	7	4		
	4	*	*	x	22	*	*	12	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.12 Example Problem 2, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
88%	37	36	36	36	133838
89%	41	40	39	39	138563
90%	48	46	45	46	145063
> 90%	No Feasible Solution Found				

Table 3.13 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	7	11	12	16	27	33	37	48	49
Reliability Level									
88%	4	4	4	5	5	3	5	4	3
89%	4	4	4	6	6	4	5	5	3
90%	5	5	5	7	6	5	6	5	4
> 90%	No Feasible Solution Found								

Table 3.14 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	1	5	10	17	20	28	32	34	47
Reliability Level									
88%	4	4	4	4	5	4	5	3	3
89%	5	5	4	4	5	4	5	4	4
90%	6	6	5	5	6	5	5	4	4
> 90%	No Feasible Solution Found								

Table 3.15 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	5	13	19	20	21	26	32	40	46
Reliability Level									
88%	4	4	5	5	4	3	3	4	4
89%	5	4	5	5	4	4	4	4	4
90%	5	5	6	6	4	5	4	5	5
> 90%	No Feasible Solution Found								

Table 3.16 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	7	16	19	37	40	42	43
Reliability Level								
88%	4	4	6	4	5	4	5	4
89%	5	4	6	4	5	5	5	5
90%	5	5	7	5	6	6	7	5
> 90%	No Feasible Solution Found							

3.14.2 Example Problem 2, Part Assignment

Eight different sets of part assignment and tool allocation problems were solved. Each problem was solved for various tooling system reliability levels. The planning model parameters were the same for all problems. The processing cost for an operation was determined on the basis of machine and part-cutting tool combination. Table 3.11 gives part assignments of different part types on different machines utilizing different tool types for example problem number two.

3.14.3 Example Problem 2, Tool Allocation

The tool allocation results for example number 2, are provided in Table 3.12 through Table 3.16. These tables include tools required to carry different required operations while maintaining minimum tooling system reliability. The assigned parts on the machine and required minimum tooling system reliability generate the tool requirements on any machine with minimum cost as the objective. However, a completely filled tool magazine would necessarily mean that total assigned processing time is large on that particular machine. This is because of the fact that tool allocation depends upon other parameters including tool life; tool inventory, magazine size and most importantly required minimum tooling system reliability. More efficient machine tool magazines are assigned higher workloads as can be seen from Table 3.16. Consequently, larger numbers of tools are needed on these machines.

The tool magazines of all machines were not filled to their capacity in all cases. There were several types of tools available for allocation, however, not all types were needed in this test problem. The alternate tool for a given operation is utilized only if the primary tools for that operation are loaded. In general, alternate tools are allocated when tool inventory constraint for primary tool is binding.

The applicability of the developed model to solve FMS part assignment and tool loading problem with tooling system reliability considerations was tested on eight problems from the literature. A change in tooling system requirements may result in a new solution, hence, part assignment is fixed and effect on tooling requirements is monitored for increased tooling system reliability levels (this is done in order to limit the number of combinations which will make analysis tediously long). Since the effect of changing tooling reliability levels is investigated in this section.

The effect of tooling system reliability on cost, part assignment and tool allocation is investigated by incrementing tooling system reliability by 1% and yet even smaller than 1% increments at the time. The other parameters remain constant. The model is run and part assignment, tool loading and overall cost are determined and summarized, Table 3.11 through Table 3.16. In all problems considered, increasing or decreasing the tooling system reliability requirement has direct effect on part assignment of different part types, tool allocation of different tools as well as overall cost.

3.15 Example Problem 3

Example problem 3 consists of five part types; these are part type 4, 9, 10, 11 and 14. Information about operation times, processing cost and tooling parameters are given in Tables 3 and 4 of the appendix, respectively. The results are presented in Table 3.17 through Table 3.22. As can be seen from tabulated results, none of the machine tool magazines were at full capacity. Each machine tool magazine is restricted to 50 tools. The solution was obtained in 180 seconds for 92% minimum tooling system reliability. None of the machine tool magazines was utilized fully.

Table 3.17 Example Problem 3, Part Assignments, No Tool Sharing

	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	16			
Part 4	Mach.												
	1	18	*	x	x	x	x	14	x	12			
	2	x	x	14	*	18	*	x	*	*			
	3	x	x	*	4	*	*	x	*	*			
	4	*	*	x	x	x	x	4	x	6			
	Op.	1	2	3	3								
	Tool	27	24	8	23								
Part 9	Mach.												
	1	*	5	x	x								
	2	x	x	x	x								
	3	x	x	6	6								
	4	12	7	*	*								
	Op.	1	1	2	2	3	4	5	5	6	6	7	8
	Tool	42	48	18	50	49	14	7	33	5	39	38	9
Part 10	Mach.												
	1	18	*	x	x	*	*	10	*	x	x	x	9
	2	x	x	*	*	18	x	x	x	15	3	6	9
	3	x	x	6	12	x	x	x	x	*	*	12	x
	4	*	*	x	x	x	18	*	8	x	x	x	x
	Op.	1	1	2	3	4	4	5	6	7	7		
	Tool	10	22	38	27	28	46	49	3	9	45		
Part 11	Mach.												
	1	x	x	x	*	x	x	*	6	*	*		
	2	4	*	20	x	*	13	20	x	20	*		
	3	*	16	*	x	*	7	x	x	x	x		
	4	x	x	x	20	x	x	x	14	x	x		
	Op.	1	1	2	2	3	3						
	Tool	4	37	28	46	16	36						
Part 14	Mach.												
	1	7	*	x	x	*	*						
	2	x	x	*	13	x	x						
	3	x	x	5	*	x	x						
	4	11	*	x	x	*	18						

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.18 Example Problem 3, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
90%	35	37	37	36	128633
91%	38	40	40	40	129504
92%	42	44	47	46	135173
> 92%	No Feasible Solution Found				

Table 3.19 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	3	4	7	9	16	24	27	42
Reliability Level								
90%	4	4	5	4	4	4	5	5
91%	4	5	6	4	5	4	5	5
92%	5	5	6	5	5	5	6	5
> 92%	No Feasible Solution Found							

Table 3.20 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	9	10	21	38	39	46	49
Reliability Level								
90%	4	5	4	4	6	5	4	5
91%	4	6	4	5	6	5	4	6
92%	4	6	5	5	7	6	5	6
> 92%	No Feasible Solution Found							

Table 3.21 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	8	18	22	23	28	38	39	46	50
Reliability Level									
90%	5	4	4	4	5	4	4	3	4
91%	6	4	4	4	5	5	4	4	4
92%	6	5	4	5	6	5	6	5	5
> 92%	No Feasible Solution Found								

Table 3.22 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	4	14	16	24	27	33	36
Reliability Level								
90%	5	4	5	4	5	5	4	4
91%	5	5	5	4	5	6	5	5
92%	6	6	6	5	6	6	6	5
> 92%	No Feasible Solution Found							

3.16 Example Problem 4

Example problem 4 consists of five part types; these are part types 5, 7, 14, 16 and 18. Information about operation times, processing cost and tooling parameters are given in Tables 3 and Table 4 of the appendix, respectively. Tool magazine capacity of each machine is limited to 50 tools. The results are presented in Table 3.23 through Table 3.28. As can be seen from Table 3.24, none of the machine tool magazines was utilized to full capacity. Solution for 95% minimum tooling system reliability was obtained in 26 seconds. None of the machine tool magazines was utilized to its full capacity.

Table 3.23 Example Problem 4, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	4	37	49	18	50	9	45	21	25	14
Part 5	Mach.										
	1	4	4	8	x	x	*	12	x	x	4
	2	x	x	4	*	3	*	*	5	*	x
	3	x	x	x	9	*	x	x	*	7	x
	4	*	4	x	x	x	x	x	x	x	8
	Op.	1	2	2	3	3	4	5	5	6	6
	Tool	49	10	22	42	48	44	31	41	6	29
Part 7	Mach.										
	1	14	x	x	8	*	7	x	x	*	14
	2	*	*	*	x	x	x	8	*	x	x
	3	x	14	*	x	x	x	7	*	x	x
	4	x	x	*	6	*	7	x	x	*	*
	Op.	1	1	2	2	3	3				
	Tool	4	37	28	46	16	36				
Part 14	Mach.										
	1	8	*	x	x	*	*				
	2	x	x	11	7	x	x				
	3	x	x	*	*	x	x				
	4	10	*	x	x	18	*				
	Op.	1	1	2	2	3	3				
	Tool	7	33	28	46	1	17				
Part 16	Mach.										
	1	*	*	x	x	x	x				
	2	x	x	*	6	*	*				
	3	x	x	*	6	*	12				
	4	12	*	x	x	x	x				
	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	19	40	32	16	36	4	37	28	46	20
Part 18	Mach.										
	1	x	x	12	*	*	*	9	x	x	x
	2	x	x	6	x	x	x	x	12	*	11
	3	10	6	4	x	x	x	x	*	10	11
	4	*	6	x	*	22	13	*	x	x	x

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.24 Example Problem 4, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
93%	34	34	34	35	109872
94%	40	39	38	39	121797
95%	47	46	44	45	128500
> 95%	No Feasible Solution Found				

Table 3.25 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	14	29	32	37	44	45	49
Reliability Level								
93%	4	4	4	4	5	4	5	5
94%	5	5	5	4	5	4	6	6
95%	6	5	6	5	6	5	7	7
> 95%	No Feasible Solution Found							

Table 3.26 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	20	21	28	31	32	46	49	50
Reliability Level								
93%	5	5	4	4	4	3	5	4
94%	6	6	4	5	4	4	5	5
95%	7	6	5	6	5	5	6	5
> 95%	No Feasible Solution Found							

Table 3.27 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	10	18	19	25	31	32	40	46
Reliability Level								
93%	5	4	5	5	4	4	3	4
94%	6	4	5	5	4	5	4	5
95%	6	5	6	6	5	5	5	6
> 95%	No Feasible Solution Found							

Table 3.28 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	4	14	16	36	37	40	42	44
Reliability Level								
93%	5	4	5	4	5	5	3	4
94%	6	5	5	4	5	5	4	5
95%	7	6	6	5	6	6	4	5
> 95%	No Feasible Solution Found							

3.17 Example Problem 5

Example problem 5 consists of five part types; these are part type 2, 13, 14, 17, and 18. Information about operation times, processing cost and tooling parameters are given in Table 3 and Table 4 of the appendix, respectively. Tool magazine capacity is limited to 50 tools. The results are presented in Table 3.29 through Table 3.34. The solution for minimum tooling system reliability of 94% was obtained in 74 seconds. None of the machine tool magazines was utilized to full capacity.

Table 3.29 Example Problem 5, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	15	*	20	*	*	20	14	6	10	*		
	2	x	x	*	*	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	*	5	x	x	*	*	*	*	x	10		
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	12	x	x	x	x	*				
	2	8	*	*	x	x	6	*	x				
	3	4	*	x	*	*	6	*	x				
	4	x	x	x	*	12	x	x	12				
	Op.	1	1	2	2	3	3						
	Tool	4	37	28	46	16	36						
Part 14	Mach.												
	1	18	*	x	x	6	*						
	2	x	x	*	7	x	x						
	3	x	x	*	11	x	x						
	4	*	*	x	x	12	*						
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	*	x	x	x	x	x	x	x	x	20	*
	2	x	x	12	*	10	*	*	15	*	20	x	x
	3	x	x	8	*	10	*	5	*	*	*	x	x
	4	20	*	x	x	x	x	x	x	x	x	*	*
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	15	*	*	*	x	x	x		
	2	x	x	22	x	x	x	x	16	*	6		
	3	*	12	*	x	x	x	x	6	*	16		
	4	*	10	x	*	7	16	8	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.30 Example Problem 5, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
92%	36	32	28	31	126544
93%	39	37	32	36	131269
94%	45	42	38	43	136269
> 94%	No Feasible Solution Found				

Table 3.31 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	2	4	7	11	16	33	37	49
Reliability Level								
92%	5	5	4	5	6	4	4	3
93%	6	5	4	6	6	4	4	4
94%	7	6	5	6	7	5	5	4
> 94%	No Feasible Solution Found							

Table 3.32 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	10	13	17	20	28	32	46	47
Reliability Level								
92%	5	5	4	4	4	3	3	4
93%	6	5	5	4	4	4	4	5
94%	6	6	5	5	5	4	5	6
> 94%	No Feasible Solution Found							

Table 3.33 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	10	13	20	28	34	40	46
Reliability Level							
92%	5	5	4	4	3	3	4
93%	6	5	5	4	4	4	4
94%	7	6	6	5	4	5	5
> 94%	No Feasible Solution Found						

Table 3.34 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	4	16	36	37	40	42
Reliability Level							
92%	4	5	4	6	3	5	4
93%	5	6	4	6	4	6	5
94%	6	7	5	7	5	7	6
> 94%	No Feasible Solution Found						

3.18 Example Problem 6

Example problem 6 consists of four part types, these are part type 1, 3, 19 and 20. In this case, maximum tool magazine capacity was restricted to 40 tool slots. Information about operation times, processing cost and tooling parameters are given in Table 3 and 4 of the appendix, respectively. The results are presented in Table 3.35 through Table 3.40. For 96% minimum tooling system reliability, solution was obtained in 101 seconds. Tool magazine of machine 2 was utilized fully.

Table 3.35 Example Problem 6, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4			
	Tool	4	37	24	16	36	5	39			
Part 1	Mach.										
	1	10	6	16	7	5	x	x			
	2	x	x	x	x	x	8	*			
	3	x	x	x	x	x	*	8			
	4	*	*	*	4	*	x	x			
	Op.	1	2	3	3	4	4	5	5	6	6
	Tool	20	6	21	25	19	40	18	50	7	33
Part 3	Mach.										
	1	x	x	x	x	x	x	x	x	6	*
	2	12	x	4	*	x	x	*	*	x	x
	3	*	*	8	*	*	*	*	12	x	x
	4	x	12	x	x	6	6	x	x	*	6
	Op.	1	1	2	3	3	4				
	Tool	21	25	14	5	39	38				
Part 19	Mach.										
	1	x	x	6	x	x	x				
	2	4	*	x	*	5	12				
	3	8	*	x	*	7	*				
	4	x	x	6	x	x	x				
	Op.	1	1	2	3	3	4	4			
	Tool	10	22	24	30	35	28	46			
Part 20	Mach.										
	1	x	x	9	x	x	x	x			
	2	*	*	*	6	*	*	8			
	3	8	8	x	10	*	*	8			
	4	x	x	7	x	x	x	x			

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.36 Example Problem 6, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
94%	26	30	30	26	87724
95%	29	34	33	29	90949
96%	34	40	39	34	96449
> 96%	No Feasible Solution Found				

Table 3.37 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	7	14	16	24	36	37
Reliability Level							
94%	3	3	4	4	5	3	4
95%	4	3	5	5	5	3	4
96%	5	4	6	5	6	3	5
> 96%	No Feasible Solution Found						

Table 3.38 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	20	21	30	38	39	46
Reliability Level							
94%	5	5	6	4	4	3	3
95%	6	5	7	4	5	4	3
96%	6	6	8	5	6	5	4
> 96%	No Feasible Solution Found						

Table 3.39 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing Allowed

Tool #	10	21	22	30	39	46	50
Reliability Level							
94%	4	5	3	4	6	4	4
95%	4	5	3	5	6	5	5
96%	5	6	4	5	7	6	6
> 96%	No Feasible Solution Found						

Table 3.40 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing Allowed

Tool #	6	14	16	19	24	33	40
Reliability Level							
94%	5	3	4	3	4	4	3
95%	6	3	4	4	5	4	3
96%	7	4	5	4	6	4	4
> 96%	No Feasible Solution Found						

3.19 Example Problem 7

Example problem 7 consists of four part types, these are part type 1, 6, 8 and 14. In this example problem, machine tool magazine capacity was set to maximum of 45 tool slots. Information about operation times, processing cost and tooling parameters are given in Table 3 and 4 of the appendix, respectively. The results are presented in Table 3.41 through Table 3.46. The solution for minimum tooling system reliability of 98% was reached in 306 seconds. In this case, none of the machine tool magazines was utilized fully.

Table 3.41 Example Problem 7, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4	
	Tool	4	37	24	16	36	5	39	
Part 1	Mach.								
	1	8	*	9	4	*	x	x	
	2	x	x	x	x	x	8	8	
	3	x	x	x	x	x	*	*	
	4	8	*	7	4	8	x	x	
	Op.	1	1	2	2				
	Tool	18	50	31	41				
Part 6	Mach.								
	1	5	x	x	x				
	2	5	5	x	x				
	3	*	5	10	10				
	4	x	x	*	*				
	Op.	1	2	3	4	4	5	5	6
	Tool	6	44	24	15	29	8	23	14
Part 8	Mach.								
	1	x	x	15	*	12	x	x	8
	2	x	5	x	x	x	x	x	x
	3	15	x	x	x	x	9	6	x
	4	*	10	*	*	3	*	*	7
	Op.	1	1	2	2	3	3		
	Tool	4	37	28	46	16	36		
Part 14	Mach.								
	1	8	*	x	x	*	9		
	2	x	x	6	6	x	x		
	3	x	x	6	*	x	x		
	4	*	10	x	x	*	9		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.42 Example Problem 7, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
96%	31	30	30	33	83564
97%	35	34	33	37	87328
98%	41	39	39	43	92772
> 98%	No Feasible Solution Found				

Table 3.43 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	14	16	18	24	29	36
Reliability Level							
96%	4	4	4	5	5	4	5
97%	4	5	5	6	6	4	5
98%	5	6	6	7	6	5	6
> 98%	No Feasible Solution Found						

Table 3.44 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	18	28	39	44	46	50
Reliability Level							
96%	5	4	4	4	4	6	3
97%	6	5	4	5	4	6	4
98%	7	6	5	5	5	7	4
> 98%	No Feasible Solution Found						

Table 3.45 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	6	8	23	28	31	41	50
Reliability Level							
96%	5	4	4	5	4	4	4
97%	6	4	5	5	4	5	4
98%	7	5	6	6	4	6	5
> 98%	No Feasible Solution Found						

Table 3.46 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	4	16	24	29	36	37	44
Reliability Level							
96%	4	5	5	4	5	5	5
97%	5	5	5	5	5	6	6
98%	6	5	6	6	6	7	7
> 98%	No Feasible Solution Found						

3.20 Example Problem 8

Example problem 8 consists of five part types, these are part type 1, 4, 13, 15 and 20. For this example problem, maximum tool magazine capacity is limited to 45 tool slots. Information about operation times, processing cost and tooling parameters are given in Tables 3 and 4 of the appendix, respectively. The results are presented in Table 3.47 through Table 3.52. The solution for minimum tooling system reliability of 93% was obtained in 776 seconds, again none of the machine tool magazines was utilized to full capacity.

Table 3.47 Example Problem 8, Part Assignments with Tooling System Reliability considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4			
	Tool	4	37	24	16	36	5	39			
Part 1	Mach.										
	1	16	*	10	16	*	x	x			
	2	x	x	x	x	x	*	*			
	3	x	x	x	x	x	11	5			
	4	*	*	6	*	*	x	x			
	Op.	1	1	2	3	3	4	4	5	5	
	Tool	7	33	5	39	21	25	27	1	17	
Part 4	Mach.										
	1	*	*	x	x	x	x	18	x	x	
	2	x	*	12	*	12	*	x	*	18	
	3	x	x	6	6	*	*	x	*	*	
	4	18	x	x	x	x	x	*	x	x	
	Op.	1	1	2	3	3	4	4	5		
	Tool	13	26	49	19	40	10	22	3		
Part 13	Mach.										
	1	*	x	12	x	x	x	x	*		
	2	*	*	*	x	x	12	*	x		
	3	x	12	x	*	*	*	*	x		
	4	x	x	x	12	*	x	x	12		
	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	11	43	14	30	35	7	33	18	50	32
Part 15	Mach.										
	1	*	7	9	x	x	*	*	x	x	x
	2	x	x	x	*	*	x	*	6	*	*
	3	x	x	x	12	*	x	8	*	6	12
	4	5	*	3	x	x	*	4	x	x	x
	Op.	1	1	2	3	3	4	4			
	Tool	10	22	24	30	35	28	46			
Part 20	Mach.										
	1	x	x	4	x	x	x	x			
	2	16	*	x	*	10	16	*			
	3	*	*	x	6	*	*	*			
	4	x	x	12	x	x	x	x			

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.48 Example Problem 8, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
91%	29	31	30	29	124819
92%	32	35	34	32	130319
93%	38	40	40	38	138594
> 93%	No Feasible Solution Found				

Table 3.49 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	14	16	24	27	43	49
Reliability Level							
91%	5	3	4	6	4	4	3
92%	6	4	5	6	4	4	3
93%	6	5	6	7	5	5	4
> 93%	No Feasible Solution Found						

Table 3.50 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	10	17	18	21	28	35
Reliability Level							
91%	4	6	4	5	4	4	4
92%	4	7	4	6	5	5	4
93%	4	7	5	7	6	6	5
> 93%	No Feasible Solution Found						

Table 3.51 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	5	26	30	32	33	39	50
Reliability Level							
91%	6	3	5	4	4	4	4
92%	6	4	6	4	4	5	5
93%	7	5	6	5	6	6	5
> 93%	No Feasible Solution Found						

Table 3.52 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	7	11	14	19	24	33
Reliability Level							
91%	4	5	4	3	4	5	4
92%	5	5	4	4	4	6	4
93%	6	6	4	5	5	7	5
> 93%	No Feasible Solution Found						

3.21 Model II; Cost Minimization, Tool Sharing Allowed

When tool sharing is permitted, all tools within the system are available to all other machines in the entire system. However, tools will need to be passed back and forth between machines as required and to serve as means of reducing overall tooling system cost. Tools transportation from one machine to the other involves lost production time, for both donor and recipient machines. This system configuration includes tool transporter as a new piece of hardware. Each time a tool is transported from one machine to the other, tool transporter carries away the worn tool into a specified location on the tool transporter device. Therefore, tool magazine capacity of any tool is not violated at any given time. Each tool on any given machine is actually backed-up by all other tools in the system, this in turn reduces the required number of tools in the system. In such case and for reliability analysis, the aggregate processing time is independent of the machine on which any given tool is loaded. The tooling reliability in this case is a function of cumulative hazard rates and total number of spares for each tool type. The model was solved for various values of minimum required tooling system reliability. The total cost was observed for different values of minimum tooling system reliability levels. A tool transporter is ready to transport tools form tool storage room to different machines as well as to exchange tools amongst machines. If a particular tool is 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 model assigns parts to machines for different required operations and allocates tool and tool spares to different machines while minimizing total cost of operation. In order to force tool sharing between machines, tool life was reduced by one half. To be able to compare the two cases no tool sharing and with tool sharing, model was reworked on the modified problem and results were compared.

Minimize

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{s=1}^{S} C_{ijks} \;.\; t_{ijks} \;.\; X_{ijks} \;+\; \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{m_s=0}^{M_s} C_s \;.\; m_s \;.\; Y_{kslm_s}$$

Subject to

Tool life requirements

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{m_s=0}^{M_s} t_{ijks} \;.\; X_{ijks} \;\le\; T_s \;.\; m_s \;.\; Y_{klsm_s} \qquad \forall \;, s \qquad (3.12)$$

Upper limit of tools available

$$\sum_{k=1}^{K}\sum_{m_s=0}^{M} m_s \;.\; Y_{klsm_s} \;\le\; A_s \qquad \forall \; s \qquad (3.13)$$

Magazine capacity

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m_s=0}^{M_s} Z_s \;.\; m_s \;.\; Y_{klsm_s} \;\le\; E_k \qquad \forall \; k \qquad (3.14)$$

Out put requirements of each part type for a given production period

$$\sum_{k=1}^{K}\sum_{s=1}^{S} X_{ijks} \;=\; q_i \qquad \forall \; i, j \qquad (3.15)$$

Spare Tool requirements

$$\sum_{k=1}^{K}\sum_{m_s=0}^{M_s} Y_{klsm_s} \;=\; 1 \qquad \forall \; s \qquad (3.16)$$

Minimum Tooling System Reliability Requirements

$$\prod_{k=1}^{K} \prod_{s=1}^{S} \prod_{m_s=0}^{M_s} R_{ksm_s} \cdot Y_{klsm_s} \geq R_{Rq} \qquad \forall s \tag{3.17}$$

The linearized form of equation (3.17) is then as follows;

$$\sum_{k=1}^{K} \sum_{s=1}^{S} \sum_{m_s=0}^{M_s} \log R_{ksm_s} \cdot Y_{klsm_s} \geq \log R_{Rq} \qquad \forall s \tag{3.18}$$

Where, X_{ijks} are integers and Y_{kslm_s} are 0/1 integers.

Where t is the cumulative working time for tool type s in the system. The objective function of this model will minimize the overall tooling system cost when tool sharing is allowed for a preset tooling system reliability, which again is governed by the minimum tooling system constraint.

$$R^{m_s}(t) = \prod_{k=1}^{K} \prod_{s=1}^{S} \left\{ \sum_{m_s=0}^{M_s-1} \frac{\left(\int_0^t \lambda(t)_s \, dt\right)^{m_s} \exp\left[-\int_0^t \lambda(t)_s \, dt\right]}{m_s!} \right\} \tag{3.19}$$

3.22 Example problem 1, Tool Sharing Allowed

Example problem one was again solved using LINGO optimization software with tool sharing allowed and for various tooling system reliability levels. Each machine has a tool magazine of size 50 tool slots. There are four part types. The production requirements of the four part types are 60, 60, 40 and 40 respectively. Twenty different tool types are available for usage in carrying required operations. Table 3.1 provides part-operation and tool compatibility matrix. Table 3.2 gives machine-tool compatibility matrix. Processing times in minutes and processing cost in dollars of each operation of a part type on a machine using different tool types are shown in Table 3.3 and Table 3.4 respectively. If a particular tool is required on a machine is not available on its tool magazine, tool transporter could bring that tool from another machine. The model assigns tools to be allocated to different machines in the system. Routes parts to different machines for required operations and decides number of tool copies required for a particular tooling system reliability while minimizing over all tooling and processing cost.

Table 3.53 Example Problem 1, Part Routing of the Different Part Types and Required Operations, Tool Sharing Allowed

	Part Type 1				Part Type 2				Part Type 3				Part Type 4			
	Operation number				Operation number				Operation number				Operation number			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Machine																
1	0	60	*	0	53	48	50	48	24	*	*	40	*	10	*	0
2	15	0	40	53	7	*	0	0	*	*	20	0	0	15	0	40
3	45	0	20	*	*	16	10	12	0	17	*	*	40	*	*	0
4	*	*	*	12	*	*	*	*	16	23	20	*	*	15	40	*

3.22.1 Analysis of the Results, Example Problem 1

The model was solved for different values of tooling system reliability and the total cost was observed. Also the number of tool slots in each machine in the system was observed, results are tabulated in Table 3.54 and Table 3.55.

To force tool transfer in the system, tool life of different tools was reduced to half. It is seen that as required tooling system reliability levels rose to higher values, different tools needed to be allocated on machines where the tools are not being used, and are transported by the tool transporter.

Table 3.54 Example Problem 1, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, Tool Sharing Allowed

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
90%	38	36	36	34	85910
93%	40	39	39	38	88705
97%	43	42	42	41	93845
98%	46	45	44	45	95280
99.3%	48	47	48	47	97170
99.5%	50	50	50	50	101375

Table 3.55 Example Problem 1, Redundancies Used, v/s Required Reliability, Tool Sharing Allowed

M/C #	Tool #	90%	93%	97%	98%	99.3%	99.5%
MACHINE 1	1	6	6	6	7	7	7
	3	5	5	6	6	6	6
	5	5	5	5	6	6	6
	7	6	7	7	8	8	9
	10	4	5	5	5	5	6
	12	5	5	6	6	7	7
	16	7	7	8	8	9	9
MACHINE 2	1	5	5	5	6	6	6
	4	6	6	6	7	7	8
	6	5	6	7	7	7	8
	7	5	5	6	7	7	7
	10	4	5	5	5	6	6
	11	5	6	6	6	7	7
	14	6	6	6	7	7	8
MACHINE 3	2	4	5	5	5	6	7
	4	5	5	5	6	6	7
	6	6	6	6	7	8	9
	8	5	5	5	6	6	6
	9	5	5	6	6	7	7
	12	6	6	7	7	8	8
	17	4	5	6	6	6	6
MACHINE 4	5	6	6	7	7	8	9
	9	4	5	6	6	7	7
	11	4	5	5	5	6	6
	13	5	5	6	6	6	7
	14	5	6	6	6	7	7
	15	5	5	5	6	6	6
	18	5	6	7	7	7	8

3.23 Example Problem 2, Tool Sharing Allowed

Table one in appendix, contains data for this problem set. Example problem 2 consists of five part types; these are part types 2, 4, 13, 17 and 18. The demand for the five part types is 20, 18, 12, 20, and 22 parts respectively. The tool magazine capacity of each machine in the system is limited to a maximum of 50. Machine and cutting tool compatibility matrix is given in Table 2 of appendix. Operation times in minutes as well as operation cost in dollars for processing of different operations of part types on different machines using different tool types is given in Table 3 and Table 4 of appendix, respectively. Example two was solved for various different minimum tooling system reliability levels. Results are analyzed to show the effect of tooling system reliability levels on cost, number of tools required and parts and operations assignment. In chapter 5 the results are compared to those achieved when genetic algorithm model is used. This chapter also shows the utilization of presented models in forecasting overall number of tools required for a given system when tool sharing is feasible.

3.23.1 Results of Example Problem 2

Table 3.56 Example Problem 2, Part Assignments, Tool Sharing Allowed

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	16	*	10	*	13	*	13	7	10	*		
	2	x	x	10	*	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	4	*	x	x	*	7	*	*	10	*		
	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	17			
Part 4	Mach.												
	1	*	8	x	x	x	x	18	x	x			
	2	x	x	*	6	12	*	x	*	*			
	3	x	x	12	*	6	*	x	11	7			
	4	10	*	x	x	x	x	*	x	x			
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	12	x	x	x	x	*				
	2	*	*	*	x	x	*	7	x				
	3	*	12	x	*	*	*	5	x				
	4	x	x	x	*	12	x	x	12				
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	8	x	x	x	x	x	x	x	x	13	*
	2	x	x	*	10	*	11	*	*	*	*	x	x
	3	x	x	*	10	*	9	*	20	9	11	x	x
	4	12	*	x	x	x	x	x	x	x	x	*	7
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	8	*	*	0	x	x	x		
	2	x	x	14	x	x	x	x	*	12	22		
	3	*	*	8	x	x	x	x	*	10	*		
	4	10	12	x	14	*	*	22	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 3.57 Example Problem 2, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, Tool Sharing Allowed

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
88%	43	42	40	40	136281
89%	48	46	43	44	139111
90%	50	50	50	50	142030

Table 3.58 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 1, Tool Sharing Allowed

Tool #	2	4	7	11	16	27	33	48	49
Reliability Level									
88%	4	5	5	4	6	4	4	6	4
89%	4	5	4	6	7	5	4	6	5
90%	5	6	5	6	7	5	5	6	5
> 90%	No Feasible Solution Found								

Table 3.59 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 2, Tool Sharing Allowed

Tool #	2	20	21	22	26	32	39	46	47
Reliability Level									
88%	5	5	3	4	4	5	5	4	5
89%	5	6	4	4	5	6	5	4	5
90%	6	6	4	5	6	6	6	5	6
> 90%	No Feasible Solution Found								

Table 3.60 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 3, Tool Sharing Allowed

Tool #	1	5	17	21	22	26	32	46	47
Reliability Level									
88%	5	4	3	5	4	4	4	4	3
89%	5	4	4	5	5	4	4	4	4
90%	5	5	5	6	5	5	5	5	4
> 90%	No Feasible Solution Found								

Table 3.61 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 4, Tool Sharing Allowed

Tool #	3	7	16	19	37	40	42	43
Reliability Level								
88%	5	4	5	4	5	4	5	4
89%	6	5	5	4	5	5	5	5
90%	7	6	5	4	6	6	6	6
> 90%	No Feasible Solution Found							

There were several types of tools available for allocation, however, not all types were needed in this example problem. The alternate tool (i.e. tool that is less efficient/reliable in processing an operation) for a given operation is utilized only if all the primary tools for that operation are loaded. In general alternate tools are allocated only when tool inventory constraint for primary tool is binding.

CHAPTER 4

GENETIC ALGORITHM

4.1 Introduction

The literature is rich with models and algorithms developed for effective yet efficient solutions to FMS planning problems. These were mostly concerned with the number of iterations and time required to get an optimal or near optimal solutions. Solving part assignment and tool allocation problems in a FMS requires effective and efficient solution techniques, Maheshwari (1992). It is then more evident that when FMS part assignment and tool allocation problems are coupled with reliability constrains, such techniques are more so required. As stated by Johnson and Papadinitriou (1985) optimal solutions to linear integer programming models is an extraordinary assignment in terms of complexity and computer time requirements. In this chapter genetic algorithm model is developed to deal with this problem.

Genetic algorithms are among optimization techniques used successfully in solving NP-hard problems Goldberg (1989). Genetic algorithms are robust solution techniques that maintain a balance between efficiency and efficacy, which is necessary in optimization type problems such as the one on hand. Genetic algorithms maintain a population of potential solutions where all other methods progress from one single point in the search space to another. At each iteration a new point in the search space is examined and if this point provides an improved solution over the previous solution (point) it is then taken as the new improved solution for that particular iteration. Otherwise, some other neighborhood is selected and tested against the current solution.

A GA performs a multidimensional search by maintaining a population of potential solutions and encourages information creation and exchange between different directions. Utilizing past information, GAs direct their search through expected improved performance and achieve consistent and reliable results, Whitley (1998). At each iteration, relatively good solutions reproduce and bad solutions disappear. An evaluation function, fitness function or objective function is used to determine the quality of the solution on hand. For detailed information on genetic algorithms and their applications, refer to Gldberg (1989); Davis (1991); Beasley et al. (1993), Khuri et al. (1994), Gen and Cheng (1997) and Michalewicz (1994).

Many global optimization techniques were used to solve optimization type problems: Tabu Search (TS), Simulated Annealing (SA), and Genetic Algorithms (GA). GA offers several advantages over the other optimization techniques; some of these advantages can be summarized as follows:

1. GA is relatively easy to implement and modify since the inputs are, population size, number of generations, and genetic algorithm operators (namely, reproduction, crossover probabilities and mutation). Dige et al. (1993); SU and HSU (1998).
2. GA outperforms SA technique in both objective function value and CPU time, Skprin-Kapov (1992). GA also outperforms SA in objective function value, Kim and Kim (1996).
3. GA obtains global optimal solution, Chen and Srivastava (1994).

4. It is easy to combine with other techniques such as SA to form useful hybrid method for solving a wide range complex problems, SU and HSU (1998), Glover et al. (1995).

5. It is not sensitive to the initial solution, since initial solutions evolve towards optimal solution relatively quickly. Rao et al (1998).

6. It has successfully been applied to solve difficult and time consuming optimization problems, Goldberg (1989).

4.2 Need for Genetic Algorithm Model

The FMS models developed include two decision variables, these are part assignment and tool loading variables. For a system with four machining centers, four part types each requiring three operations, ten different tools and three tool copies of each tool type, there will be 1440 part assignment variables (4*4*3*10*3) and 120 tool allocation variables (4*10*3). Evidently many of these variables are equal to zero for any real life problem. However, the number of variables will still be beyond the ability of easy efficient solutions algorithms. These models though solvable are generally too large to be computationally feasible, Shanker and Tzen, (1987). Thus, practical use of these models requires efficient solution procedures (algorithms). It is worth noticing that available software packages are cost ineffective and require substantial non-realistic computational times. The following reasons will further support the need for more efficient and robust solution algorithms:

- Non existence of solution procedures for the FMS part assignment, tool-loading problem coupled with FMS tooling system reliability considerations.
- Large number of decision variables involved.
- High time complexity of the planning models as explained above.
- Need for high cost computer time and resources.
- Timely manner solutions.
- Relatively easy to understand and implement solutions.
- Works as tool for integrated part assignment, tool loading and reliability considerations.
- Solutions executed on a personal computer in real time.

4.3 Types of Genetic Algorithms

Different types of genetic algorithms have been developed, these vary, however, the basic building blocks for each GA remains to be the same. Two types of genetic algorithms are being used, the standard GA or some times called the traditional GA and the steady state GA.

4.3.1 Standard Genetic Algorithms

Standard genetic algorithms use binary encoding, generational reproduction and simple single point crossover and mutation operators. During reproduction parent string produce two offspring and vanish. Figure 4.1 shows the basic structure of a standard GA. The basic features of these genetic algorithms are as follows:

1. The population size remains the same throughout the iteration stages, two mating parents create two offspring and in turn they vanish, Holland (1975).
2. Reproduction is based on fitness value and crossover rate. Generations of strings are reproduced according to their fitness value and parent strings are selected according to crossover probability.
3. Higher chances of creating duplicate strings.
4. Multiple reproduction and recombination occurs at one time.

4.3.2 Steady State Genetic Algorithms

Several disadvantages are associated with standard genetic algorithms. After crossover takes place, parent strings are lost, and eventually all parent sets no longer exist, their children replace them. In this case there is a chance that best solutions are lost. Another disadvantage for standard genetic algorithms is the possibility of duplicate strings. A steady state genetic algorithm developed by Whitley and Kauth (1988) takes care of the two disadvantages associated with standard genetic algorithms. The software is called GENOCOP. The main features of steady state algorithms are:

1 All strings are ranked according to their fitness values.
2. One at a time recombination and replacement takes place in every generation.
3. For every generation, parent strings and their offspring remain and the worst solution in population dies.
4. Best solutions are kept, while, the worst solutions are discarded.

5. A selection bias is used to select parent strings. Since there is only one interaction at a time, it is very important to select the individuals from the population that will undergo recombination. Selection bias is used instead of crossover.
6. No chance for creating duplicate strings.

4.4 Genetic Algorithm Model

The mathematical models developed work efficiently on small size problems. However, as the problem size becomes larger, the computational times increase exponentially due to the increased number of integer variables. This in turn makes it impossible for carrying out on time decisions, a genetic algorithm is developed to reduce computational times required for achieving optimal or near optimal solutions for large size problems. There are several different algorithms that deal with the part assignment and tool loading problem, however, tooling system reliability coupled with the choice of multiple tool copies to boost overall tooling system reliability was not extensively studied. For the optimization problem with reliability constraint, the GA needs to contain the following components:

1. A genetic representation for the different potential solutions to the problem.
2. A procedure for creating initial population.
3. A fitness function to evaluate potential solutions.
4. Genetic operators for altering composition of off springs resulting from reproduction.

5. Parameter values such as population size, number of generations, crossover probability and location, etc.

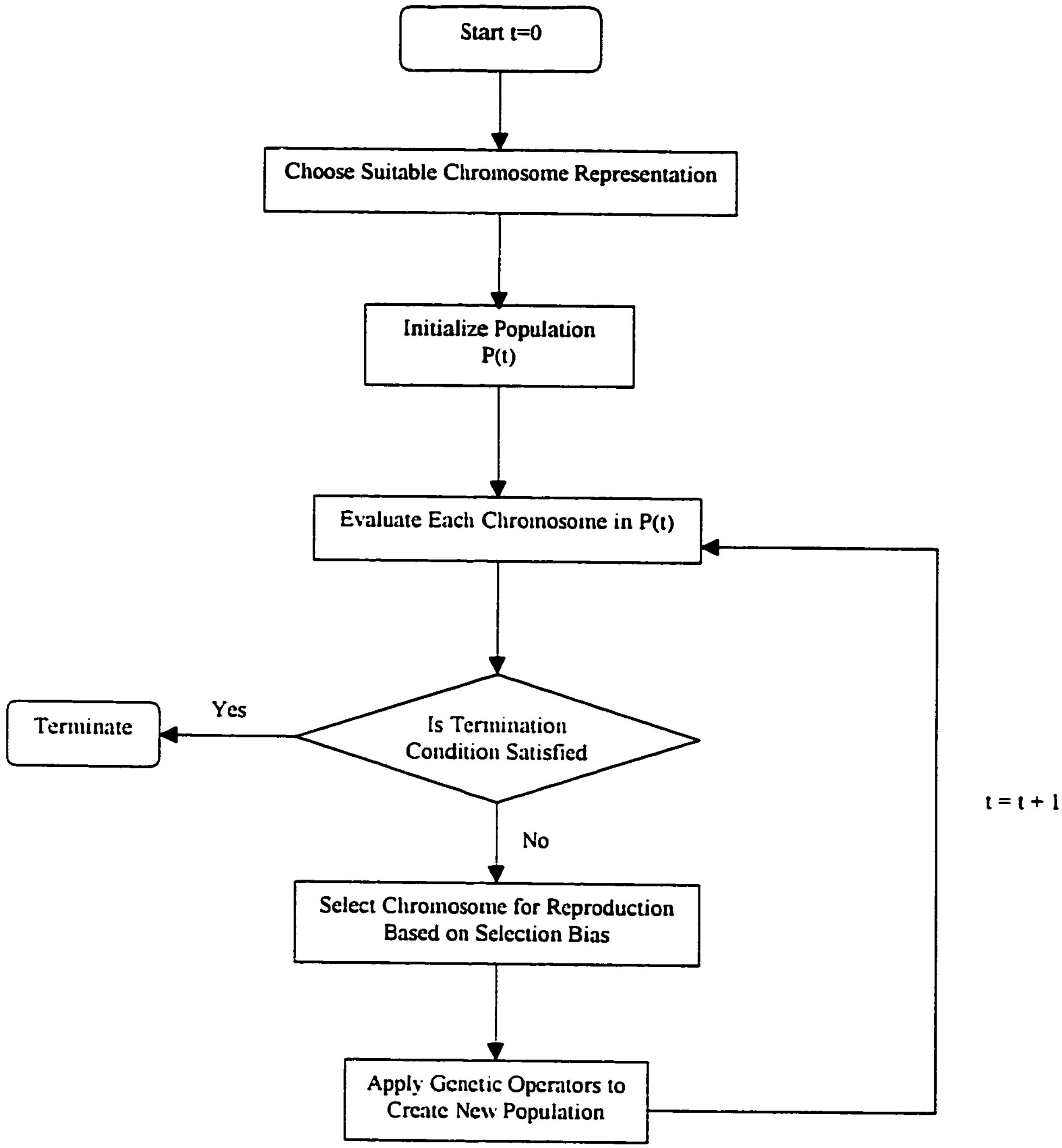

Figure 4.1 Standard Genetic Algorithm Representation

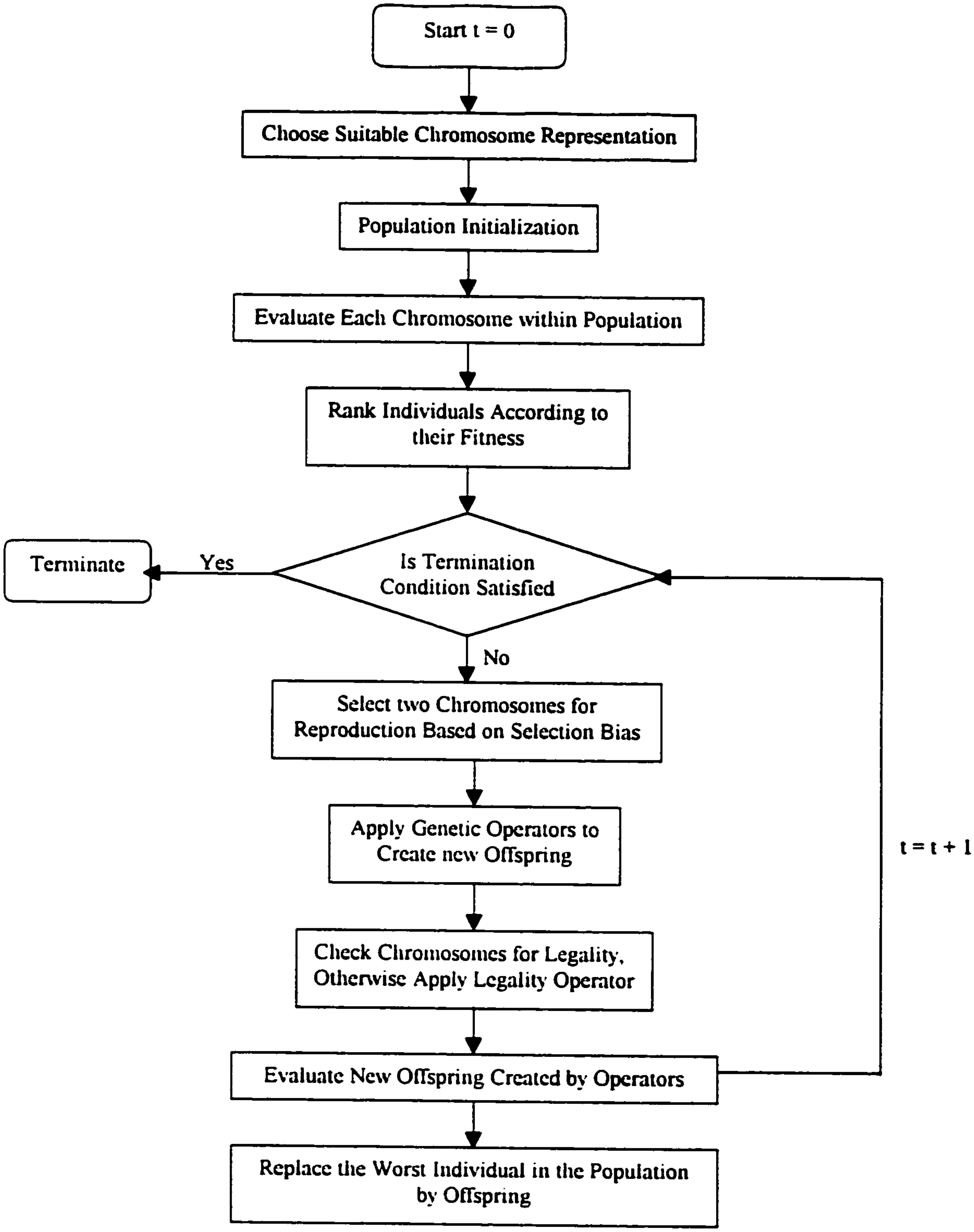

Figure 4.2 Steady State Genetic Algorithm Representation

4.4.1 Chromosome Representation

The first step in solving the cost minimization of the part assignment, tool-loading problem with a preset tooling system reliability level is to choose an appropriate representation. The GA approach for the reliability problem in hand utilizes a permutation type representation. Potential solutions differ according to the operation-machine-tool-tool copy(s) assignments. Each chromosome embodies a list of operation-machine-tool and tool copy(s), which represents a potential solution to the problem.

Different combinations of part-operation-machine-tool and tool copy(s) point to different sets of solutions, Figure 4.3 below. Each chromosome is composed of genes where each gene is constructed as follows:

[Part number | Machine number | Tool type | Number of tool copy(s) assigned]

For illustration the chromosome representation of a problem, which consists of 2 part numbers, 2 machines and any number of copies, would be as follows:

1 2 7 6	1 2 3 4	2 1 2 2	2 1 7 3
Operation 1, Part 1	Operation 2, Part 1	Operation 1, Part 2	Operation 2, Part 2

Figure 4.3 Chromosome Representation

In the above figure, relative position of each gene in the chromosome represents the operation number for that part type (i.e. first appearance of part 1 in the chromosome means first operation, the second appearance is operation two of that part type and so on).

4.4.2 Initialization

Once the chromosome representation is completed, the creation of an initial population is started. For the part assignment, tool loading and reliability constrained model; an initial population was generated randomly via a recursive procedure that lists all possible permutations randomly. Figure 4.5 shows an example of such an initial population. The number of randomly generated solutions (N) is to be specified by the decision-maker.

4.4.3 Fitness Function

For a GA to search for an optimal solution it starts with a group of initial solutions (chromosomes) and iteratively moves towards better sets of solutions. In every iteration (generation) the fitness function (objective function) evaluates each solution and selects based on fitness values solutions (parent chromosomes) for reproduction. The number of copies to be reproduced by a particular parent is directly proportional to the value of its fitness (which is the essence of the process of natural selection). Therefore highly fit chromosomes (solutions) are selected and poorly fit chromosomes are truncated.

In the reliability problem, the value of the fitness function for a particular solution is found through the assignment of operations to machines, tools to different machines and the required number of tool copies for a particular minimum overall tooling system reliability. The GA continues from generation to generation thereby saving the best solutions of each generation and discarding those of lower fitness values.

4.4.4 Genetic Algorithm Operators

Genetic algorithm operators are employed to make certain that the search space is well and comprehensively searched. The genetic operators are reproduction, crossover and mutation are described below.

4.4.4.1 Reproduction

In reproduction the parent chromosomes are sent to a mating pool where they get subjected to genetic operators. The chance of the selection of any resulting string is a function of its fitness value. The roulette wheel parent selection is most widely used as a selection procedure.

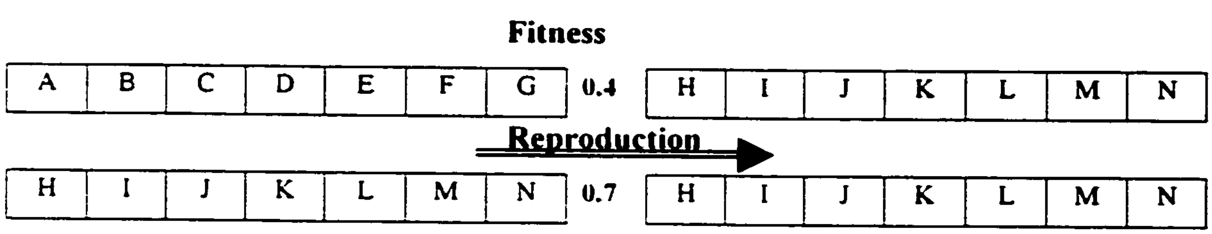

Figure 4.4 Reproduction Process

Chromosomes	Population			
Solution 1	1 2 7 6	1 2 3 4	2 1 2 2	2 1 7 3
Solution 2	2 1 4 2	1 2 1 3	2 1 1 1	1 2 5 6
.	. . . .	. . . .	. . . .	. . . .
.	. . . .	. . . .	. . . .	. . . .
Solution N	1 1 5 4	1 2 4 3	2 2 1 2	2 2 7 5

Figure 4.5A List of Feasible Solutions to the Reliability Problem

Chromosomes	Population				
Feasible Solution 1	X11 K2 S1 m	X12 K1 S3 m	X13 K2 S5 m	X21 K3 S1 m	X22 K2 S2 m
Feasible Solution 2	X11 K3 S2 m	X12 K2 S3 m	X13 K1 S5 m	X21 K3 S1 m	X22 K2 S4 m
. . . . .	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .
Feasible Solution N	X11 K1 S6 m	X12 K2 S3 m	X13 K3 S5 m	X21 K1 S1 m	X22 K2 S2 m

Figure 4.5B List of Feasible Solutions to the Reliability Problem

4.4.4.2 Crossover

String structures are randomly paired and mated. A string structure may mate with a copy of it self. Crossover location points are randomly selected, then segments between the crossover points are exchanged with another string. Crossover is the main genetic function in genetic algorithms. To illustrate suppose that the two structures considered are as shown in Figure 4.6; which were selected for mating relative to their fitness values. If the crossover points are randomly set at gene 4 and gene 12, the resulting structure for the generation of the next iteration are when all structures are mated the result is the population available for the next generation and the current mating structures are neglected and so on.

4.4.4.3 Mutation

Mutations are occasional events, they are considered to be a secondary operation of genetic algorithms Figure 4.7. The main purpose for mutation to get genetic diversity within the population. This in turn would at times help regain information that may get lost in earlier generations or providing genes, which were not present in the initial population. The mutation rate is defined as the percentage of the total number of genes in the population. The mutation rate controls the rate at which new genes are introduced into the population for trial. If it is too low, many genes that would have been useful are never tried out. But if it is too high, there will be much random perturbation, the offspring will start losing their resemblance to the parents, and the algorithm will lose the ability to learn from the history of the search.

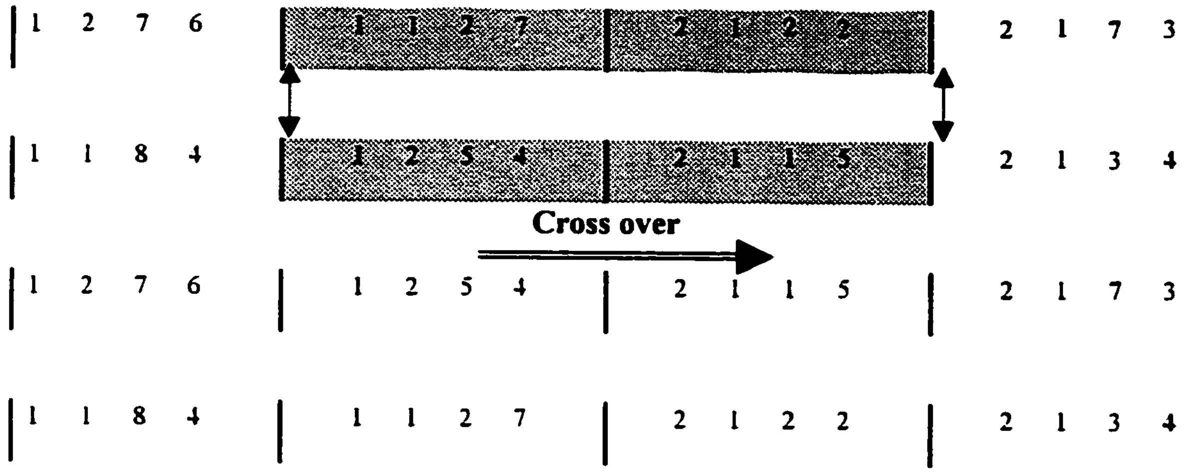

Figure 4.6 Crossover Process

Mutation rate is usually fixed, however Whitley et al (1998) introduced what he called adaptive mutation. Adaptive mutation is a technique through which the probability to perform mutation is increased with the increase of genetic homogeneity in the population.

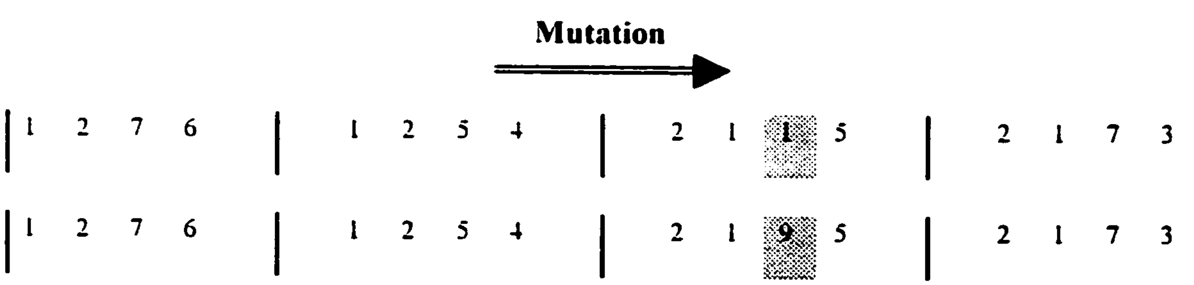

Figure 4.7 Mutation Operator

4.5 GA Parameter Values

In pursuit of solving a complex problem such that of FMS tooling system reliability, the choice of a class of optimization algorithms need to be selected to handle the system on hand. It is also essential to decide the various parameters, which play a significant part in the solution of the reliability problem, parameters such as crossover, population size, mutation rate and number of generations. If these parameter values are not set properly poor GA performance can be expected. In this dissertation, substantial effort was directed towards the determination of the best values for these parameters, this in turn was done through computational experiments.

CHAPTER 5

PROPOSED METHODOLOGY AND COMPUTATIONAL RESULTS

5.1 An Overview

The way FMS tooling system activities are set can have a significant impact on the ability of the system to meet its objectives including cost, on time delivery as well as tool utilization and overall tooling system reliability. Hence, the objective is to minimize total cost and to maintain high level of FMS tooling system reliability. The genetic algorithm process represents a potentially powerful tool for improvements in total cost with respect to attaining significantly high FMS tooling system reliability levels, this is done through better tool allocation and usage.

This section describes, a generic model for the part assignment, tool loading problem with FMS tooling system reliability. The GA is best applied to problems with various machines capable of carrying a large number of tools where each tool has a number of redundancies. Because of tool flexibility, which results in machines having alternate choice of tools, the capability to react quickly to different types of loads exists.

The task of solving the tool loading and part assignment becomes difficult when there exists different combinations of tool loading and when tools can process different operations on a variety of parts on more than one machine. The alternate routing flexibility and different reliability levels of the different tools gives rise to tool flexibility, due to which the possible number of feasible assignment of resources grow exponentially and finding a satisfactory assignment of resources becomes a formidable task. This is shown in Figure 5.1, which shows two parts each having four operations. Operation 1 of part 1 can be performed utilizing tools 2, 3, 7 and 10 and so on.

Moreover from Figure 5.2, tool 2 can be mounted on machine 1, and 2. Tool 3 can be mounted on machine 2, 3 and 4 and so on. The total number of possible assignment of resources in this case would be 480 (2x3x4x10x2). If it was assumed that tools are not the constraining factor and each tool can only have one spare, the total number of possible assignment of resources will be 240. Therefore, by just adding one complexity to the problem the search space increased from 240 to 480. In the case where there are 20 tool types, search space grows to 960. Figure 5.4 shows some of the possible assignment of resources.

5.2 Methodology

Based on the literature review, it is concluded that reliability optimization in FMS has not been fully studied and analyzed. Hence this research focuses on this issue. In an FMS tools may break; fail; or perform in a non-acceptable manner. This calls for a procedure to ensure high levels of FMS tooling system reliability. There are two common ways to improve overall tooling system reliability, the first is by improving the quality of each single tool, this, however, turns to become very expensive after reaching some tool quality level.

	Part 1			Part 2		
Operations	X11	X12	X13	X21	X22	X23
Tools	S2 S3 S7 S10	S1 S2 S3 S5	S2 S6	S6 S8 S9	S4 S10	S1 S3 S7

Figure 5.1 Operation-Tool Information

The second is by introducing enough redundancies to ensure desirable reliability levels, this approach faces the obstacle of tool magazine limited slots and the fact that individual tools are highly expensive.

The approach followed in this research is the incorporation of tool redundancies in order to optimize the FMS reliability levels. The procedure calls for setting a certain tooling system reliability level and then deciding the number of tools required for that reliability level and then optimizing the cost associated with such level. This gives the designer a better insight of the number of tools required and serves as a guide in the decision process regarding trade off between tooling system reliability and cost. The research work in this thesis dwells on the following:

1. The use of accurate and representative reliability relationships developed for this topic.
2. Solving large-scale problems with different sets of assumptions.
3. Use of genetic algorithm in the solution procedures for large-scale FMS problems.
4. Development of models in the cases where, tool sharing is not allowed and for that where tool sharing is allowed.

		Tools				
		S1	S2	S3	S7	S10
Machines	k1	1	1	0	0	1
	k2	0	1	1	0	0
	k3	1	0	1	1	1
	k4	1	0	1	0	0

Figure 5.2 Machine-Tool Information

5.3 Limitations of Existing Models

A comprehensive review of the literature regarding FMS part assignment, tool loading with tooling system reliability considerations was presented in chapter 2. Although differences exist in the way objective functions and constraint presentation, part assignment models aim at assigning different part operations to different tools in order to fulfill a certain objective. Whereas tool loading problem formulation aim at assigning the required number of tools to different machines to complete the required task. These approaches, are able to assign parts and load tools on different machines, however, they have some limitations:

1. A thorough review of the literature fails to reveal a single model that incorporates tooling system reliability in the planning stages of FMS system developments. Tooling reliability is studied outside the context of the part assignment and tool loading problem.

2. Presented models are either part assignment and tool loading formulations or tooling system reliability models only.

3. The stochastic nature of tools is not integrated in many part assignment and tool loading formulations.

	X11	X12	X13	X21	X22	X23
1	k1 S1 m	k3 S3 m	k3 S7 m	k4 S2 m	k1 S3 m	k2 S4 m
2	k1 S7 m	k3 S3 m	k3 S2 m	k4 S1 m	k1 S5 m	k2 S2 m
3	k4 S8 m	k3 S5 m	k1 S3 m	k2 S9 m	k2 S2 m	k4 S10 m

Figure 5.3 List of Assigned Resources

5.4 Thesis Statement

The research conducted in this thesis is directed at developing a cost minimization model for the part assignment tool loading FMS problem, which address tool system reliability simultaneously. The thesis of this research states that tooling system reliability can be integrated in FMS planning decisions, and that such model will complement some of the apparent limitations in the existing models. This model aims at helping FMS decision maker to dictate a minimum tooling system reliability and go about optimizing the cost of the part assignment and tool loading of FMS. A solution methodology is also presented in this thesis. The solution takes into account part assignment and tool loading along with tooling system reliability of FMS under consideration.

5.5 Part Assignment, Tool and Spare Tool Allocation

The assignment of parts to machines and loading of different tool types to machines along with number of required spares for achieving minimum cost and fulfilling reliability constraint is process plan dependent. The process plan determines the machines required for all tasks in the system. For GA formulation the assignment of parts operations to machines can be done using part-operation machine information matrix. If an operation cab be performed on a machine then the value in that matrix cell is 1, otherwise zero as shown in Figure 5.3. For the problem on hand, a combination of part assignment, tool loading and spare requirements are done simultaneously.

5.6 Problem Description

The optimization problem may be stated as: "Given process plans for each part in a FMS consisting of k machine types, s number of tools of each tool type, the objective is to find a feasible solution for a given set of part orders such that cost is minimized and certain level of tooling reliability constraint not violated." The prerequisites of this problem is the part-operation and machine compatibility matrix, tool machine compatibility matrix, number of parts required, demands for each part type, tool life information, number of machines and their tool magazine capacities, number of tools available and the span of each production period. Required also, are the processing times and cost of different elements of parts on machines using different tool types.

5.7 Genetic Algorithm Model

The GA is constructed to solve the part assignment, tool loading with tool reliability considerations, the problem is handled in the following way:

1. Chromosome Representation:

The model considers a number of machines, tools and tool copies as a chromosome (feasible solution). The length of each chromosome is equal to the total number of operations multiplied by the number of parts for the problem to be solved (for a problem with four part types, chromosome length is to be multiplied by four). Different combinations of operation-machine-tool-tool copies represent different solutions to the reliability problem on hand.

2. Initialization:

The initial parameters along with a diversified population of solutions are selected, this is done in the following manner:

- Set population size (POPSIZE).
- Set the number of generations (NUMGENERATIONS).
- Set selection bias (SELBIAS), where SELBIAS is a floating number that sets the elected favor to be allocated for superior individuals in a particular population.
- Read the processing times, processing cost, number of tools available of each tool type, tool life and reliability data for all tools.
- Create initial population of solutions of size POPSIZE and name 'OLDPOPULATION'.

- Calculate the objective function for all the solutions present in the initial population using the reliability algorithm.
- For initial generation; set NEWGENEARTION = 1.

4. **Recombination:**

Recombination is explained in the following steps;

- Apply recombination to the OLDPOPULATION to form a new population.
- Select two parents from the initial population based on the following criterion:

Solution number to be selected is found through relationship developed by (Whitley,1989);

$$FeasibleSolutionSelected\,FromSorted\,Population = \frac{PSIZE * (SBIAS - \sqrt{(SBIAS)^2 - 4 * (SBIAS - 1)} * (Random()))}{2/(SBIAS - 1)}$$

Simple crossover is applied to both selected feasible solutions (parents) to form a new feasible solution (offspring).

- Objective function is calculated for the resulting offspring.
- Objective function value of offspring is compared to that of all solutions in population. If value is better than any of the solutions in the population then replace offspring with that with worst objective function in population.

4. New Generation:

- If GEN < NEWGEN; then increment GEN by 1 and the current generation becomes OLDPOPULATION. Go to 3.

- If GEN = NEWGEN stop.

The best solution is the solution with lowest objective function value in the current population.

5.8 Genetic Algorithm Parameters

The selection of best combination of genetic algorithm parameters is the most difficult and time consuming. In this problem the genetic algorithm parameters are population size (PSIZE), selection bias (SELBIAS) and (AMUT) which represents the adaptive mutation rate. Different combinations of these parameters were tested in order to arrive at a suitable set for the tooling system reliability problem. Population sizes of 40 and up to 70 with an increment of 10 were used. SELBIAS ranging from 1.1 to 1.9 and incremented by 0.1; the mutation rates varied from 0.1 to 0.9 in a step of 0.2, and between 200 and 500 generations were used. Table 5.1 gives parameters values for GA calculations for example problem one with four parts, four operations, twenty tool types and several tool copies for each tool type.

Example problem 1 was run for different combinations of population size, selection bias and mutation rate. The performance measure is cost minimization for various minimum tooling system reliability. The search process begins with the proper representation in the form of a feasible solution and evaluation of each solution in the population, and the application of genetic operators to this population for improved solutions. The process continues for a specified number of generations. The results for reliability levels of 99.5% and 99.7% are given in Table 5.2A through Table 5.3B respectively. The population size was varied from 40 to 70 with an interval of 10. The selection bias was varied from 1.1 to 1.9 in a step of 0.1 and mutation rate was varied from 0.1 to 0.9 in a step of 0.2. The number of generations was varied between 200 to 500.

Table 5.1 Parameters Values for GA Calculations

Parameters	Levels Used
Number of Generations	200 300 400 500
Population Size (PSIZE)	40 50 60 70
Selection Bias (SBIAS)	1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
Adaptive Mutation Rate (AMUT)	0.1 0.3 0.5 0.7 0.9

Table 5.2A Example Problem 1, Total FMS Tooling Cost of $94606 with 99.3% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	97381	200	97306	200	95624	200	96223	200
	0.3	97331	300	96306	300	94606	300	95973	300
	0.5	95131	500	95648	500	94606	500	94606	500
	0.7	94606	500	94606	500	95898	500	96198	500
	0.9	94481	500	94606	500	96423	500	94606	500
1.2	0.1	96220	200	96323	200	96398	200	96373	200
	0.3	94606	300	94606	300	95423	300	96098	300
	0.5	94606	500	95048	500	94606	500	94606	500
	0.7	96148	500	95523	500	94606	500	94606	500
	0.9	94606	500	96298	500	94606	500	94606	500
1.3	0.1	95698	200	95673	200	95648	200	96973	200
	0.3	95173	300	95598	300	95648	300	96223	300
	0.5	94606	500	95073	500	94606	500	94606	500
	0.7	95173	500	94606	500	96220	500	94606	500
	0.9	94606	500	95298	500	95298	500	94748	500
1.4	0.1	94606	200	96973	200	96973	200	96223	200
	0.3	94606	300	95073	300	96223	300	95723	300
	0.5	94713	500	93923	500	95473	500	94606	500
	0.7	94606	500	94838	500	96248	500	94606	500
	0.9	94606	500	94838	500	96748	500	94606	500
1.5	0.1	95073	200	96223	200	96973	200	96748	200
	0.3	96248	300	95598	300	96973	300	95723	300
	0.5	95598	500	95073	500	96223	500	95723	500
	0.7	95423	500	96973	500	95723	500	94606	500
	0.9	94748	500	94748	500	94606	500	96248	500

Table 5.2B Example Problem 1, Total FMS Tooling Cost of $94606 with 99.3% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
	0.1	95073	200	95723	200	96398	200	96973	200
1.6	0.3	94998	300	95723	300	95598	300	**94606**	300
	0.5	93523	500	**94606**	500	**94606**	500	**94606**	500
	0.7	**94606**	500	95823	500	96748	500	**94606**	500
	0.9	**94606**	500	95823	500	96948	500	96373	500
1.7	0.1	95898	200	96170	200	96948	200	95175	200
	0.3	95150	300	96645	300	96948	300	95623	300
	0.5	95150	500	96720	500	**94606**	500	95673	500
	0.7	95648	500	96720	500	**94606**	500	95673	500
	0.9	95923	500	**94606**	500	**94606**	500	95598	500
1.8	0.1	95125	200	96898	200	95823	200	96198	200
	0.3	94650	300	**94606**	300	**94606**	300	95125	300
	0.5	**94606**	500	96245	500	**94606**	500	**94606**	500
	0.7	94650	500	94950	500	**94606**	500	95598	500
	0.9	94650	500	96023	500	96370	500	95673	500
1.9	0.1	95125	200	96748	200	94950	200	94650	200
	0.3	95125	300	95823	300	**94606**	300	**94606**	300
	0.5	94850	500	95125	500	96245	500	**94606**	500
	0.7	94625	500	95125	500	94650	500	**94606**	500
	0.9	94100	500	94100	500	**94606**	500	**94606**	500

Table 5.3A Example Problem 1, Total FMS Tooling Cost of $97581 with 99.7% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	103246	200	101139	200	100085	200	102720	200
	0.3	102193	300	98505	300	99032	300	98505	300
	0.5	97979	500	98505	500	100085	500	**97581**	500
	0.7	**97581**	500	98042	500	98505	500	98042	500
	0.9	98042	500	100928	500	100085	500	99559	500
1.2	0.1	102719	200	99032	200	101139	200	102193	200
	0.3	98505	300	100928	300	99559	300	99032	300
	0.5	100928	500	102719	500	**97581**	500	**97581**	500
	0.7	98505	500	102719	500	98505	500	100085	500
	0.9	101666	500	100085	500	100085	500	**97581**	500
1.3	0.1	98505	200	99559	200	99267	200	99268	200
	0.3	99559	300	98505	300	98505	300	100928	300
	0.5	99032	500	98505	500	98505	500	101666	500
	0.7	100258	500	**97581**	500	100085	500	**97581**	500
	0.9	102192	500	100928	500	100085	500	98042	500
1.4	0.1	98042	200	100928	200	97852	200	100928	200
	0.3	995599	300	98505	300	98505	300	97979	300
	0.5	97979	500	101139	500	99559	500	**97581**	500
	0.7	97979	500	99032	500	99559	500	97979	500
	0.9	101139	500	99559	500	99032	500	99032	500
1.5	0.1	104371	200	102955	200	101321	200	106273	200
	0.3	101865	300	101865	300	**97581**	300	101865	300
	0.5	102955	500	101865	500	101865	500	100776	500
	0.7	101865	500	102410	500	101321	500	100233	500
	0.9	104371	500	101321	500	102410	500	105679	500

Table 5.3B Example Problem 1, Total FMS Tooling Cost of $97581 with 99.7% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	101139	200	99032	200	100085	200	102193	200
	0.3	98505	300	100928	300	98381	300	99524	300
	0.5	105134	500	98505	500	99032	500	99032	500
	0.7	100085	500	99032	500	100085	500	**97581**	500
	0.9	99032	500	97979	500	100085	500	100085	500
1.7	0.1	98505	200	985359	200	98505	200	100085	200
	0.3	98505	300	100085	300	100085	300	99524	300
	0.5	98505	500	98505	500	98505	500	98257	500
	0.7	99360	500	99559	500	100928	500	99559	500
	0.9	98042	500	101666	500	97979	500	99953	500
1.8	0.1	100085	400	98505	400	100085	400	98505	400
	0.3	99528	400	98042	400	97979	400	99032	400
	0.5	100928	400	100085	400	**97581**	400	**97581**	400
	0.7	99032	400	100928	400	990310	400	100085	400
	0.9	101139	400	97979	400	101865	400	98111	400
1.9	0.1	100928	400	98505	400	98505	400	99032	400
	0.3	100085	400	98111	400	99559	400	99032	400
	0.5	100085	400	100085	400	99559	400	98505	400
	0.7	103499	400	100085	400	99032	400	98505	400
	0.9	103499	400	102719	400	101139	400	96925	400

Table 5.4 Example Problem 1, Part Routing of the Different Part Types and Required Operations, No Tool Sharing

	Part Type 1				Part Type 2				Part Type 3				Part Type 4			
	Operation number				Operation number				Operation number				Operation number			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Machine																
1	0	60	*	17	48	50	15	34	34	*	*	40	*	9	*	7
2	12	0	45	36	12	*	25	0	*	*	27	0	0	22	0	33
3	48	0	15	*	*	10	10	26	0	17	*	*	40	*	*	0
4	*	*	*	7	*	*	*	*	6	23	13	*	*	9	40	*

Table 5.5 Example Problem 1, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
80%	29	31	30	29	78536
90%	31	34	32	30	80806
95%	34	37	34	33	84831
97%	38	41	39	38	87831
98.8%	41	43	41	41	92107
99.3%	45	46	45	44	94606
99.7%	47	49	50	48	97581

Table 5.6 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
1	4	4	5	5	6	6	7
3	4	4	5	5	6	6	6
5	4	4	4	5	5	6	6
7	5	6	6	7	7	7	8
10	4	4	4	5	5	6	6
12	4	4	5	5	6	6	7
16	4	5	5	6	6	7	7

Table 5.7 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
1	5	5	5	6	6	6	7
6	5	6	7	7	7	8	8
7	4	4	5	5	6	6	6
10	5	6	6	7	7	8	8
11	4	4	5	5	6	6	7
19	4	5	5	6	6	6	7
20	4	4	4	5	5	6	6

Table 5.8 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
2	4	5	5	6	6	6	7
4	5	5	6	6	6	7	8
6	4	4	4	5	5	6	6
8	4	4	4	5	6	6	7
9	4	5	5	6	6	6	7
12	5	5	5	6	6	7	8
17	4	4	5	5	6	7	7

Table 5.9 Example Problem 1, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	80%	90%	95%	97%	98.8%	99.3%	99.7%
5	4	5	5	6	7	7	8
9	4	4	5	6	6	7	7
11	4	4	4	5	5	6	6
13	4	4	5	5	6	6	7
14	5	5	6	6	7	8	8
15	4	4	4	5	5	5	6
18	4	4	4	5	5	5	6

5.9 Computational Experience, No Tool Sharing Allowed

5.9.1 Example Problem 1, No Tool Sharing

For example problem one, it was observed that minimum cost of $94606 for minimum tooling system reliability of 99.3%, which was obtained for several cases with different combination of PSIZE, SBIAS, and AMUT. The solution converged to best solution for a population size of 60 and SBIAS of 1.3 and AMUT of 0.5 and it took 500 generations to converge. The best combination that took the least number of generations which was 200, is a SBIAS of 1.4 and AMUT of 0.1. Other values of population size, SBIAS and AMUT of course attained the optimal value, but it took more number of generations to converge. As far as selection bias is concerned, all values of SBIAS eventually yielded good results, some for a smaller population size and some for large population size. The best population size observed was 60, larger population size of value greater than 70 were tried, but no improvements were observed over this optimal value.

Larger population size resulted in large number of generations to converge to optimal value, resulting in large computational time. As far as mutation rate, a low value of 0.3 or 0.1 was found to be a better choice.

For reliability level of 99.7% a cost of $97581 was obtained. For this case, the best combination of parameter values found to converge to an optimal value were PSIZE of 60, SBIAS of 1.5 and AMUT of 0.3, and number of generations it took to converge was 300 generations. It can be observed from the previous discussion that for the same problem by only varying the reliability level, the optimal cost was found with different combinations of parameter values. Hence, it can be concluded from this discussion that these parameters of PSIZE, SBIAS, and AMUT were very much dependent on the chosen problem. The tool allocation results for example problem 1 are provided in Table 5.6 through 5.9. In this case and as shown in Table 5.5, tool magazine of machine 3 was utilized to full capacity. The problem was solved in 0.16 seconds of CPU time for minimum tooling system reliability of 99.7%. A minimum cost value of 97581 was obtained.

Different parameter values of GA yield significant results for the same problem, and hence, several experiments should be run before a decision can be made on exact parameter values. Since computation times for genetic algorithms are usually small, it may not be difficult to conduct such experiments. Similar trends were obtained when different reliability levels were used such as 80%, 90%, 95%, 97% and 98.8%.

Table 5.10A Example Problem 2, Total FMS Tooling Cost of $133525, 89% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	134859	200	137111	200	135757	200	136633	200
	0.3	135757	300	136633	300	**133525**	300	113485	300
	0.5	134859	400	133597	400	**133525**	500	**133525**	400
	0.7	**133525**	500	**133525**	500	133597	500	136633	500
	0.9	135681	500	**133525**	500	133597	500	**133525**	500
1.2	0.1	135546	200	138587	200	135757	200	133597	200
	0.3	**133525**	300	**133525**	300	133597	300	133597	300
	0.5	**133525**	400	138587	500	**133525**	500	**133525**	500
	0.7	134859	400	138254	500	**133525**	500	**133525**	500
	0.9	**133525**	500	133597	500	**133525**	500	**133525**	500
1.3	0.1	136633	200	134859	200	133757	200	135546	200
	0.3	133850	300	133663	300	133612	300	133807	300
	0.5	**133525**	500	133713	300	**133525**	500	**133525**	500
	0.7	133875	500	**133525**	500	133713	500	**133525**	500
	0.9	**133525**	500	133850	500	133580	500	133713	500
1.4	0.1	**133525**	200	136658	200	133756	200	133575	200
	0.3	**133525**	300	133875	300	134597	300	136558	300
	0.5	133875	500	133597	400	133836	500	**133525**	500
	0.7	**133525**	500	133850	400	135994	500	**133525**	500
	0.9	**133525**	500	133682	400	133576	500	**133525**	500
1.5	0.1	133875	200	134589	200	134589	200	133713	200
	0.3	133875	300	134589	200	135756	300	134589	300
	0.5	136708	500	133597	300	135756	500	133597	500
	0.7	138587	500	133713	300	133713	500	**133525**	500
	0.9	133597	500	133850	500	**133525**	500	133850	500

Table 5.10B Example Problem 2, Total FMS Tooling Cost of $133525, 89% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	135832	200	135884	200	136633	200	136831	200
	0.3	133722	300	136633	300	134859	300	134859	300
	0.5	133597	300	**133525**	500	**133525**	500	**133525**	500
	0.7	**133525**	500	134859	500	133722	500	**133525**	500
	0.9	**133525**	500	136831	500	135832	500	**133525**	500
								136633	
1.7	0.1	135796	200	136708	200	138152	200	136633	200
	0.3	137520	300	136908	300	137570	300	136958	200
	0.5	136633	400	137158	500	**133525**	500	136633	200
	0.7	134859	400	134859	500	**133525**	500	136633	400
	0.9	133800	500	**133525**	500	**133525**	500	103485	400
1.8	0.1	136906	200	136633	200	137570	200	136908	200
	0.3	136831	200	**133525**	300	**133525**	300	136958	400
	0.5	**133525**	500	133722	500	**133525**	500	**133525**	400
	0.7	136831	500	133772	500	**133525**	500	136908	400
	0.9	135796	500	133597	500	137570	500	133772	500
1.9	0.1	134025	200	134859	200	133836	200	133713	300
	0.3	137795	300	133875	300	**133525**	200	**133525**	300
	0.5	134859	300	138587	400	135994	200	**133525**	300
	0.7	133875	500	133597	400	135994	300	**133525**	500
	0.9	133757	500	133800	400	**133525**	300	**133525**	500

Table 5.11A Example Problem 2, Total FMS Tooling Cost of $139300, 90% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	106768	300	104589	200	103499	200	106224	200
	0.3	105679	300	101865	300	102410	300	101865	200
	0.5	101321	400	101865	500	103499	500	**139300**	500
	0.7	**139300**	500	101865	500	101865	500	101865	500
	0.9	101865	500	104371	500	103499	500	102955	500
1.2	0.1	106223	200	102410	200	104589	200	105679	200
	0.3	101865	200	104371	300	102955	300	102410	300
	0.5	104371	300	106223	500	**139300**	500	**139300**	500
	0.7	101865	300	106323	500	101865	500	103499	400
	0.9	105134	500	103499	500	103499	500	**139300**	400
1.3	0.1	101865	200	102955	200	100776	200	100907	200
	0.3	102955	400	101865	300	101321	300	104371	300
	0.5	102410	400	101865	500	101865	500	105134	300
	0.7	100907	500	**139300**	500	103500	500	**139300**	500
	0.9	105679	500	104371	500	103500	500	101865	500
1.4	0.1	104589	300	104371	200	100776	200	104371	200
	0.3	103499	300	101865	300	101865	300	101321	300
	0.5	102955	400	104589	500	102955	500	**139300**	400
	0.7	101321	500	102410	500	102955	500	101321	400
	0.9	104589	500	102955	500	102410	500	102410	500
1.5	0.1	104371	200	102955	200	101321	200	106273	200
	0.3	101865	300	101865	300	**139300**	300	101865	300
	0.5	102955	400	101865	500	101865	500	100776	400
	0.7	101865	500	102410	500	101321	500	100233	500
	0.9	104371	500	101321	500	102410	500	105679	500

Table 5.11B Example Problem 2, Total FMS Tooling Cost of $139300, 90% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	104589	200	102410	200	103499	200	105697	200
	0.3	101865	300	104371	300	100907	300	100776	300
	0.5	105134	500	101865	500	102410	500	102410	500
	0.7	103499	500	102410	500	103499	500	**139300**	500
	0.9	102410	500	101321	500	103499	500	103499	500
1.7	0.1	101685	200	100907	200	101865	200	103499	200
	0.3	101685	300	103499	300	103499	300	100776	300
	0.5	101685	500	101865	500	101865	500	101321	500
	0.7	100776	500	102955	500	104371	500	102955	500
	0.9	101685	500	105134	500	101321	500	100776	500
1.8	0.1	103499	400	101865	400	103499	400	101865	400
	0.3	101321	400	101865	400	100231	400	102410	400
	0.5	104371	400	103499	400	**139300**	400	**139300**	400
	0.7	102410	400	104371	400	102410	400	103499	400
	0.9	104589	400	110132 1	400	101865	400	100776	400
1.9	0.1	104371	400	101685	400	101865	400	102410	400
	0.3	103499	400	104044	400	102955	400	102410	400
	0.5	103499	400	103499	400	102955	400	101866	400
	0.7	103499	400	103499	400	102410	400	101866	400
	0.9	103499	400	106223	400	104589	400	100231	400

Table 5.12 Example Problem 2, Part Routing of Different Part Types and Required Operations, No Tool Sharing

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	*	8	10	*	*	9	16	4	*	10		
	2	x	x	*	10	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	*	12	x	x	11	*	*	*	*	10		
	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	17			
Part 4	Mach.												
	1	*	9	x	x	x	x	18	x	x			
	2	x	x	12	*	12	*	x	*	18			
	3	x	x	*	6	*	6	x	*	*			
	4	*	9	x	x	x	x	*	x	x			
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	12	x	x	x	x	*				
	2	*	6	*	x	x	*	*	x				
	3	6	*	x	*	*	12	*	x				
	4	x	x	x	6	6	x	x	12				
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	9	x	x	x	x	x	x	x	x	10	*
	2	x	x	*	*	*	11	14	6	*	20	x	x
	3	x	x	20	*	9	*	*	*	*	*	x	x
	4	*	11	x	x	x	x	x	x	x	x	10	*
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	*	14	*	13	x	x	x		
	2	x	x	11	x	x	x	x	9	*	12		
	3	12	10	11	x	x	x	x	*	13	10		
	4	*	*	x	*	8	9	*	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.13 Example Problem 2, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
88%	37	39	34	35	129775
89%	40	42	38	39	133525
90%	47	48	44	46	139300
> 90%	No Feasible Solution Found				

Table 5.14 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	2	7	11	27	33	36	37	48	49
Reliability Level									
88%	3	4	4	3	5	4	5	5	4
89%	4	4	4	4	5	4	5	5	5
90%	4	5	5	5	6	5	6	6	5
> 90%	No Feasible Solution Found								

Table 5.15 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	12	17	20	21	26	32	34	47
Reliability Level									
88%	5	4	4	4	4	4	4	5	4
89%	6	5	4	5	4	5	4	5	4
90%	7	5	5	5	4	6	5	6	5
> 90%	No Feasible Solution Found								

Table 5.16 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	10	13	19	25	28	32	39	40	46
Reliability Level									
88%	5	4	4	5	4	4	4	4	4
89%	6	5	5	5	4	5	4	4	4
90%	6	5	5	6	5	5	5	4	5
> 90%	No Feasible Solution Found								

Table 5.17 Example Problem 2, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	4	11	19	33	36	40	48
Reliability Level								
88%	4	4	5	4	5	5	5	4
89%	5	5	5	4	5	6	6	5
90%	6	6	6	5	6	6	7	5
> 90%	No Feasible Solution Found							

5.9.2 Example Problem 2, No Tool Sharing

Example problem 2 was solved for various tooling system reliability levels. The planning model parameters were the same for all problems. The processing cost for an operation was determined on the basis of machine and part-cutting tool combination. Table 5.10 gives part assignments of different part types on different machines utilizing different tool types for example problem number two.

The tool allocation results for example problem 2, are provided in Table 3.14 through Table 5.17. These tables include tools required to carry different required operations while maintaining minimum tooling system reliability. The assigned parts on the machine and required minimum tooling system reliability generate the tool requirements on any machine with minimum cost as the objective. However, a completely filled tool magazine would necessarily mean that total assigned processing time is large on that particular machine. This is because of the fact that tool allocation depends upon other parameters including tool life; tool inventory, magazine size and most importantly required minimum tooling system reliability.

More efficient machine tool magazines are assigned higher workloads as can be seen from Table 5.13. Consequently, larger numbers of tools are needed on these machines. None of the machine tool magazines was not filled to its capacity in all cases, Table 5.13. There were several types of tools available for allocation, however, not all types were needed in this test problem. The alternate tool for a given operation is utilized only if the primary tools for that operation are loaded. In general, alternate tools are allocated when tool inventory constraint for primary tool is binding. A total cost value of 139300 was obtained in 2.47 seconds of CPU time for minimum tooling system reliability of 90%.

The applicability of the developed model to solve FMS part assignment and tool loading problem with tooling system reliability considerations was tested on eight example problems retrieved in part from literature. A change in tooling system requirements may result in a new solution, hence, part assignment is fixed and effect on tooling requirements is monitored for increased tooling system reliability levels (this is done in order to limit the number of combinations which will make analysis tediously long), since the effect of changing tooling system reliability levels is investigated in this section.

The effect of tooling system reliability on cost, part assignment and tool allocation is investigated by incrementing tooling system reliability by 1% and yet even smaller than 1% increments at the time. The other parameters remain constant. The model is run and part assignment, tool loading and overall cost are determined and summarized, Table 5.14 through Table 5.17. In all problems considered, increasing or decreasing the tooling system reliability requirement has direct effect on part assignment of different part types, tool allocation of different tools as well as overall cost.

5.9.3 Example Problem 3, No Tool Sharing

Example 3 consists of five part types; these are part type 4, 9, 10, 11 and 14. Information about operation times, processing cost and tooling parameters are given in Tables 3 and 4 of the appendix, respectively. The results are presented in Table 5.18A through Table 5.24. In this case and as shown in Table 5.20, none of the machine tool magazines was filled to its capacity. The problem was solved in 55.42 seconds of CPU time for minimum tooling system reliability of 92% and a total cost value of 132050 was obtained.

Table 5.18A Example Problem 3, Total FMS Tooling Cost of $132050, 92% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	143934	300	136011	200	**132050**	200	135284	200
	0.3	141426	300	134286	300	**132050**	300	**132050**	300
	0.5	138513	400	133290	400	136257	400	133290	500
	0.7	138513	500	**132050**	500	138513	400	**132050**	500
	0.9	**132050**	500	**132050**	500	142019	500	135523	500
1.2	0.1	**132050**	200	137652	300	141426	200	134286	200
	0.3	133580	200	**132050**	300	**132050**	300	**132050**	300
	0.5	133580	500	**132050**	500	147528	300	**132050**	500
	0.7	**132050**	500	136257	500	**132050**	500	136517	500
	0.9	141426	500	138513	500	**132050**	500	138513	500
1.3	0.1	133290	200	138222	200	137652	200	133290	200
	0.3	137541	300	**132050**	300	141426	200	133290	300
	0.5	139411	500	139126	400	**132050**	500	**132050**	500
	0.7	137541	500	143827	400	133465	500	135523	500
	0.9	**132050**	500	140989	500	137856	500	**132050**	500
1.4	0.1	137541	200	135281	200	143934	200	138222	200
	0.3	**132050**	300	133580	300	141426	200	139126	300
	0.5	**132050**	300	138512	300	138513	500	137541	400
	0.7	133580	400	**132050**	500	137541	500	**132050**	500
	0.9	**132050**	500	139126	500	137541	500	**132050**	500
1.5	0.1	137541	200	137541	200	133465	300	133465	200
	0.3	136257	300	141426	300	133465	300	133465	300
	0.5	135580	300	140989	300	133465	500	**132050**	500
	0.7	135580	400	135580	400	133465	500	133465	500
	0.9	133465	400	133465	500	133465	500	133465	500

Table 5.18B Example Problem 3, Total FMS Tooling Cost of $132050, 92% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	**132050**	200	133465	200	137541	200	**132050**	200
	0.3	133465	300	**132050**	300	133580	300	**132050**	300
	0.5	133465	500	133465	400	133465	400	141426	500
	0.7	135580	500	133465	400	**132050**	500	141426	500
	0.9	135580	500	135580	500	133580	500	141426	500
1.7	0.1	135580	200	139411	200	133465	200	133465	200
	0.3	135580	300	**132050**	300	135580	300	135580	300
	0.5	133465	500	137541	500	135580	500	**132050**	500
	0.7	133465	500	133580	500	137541	500	**132050**	500
	0.9	133465	500	133465	500	141426	500	133465	500
1.8	0.1	137541	200	137541	200	138513	200	137541	200
	0.3	**132050**	400	141426	200	**132050**	400	135580	300
	0.5	133465	500	133465	300	**132050**	400	**132050**	400
	0.7	137541	500	135580	400	137541	400	141426	400
	0.9	135580	500	138513	400	141426	400	133465	400
1.9	0.1	141426	200	140989	300	**132050**	400	133465	200
	0.3	137541	300	**132050**	400	133465	400	133465	300
	0.5	137541	500	137541	400	**132050**	400	137541	500
	0.7	133465	500	137541	400	135580	500	137541	500
	0.9	138513	500	133465	400	133465	500	133580	500

Table 5.19 Example Problem 3, Part Assignments, No Tool Sharing

	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	16			
Part 4	Mach.												
	1	*	10	x	x	x	x	14	x	10			
	2	x	x	*	5	*	7	x	*	x			
	3	x	x	13	*	*	11	x	8	x			
	4	8	*	x	x	x	x	4	x	*			
	Op.	1	2	3	3								
	Tool	27	24	8	23								
Part 9	Mach.												
	1	7	12	x	x								
	2	x	x	x	x								
	3	x	x	*	7								
	4	5	*	*	5								
	Op.	1	1	2	2	3	4	5	5	6	6	7	8
	Tool	42	48	18	50	49	14	7	33	5	39	38	9
Part 10	Mach.												
	1	*	7	x	x	9	x	*	9	x	x	x	6
	2	x	x	8	*	9	x	x	x	*	7	5	12
	3	x	x	10	*	x	x	x	x	11	*	13	x
	4	11	*	x	x	x	18	9	*	x	x	x	x
	Op.	1	1	2	3	4	4	5	6	7	7		
	Tool	10	22	38	27	28	46	49	3	9	45		
Part 11	Mach.												
	1	x	x	x	9	x	x	*	10	12	*		
	2	8	*	10	x	10	*	20	x	8	*		
	3	*	12	10	x	*	10	x	x	x	x		
	4	x	x	x	11	x	x	x	10	x	x		
	Op.	1	1	2	2	3	3						
	Tool	4	37	28	46	16	36						
Part 14	Mach.												
	1	*	9	x	x	10	*						
	2	x	x	11	*	x	x						
	3	x	x	*	7	x	x						
	4	*	9	x	x	8	*						

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.20 Example Problem 3, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
90%	36	37	32	35	124090
91%	39	41	35	38	125315
92%	45	47	40	44	132050
> 92%	No Feasible Solution Found				

Table 5.21 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	3	9	16	24	27	33	37	48	49
Reliability Level									
90%	4	3	5	4	5	4	4	4	3
91%	4	4	5	4	5	4	4	5	4
92%	5	4	5	5	6	5	5	6	4
> 92%	No Feasible Solution Found								

Table 5.22 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	9	10	18	25	28	38	39	49
Reliability Level								
90%	5	3	5	3	4	4	4	5
91%	6	3	5	3	4	4	5	6
92%	6	3	7	4	4	5	6	7
> 92%	No Feasible Solution Found							

Table 5.23 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	1	5	18	22	23	25	38	46
Reliability Level								
90%	4	4	4	3	4	4	4	5
91%	4	5	4	4	4	4	5	5
92%	5	6	5	4	4	5	5	6
> 92%	No Feasible Solution Found							

Table 5.24 Example Problem 3, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	7	14	16	23	27	37	42
Reliability Level								
90%	5	5	5	3	3	6	4	4
91%	6	6	5	4	3	6	4	4
92%	6	7	6	4	4	7	5	5
> 92%	No Feasible Solution Found							

5.9.4 Example Problem 4, No Tool Sharing

Example 4 consists of three part types; these are part type 5, 14 and 18. Information about operation times, processing cost and tooling parameters are given in Tables 3 and Table 4of the appendix, respectively. The results are presented in Table 5.25A through Table 5.31.

In this case, none of the machine tool magazines capacities were fully utilized, Table 5.27. The problem was solved in 1.26 seconds of CPU time for minimum tooling system reliability of 95%. For this particular problem, mathematical model was able to obtain same results with GA, however, total cost was obtained in 26 seconds.

Table 5.25A Example Problem 4, Total FMS Tooling Cost of $128500, 95% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	129910	200	136209	200	138414	200	130350	200
	0.3	**128500**	300	136270	300	134037	300	**128500**	300
	0.5	130350	300	**128500**	300	134037	300	135551	500
	0.7	**128500**	500	**128500**	400	133580	500	133580	500
	0.9	138414	500	132177	500	**128500**	500	136209	500
1.2	0.1	136270	200	134760	200	13551	200	136209	200
	0.3	136209	300	**128500**	300	13551	300	**128500**	300
	0.5	129910	300	132177	500	**128500**	500	135551	500
	0.7	**128500**	400	132177	500	**135551**	500	134037	500
	0.9	134037	500	135580	500	**128500**	500	133580	500
1.3	0.1	133580	200	134760	200	138414	200	130350	200
	0.3	134037	300	134037	200	134037	300	129350	300
	0.5	132177	400	139910	300	133580	500	130350	500
	0.7	132177	500	136209	400	133580	500	134037	500
	0.9	129910	500	13551	500	134037	500	132177	500
1.4	0.1	133551	200	132177	200	130350	200	130350	200
	0.3	129910	300	132177	300	**128500**	300	129910	300
	0.5	**128500**	300	**128500**	300	134037	400	**128500**	500
	0.7	134760	300	132177	400	132174	400	**128500**	500
	0.9	133580	500	132177	400	132174	400	**128500**	500
1.5	0.1	138414	200	130350	200	132174	200	136270	200
	0.3	136270	300	**128500**	200	**128500**	300	134037	300
	0.5	132177	300	132177	400	129910	300	134037	500
	0.7	134760	500	134760	500	129910	400	**128500**	500
	0.9	130350	500	136209	500	133580	400	138414	500

Table 5.25B Example Problem 4, Total FMS Tooling Cost of $128500, 95% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	135551	200	133580	200	134760	200	136209	200
	0.3	136270	200	**128500**	500	**128500**	300	138414	300
	0.5	134037	200	134037	500	**128500**	400	133551	500
	0.7	**128500**	300	132177	500	133580	400	**128500**	500
	0.9	130350	500	132177	500	129910	500	136270	500
1.7	0.1	132177	200	145075	200	133277	200	129910	200
	0.3	135551	300	138414	300	133277	300	**128500**	300
	0.5	**128500**	300	135551	500	**128500**	400	136209	500
	0.7	133551	500	133580	500	**128500**	500	136209	500
	0.9	134760	500	133580	500	134037	500	138414	500
1.8	0.1	134037	200	132177	200	132177	300	136209	400
	0.3	136270	300	**128500**	200	132177	300	**128500**	400
	0.5	136270	400	129910	400	**128500**	300	134037	400
	0.7	133551	400	133551	400	132177	500	132177	400
	0.9	132177	500	134760	400	**128500**	500	129910	400
1.9	0.1	129910	200	136270	200	132177	200	130350	500
	0.3	136270	300	138414	300	129910	300	**128500**	500
	0.5	136209	500	136209	300	**128500**	400	132177	500
	0.7	136209	500	134760	500	130350	500	130350	500
	0.9	132177	500	133580	500	132177	500	136270	500

Table 5.26 Example Problem 4, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	4	37	49	18	50	9	45	21	25	14
Part 5	Mach.										
	1	4	4	8	x	x	*	12	x	x	4
	2	x	x	4	*	3	*	*	5	*	x
	3	x	x	x	9	*	x	x	*	7	x
	4	*	4	x	x	x	x	x	x	x	8
	Op.	1	2	2	3	3	4	5	5	6	6
	Tool	49	10	22	42	48	44	31	41	15	29
Part 7	Mach.										
	1	14	x	x	8	*	7	x	x	*	14
	2	*	*	*	x	x	x	8	*	x	x
	3	x	14	*	x	x	x	7	*	x	x
	4	x	*	x	6	*	7	x	x	*	*
	Op.	1	1	2	2	3	3				
	Tool	4	37	28	46	16	36				
Part 14	Mach.										
	1	8	*	x	x	*	*				
	2	x	x	11	7	x	x				
	3	x	x	*	*	x	x				
	4	10	*	x	x	18	*				
	Op.	1	1	2	2	3	3				
	Tool	7	33	28	46	1	17				
Part 16	Mach.										
	1	*	*	x	x	x	x				
	2	x	x	*	6	*	*				
	3	x	x	*	6	*	12				
	4	12	*	x	x	x	x				
	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	19	40	32	16	36	4	37	28	46	20
Part 18	Mach.										
	1	x	x	12	*	*	*	9	x	x	x
	2	x	x	6	x	x	x	x	12	*	11
	3	10	6	4	x	x	x	x	*	10	11
	4	*	6	x	*	22	13	*	x	x	x

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.27 Example Problem 4, Effect of Tooling System Required Reliability on Magazine Occupancy and total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
93%	35	34	34	35	109872
94%	40	39	38	39	121797
95%	47	46	44	45	128500
> 95%	No Feasible Solution Found				

Table 5.28 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	14	29	32	37	44	45	49
Reliability Level								
93%	4	4	4	4	5	4	5	5
94%	5	5	5	4	5	4	6	6
95%	6	5	6	5	6	5	7	7
> 95%	No Feasible Solution Found							

Table 5.29 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	20	21	28	31	32	46	49	50
Reliability Level								
93%	5	5	4	4	4	3	5	4
94%	6	6	4	5	4	4	5	5
95%	7	6	5	6	5	5	7	5
> 95%	No Feasible Solution Found							

Table 5.30 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	10	18	19	25	31	32	40	46
Reliability Level								
93%	5	4	5	5	4	4	3	4
94%	6	4	5	5	4	5	4	5
95%	6	5	6	6	5	5	5	6
> 95%	No Feasible Solution Found							

Table 5.31 Example Problem 4, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	4	14	16	36	37	40	42	44
Reliability Level								
93%	5	4	5	4	5	5	3	4
94%	6	5	5	4	5	5	4	5
95%	7	6	6	5	6	6	4	6
> 95%	No Feasible Solution Found							

5.9.5 Example Problem 5, No Tool Sharing

Example problem 5 consists of three part types, these are part type 2, 13, 14, 17, and 18. Information about operation times, processing cost and tooling parameters are given in Tables 3 and 4 of the appendix, respectively. The results are presented in Table 5.32A through Table 5.38. In this case and as can be seen from Table 5.34, none of the machine tool magazines were filled to their capacity. The problem was solved in 36.30 seconds of CPU time for minimum tooling system reliability of 94%. Total cost of 129565 was obtained.

Table 5.32A Example Problem 5, Total FMS Tooling Cost of $129565, 94% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	138634	200	134747	200	133711	200	133711	200
	0.3	136690	300	133711	300	**129565**	300	132026	300
	0.5	132026	300	133711	500	135395	300	138634	500
	0.7	**129565**	500	132026	500	134818	300	**129565**	500
	0.9	131640	500	131640	500	136690	500	133711	500
1.2	0.1	133711	200	138634	200	133451	200	139302	200
	0.3	134747	300	137818	300	137818	300	136690	300
	0.5	**129565**	400	133451	400	138634	500	**129565**	500
	0.7	135395	500	137818	400	133711	500	136690	500
	0.9	137818	500	138634	500	133451	500	139302	500
1.3	0.1	139302	200	139302	200	136690	200	135395	200
	0.3	135395	200	137818	300	132026	200	134747	300
	0.5	133711	500	135395	400	133451	500	133451	500
	0.7	**129565**	500	133451	400	**129565**	500	134747	500
	0.9	138634	500	133711	400	133711	500	134747	500
1.4	0.1	136690	200	131640	200	133711	200	128634	200
	0.3	137818	300	132026	300	133451	300	139302	300
	0.5	136690	400	**129565**	300	133711	400	134747	500
	0.7	136690	400	133711	300	136690	500	133451	500
	0.9	136690	400	132026	500	137818	500	134395	500
1.5	0.1	135395	200	131640	200	134747	200	132026	200
	0.3	138634	300	**129565**	300	**129565**	300	131640	300
	0.5	134747	300	131640	400	133451	300	135395	500
	0.7	133711	500	133451	500	136690	500	134747	500
	0.9	133711	500	133451	500	133450	500	135395	500

Table 5.32B Example Problem 5, Total FMS Tooling Cost of $129565, 94% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	135395	200	138634	200	133451	200	131640	200
	0.3	132026	200	136690	300	**129565**	300	133451	300
	0.5	132026	500	135395	500	132026	500	**129565**	500
	0.7	133711	500	134747	500	**129565**	500	**129565**	500
	0.9	134747	500	137818	500	131640	500	**129565**	500
1.7	0.1	**129565**	200	134747	200	138634	200	134711	200
	0.3	**129565**	300	133451	300	135395	300	133451	300
	0.5	133711	400	133690	500	135395	500	131640	500
	0.7	133451	500	132026	500	133711	500	137818	500
	0.9	**129565**	500	132026	500	139302	500	138634	500
1.8	0.1	132026	200	132026	200	134747	200	135395	400
	0.3	132026	300	**129565**	300	133451	300	132026	400
	0.5	132026	300	131640	400	**129565**	400	138634	400
	0.7	133451	400	132026	400	136690	400	138634	400
	0.9	131640	500	135395	500	133711	500	134747	400
1.9	0.1	137818	300	133711	300	135395	300	136690	400
	0.3	133451	300	133711	300	133711	300	133451	500
	0.5	133451	300	133711	300	133451	300	136690	500
	0.7	132026	400	133711	400	131640	400	133451	500
	0.9	137818	500	133711	500	133450	500	138634	500

Table 5.33 Example Problem 5, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	*	10	*	12	10	*	*	*	10	10		
	2	x	x	*	8	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	10	*	x	x	10	*	13	7	x	*		
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	6	x	x	x	x	*				
	2	*	6	6	x	x	*	8	x				
	3	6	*	x	*	12	4	*	x				
	4	x	x	x	*	*	x	x	12				
	Op.	1	1	2	2	3	3						
	Tool	4	37	28	46	16	36						
Part 14	Mach.												
	1	13	*	x	x	6	6						
	2	x	x	*	*	x	x						
	3	x	x	6	12	x	x						
	4	5	*	x	x	6	*						
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	9	x	x	x	x	x	x	x	x	*	9
	2	x	x	*	10	*	9	*	15	*	20	x	x
	3	x	x	10	*	11	*	5	*	*	*	x	x
	4	1	*	x	x	x	x	x	x	x	x	*	11
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	7	7	10	*	x	x	x		
	2	x	x	22	x	x	x	x	*	*	22		
	3	*	22	*	x	x	x	x	7	15	*		
	4	*	*	x	8	*	12	*	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.34 Example Problem 5, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
92%	34	36	31	32	119865
93%	38	40	34	36	123590
94%	45	46	39	42	129565
> 94%	No Feasible Solution Found				

Table 5.35 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	12	13	16	36	43	48	49
Reliability Level								
92%	4	4	4	5	5	4	4	4
93%	4	4	5	6	5	5	4	5
94%	5	5	5	7	6	6	5	6
> 94%	No Feasible Solution Found							

Table 5.36 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	12	17	20	22	26	32	47	49
Reliability Level								
92%	5	5	4	4	4	6	4	4
93%	6	6	4	5	4	6	4	5
94%	7	6	5	5	5	7	5	6
> 94%	No Feasible Solution Found							

Table 5.37 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	1	10	13	28	34	40	46
Reliability Level							
92%	5	4	5	5	4	4	4
93%	6	4	5	5	4	5	5
94%	6	5	6	6	5	5	6
> 94%	No Feasible Solution Found						

Table 5.38 Example Problem 5, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	4	7	16	33	42	43
Reliability Level							
92%	4	5	5	5	5	4	4
93%	5	6	5	6	5	4	5
94%	6	7	6	7	6	5	5
> 94%	No Feasible Solution Found						

5.9.6 Example Problem 6, No Tool Sharing

Example problem 6 consists of eight part types, these are part type 1, 3, 19 and 20. Information about operation times, processing cost and tooling parameters are given in Table 3 and 4 of the appendix, respectively. The results are presented in Table 5.39 through Table 5.45. In this case, machine tool magazines of machine 2, 3 and 4 were fully utilized, Table 5.41. The problem was solved in 3.40 seconds for minimum tooling system reliability of 96%, a total cost of 95185 was obtained.

Table 5.39A Example Problem 6, Total FMS Tooling Cost of $95185, 96% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	98231	200	107781	200	102133	200	105112	200
	0.3	97088	300	102299	300	101142	300	104561	300
	0.5	98231	300	104561	500	**95185**	500	104561	500
	0.7	**95185**	500	105112	500	99099	500	107781	500
	0.9	102299	500	109351	500	96088	500	104561	500
1.2	0.1	102299	200	97088	200	109351	200	102133	200
	0.3	107781	300	**95185**	300	102299	300	97058	300
	0.5	101142	500	99099	500	101142	500	**95185**	500
	0.7	99099	500	96137	500	107781	500	98231	500
	0.9	99099	500	101142	500	107781	500	96137	500
1.3	0.1	101142	200	98231	200	104561	200	104531	200
	0.3	120299	300	96137	300	102133	300	104561	300
	0.5	109351	400	**95185**	500	**95185**	500	104561	500
	0.7	105112	500	96137	500	105112	500	104561	500
	0.9	107781	500	**95185**	500	102133	500	102133	500
1.4	0.1	99099	200	98231	200	102299	200	139351	200
	0.3	99099	300	102133	300	102299	300	104561	300
	0.5	**95185**	500	105112	300	101142	400	102133	500
	0.7	**95185**	500	102133	500	97158	400	98231	500
	0.9	98231	500	107781	500	102299	500	101142	500
1.5	0.1	104561	200	**95185**	200	107781	200	96137	200
	0.3	102133	300	97088	300	104561	300	97088	300
	0.5	99099	400	99099	500	105112	500	96137	500
	0.7	101142	400	99099	500	102133	500	96137	500
	0.9	105112	500	102299	500	101142	500	76137	500

Table 5.39B Example Problem 6, Total FMS Tooling Cost of $95185, 96% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	105112	200	97088	200	98231	200	102133	200
	0.3	109351	300	**95185**	300	97088	300	105112	300
	0.5	104561	400	96137	500	96137	500	99099	400
	0.7	140561	400	102133	500	**95185**	500	104561	500
	0.9	102133	500	101142	500	97088	500	104561	500
1.7	0.1	101142	200	105112	200	107781	200	98231	200
	0.3	104561	300	102299	200	102299	300	97088	300
	0.5	101142	300	102133	500	105112	500	**95185**	500
	0.7	101142	500	107781	500	102133	500	**95185**	500
	0.9	98231	500	139351	500	101142	500	96137	500
1.8	0.1	97088	400	107781	400	98231	400	99099	200
	0.3	98231	400	104561	400	97088	400	98231	300
	0.5	99099	400	102299	500	98231	400	97088	300
	0.7	101142	500	102299	500	98231	400	102133	400
	0.9	96137	500	101142	500	99099	400	98231	400
1.9	0.1	104561	300	98231	200	104561	200	96137	200
	0.3	101142	300	97088	200	102133	300	98231	200
	0.5	101142	300	96137	300	102299	500	97088	200
	0.7	102133	300	99099	400	102133	500	96137	400
	0.9	101142	400	97088	400	104561	500	101142	400

Table 5.40 Example Problem 6, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4			
	Tool	4	37	24	16	36	5	39			
Part 1	Mach.										
	1	6	5	4	7	*	x	x			
	2	x	x	x	x	x	*	8			
	3	x	x	x	x	x	8	*			
	4	*	5	12	9	*	x	x			
	Op.	1	2	3	3	4	4	5	5	6	6
	Tool	20	6	21	25	19	40	18	50	7	33
Part 3	Mach.										
	1	x	x	x	x	x	x	x	x	6	6
	2	*	x	5	*	x	x	12	*	x	x
	3	12	6	*	7	*	*	*	*	x	x
	4	x	6	x	x	7	5	x	x	*	*
	Op.	1	1	2	3	3	4				
	Tool	21	25	14	5	39	38				
Part 19	Mach.										
	1	x	x	7	x	x	x				
	2	*	*	x	*	12	7				
	3	*	12	x	*	*	5				
	4	x	x	5	x	x	x				
	Op.	1	1	2	3	3	4	4			
	Tool	10	22	24	30	35	28	46			
Part 20	Mach.										
	1	x	x	16	x	x	x	x			
	2	*	16	*	8	*	*	*			
	3	*	*	x	8	*	16	*			
	4	x	x	*	x	x	x	x			

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.41 Example Problem 6, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
94%	29	31	31	29	86699
95%	32	35	34	34	88935
96%	38	40	40	40	95185
> 96%	No Feasible Solution Found				

Table 5.42 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	7	14	16	24	33	37
Reliability Level							
94%	4	4	4	4	5	4	4
95%	4	4	5	4	6	5	4
96%	5	5	5	5	7	6	5
> 96%	No Feasible Solution Found						

Table 5.43 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	6	18	21	22	30	38	39
Reliability Level							
94%	5	4	4	4	4	4	6
95%	6	5	4	4	5	4	7
96%	7	5	5	5	6	5	7
> 96%	No Feasible Solution Found						

Table 5.44 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	5	6	20	25	28	30	38
Reliability Level							
94%	4	4	4	6	4	4	5
95%	4	4	5	7	4	5	5
96%	5	5	6	7	5	6	6
> 96%	No Feasible Solution Found						

Table 5.45 Example Problem 6, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	6	14	16	19	24	37	40
Reliability Level							
94%	4	4	4	5	4	4	4
95%	5	4	5	5	5	5	5
96%	6	5	6	6	6	5	6
> 96%	No Feasible Solution Found						

5.9.7 Example Problem 7, No Tool Sharing

Example problem 7 consists of three part types, these are part type 1, 6, 8 and 14. Information about operation times, processing cost and tooling parameters are given in Table 3 and 4 of the appendix, respectively. The results are presented in Table 5.46A through Table 5.52. In this case, none of the machine tool magazines was utilized to its full capacity. The cost of 92772 was obtained in 94.36 seconds for minimum tooling system reliability of 98%. As can be seen from Table 3.42, mathematical model was able to obtain same minimum cost of 92772, however, problem was solved in 306 seconds.

Table 5.46A Example Problem 7, Total FMS Tooling Cost of $92772, 98% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	95741	200	97596	200	94859	200	93792	200
	0.3	96854	300	96854	200	**92772**	300	93792	300
	0.5	94859	500	98617	500	95741	300	**92772**	400
	0.7	94859	500	98978	500	96854	500	**92772**	400
	0.9	98617	500	98978	500	97596	500	94859	500
1.2	0.1	100379	200	96854	200	98617	200	96854	200
	0.3	98617	300	**92772**	300	101678	300	**92772**	300
	0.5	98978	500	**92772**	500	102049	500	94859	300
	0.7	97596	500	94859	500	96854	500	93792	500
	0.9	102049	500	95741	500	97596	500	98978	500
1.3	0.1	97596	200	94859	200	93972	200	99630	200
	0.3	**92772**	300	101678	300	**92772**	300	96854	200
	0.5	**92772**	500	96854	400	93972	500	**92772**	500
	0.7	95741	500	102049	500	93972	500	**92772**	500
	0.9	94859	500	98978	500	100379	500	101678	500
1.4	0.1	94859	200	98617	200	94859	200	93792	200
	0.3	95741	300	96854	300	93792	300	93792	300
	0.5	95741	400	**92772**	500	**92772**	500	99630	500
	0.7	97596	400	101678	500	98978	500	**92772**	500
	0.9	95741	500	98617	500	99630	500	99630	500
1.5	0.1	96854	200	95596	200	100379	200	95741	200
	0.3	**92772**	300	97596	300	100379	300	93792	300
	0.5	96854	500	101678	500	100379	500	**92772**	500
	0.7	98978	500	98617	500	98617	500	93792	500
	0.9	97596	500	102049	500	98978	500	96854	500

Table 5.46B Example Problem 7, Total FMS Tooling Cost of $92772, 98% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	99630	200	98617	200	98978	200	94859	200
	0.3	96854	300	99630	300	95741	300	95741	300
	0.5	97596	500	96854	500	97596	500	**92772**	500
	0.7	97546	500	94859	500	95741	500	95741	500
	0.9	101678	500	93792	500	102049	500	98617	500
1.7	0.1	100379	200	95741	200	94859	200	96854	200
	0.3	98617	300	99630	300	94859	300	97596	300
	0.5	97596	500	96854	500	95741	500	102049	500
	0.7	96854	500	97596	500	96854	500	99630	500
	0.9	102049	500	94859	500	96854	500	101678	500
1.8	0.1	98978	300	98617	400	93792	200	94859	200
	0.3	98978	300	95741	400	94859	300	98617	200
	0.5	98978	400	101678	400	**92772**	400	96854	300
	0.7	100379	400	98617	400	97596	400	96854	300
	0.9	98978	400	101678	400	98978	400	98978	400
1.9	0.1	95741	200	94859	400	94859	300	97596	400
	0.3	99630	300	96854	400	97596	300	99630	400
	0.5	99630	500	93792	400	94859	500	99630	400
	0.7	95741	500	93792	400	95741	500	99630	400
	0.9	102049	500	98978	400	94859	500	101678	400

Table 5.47 Example Problem 7, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4	
	Tool	4	37	24	16	36	5	39	
Part 1	Mach.								
	1	8	*	9	4	*	x	x	
	2	x	x	x	x	x	8	8	
	3	x	x	x	x	x	*	*	
	4	8	*	7	4	8	x	x	
	Op.	1	1	2	2				
	Tool	18	50	31	41				
Part 6	Mach.								
	1	5	x	x	x				
	2	5	5	x	x				
	3	*	5	10	10				
	4	x	x	*	*				
	Op.	1	2	3	4	4	5	5	6
	Tool	6	44	24	15	29	8	23	14
Part 8	Mach.								
	1	x	*	15	*	8	x	x	8
	2	x	5	x	x	x	x	x	x
	3	15	x	x	x	x	9	6	x
	4	*	10	*	*	8	*	*	7
	Op.	1	1	2	2	3	3		
	Tool	4	37	28	46	16	36		
Part 14	Mach.								
	1	8	*	x	x	*	9		
	2	x	x	6	6	x	x		
	3	x	x	6	*	x	x		
	4	*	10	x	x	*	9		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.48 Example Problem 7, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
96%	31	30	30	33	83564
97%	35	34	33	37	87328
98%	41	39	39	43	92772
> 98%	No Feasible Solution Found				

Table 5.49 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	4	14	16	18	24	29	36
Reliability Level							
96%	4	4	4	5	5	4	5
97%	4	5	5	6	6	4	5
98%	5	6	6	7	6	5	6
> 98%	No Feasible Solution Found						

Table 5.50 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	18	28	39	44	46	50
Reliability Level							
96%	5	4	4	4	4	6	3
97%	6	5	4	5	4	6	4
98%	7	6	5	5	5	7	4
> 98%	No Feasible Solution Found						

Table 5.51 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	6	8	23	28	31	41	50
Reliability Level							
96%	5	4	4	5	4	4	4
97%	6	4	5	5	4	5	4
98%	7	5	6	6	4	6	5
> 98%	No Feasible Solution Found						

Table 5.52 Example Problem 7, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	4	16	24	29	36	37	44
Reliability Level							
96%	4	5	5	4	5	5	5
97%	5	5	5	5	5	6	6
98%	6	5	6	6	6	7	7
> 98%	No Feasible Solution Found						

5.9.8 Example Problem 8, No Tool Sharing

Example problem 8 consists of three part types, these are part type 1, 4, 13, 15 and 20. Information about operation times, processing cost and tooling parameters are given in Tables 3 and 4 of the appendix, respectively. The results are presented in Table 5.53A through Table 5.59. As shown in Table 5.55, none of the machine tool magazines was utilized to its full capacity. A minimum cost of 129098 was obtained in 183.40 seconds for minimum tooling system reliability of 93%.

Table 5.53A Example Problem 8, Total FMS Tooling Cost of $129098, 93% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	131873	200	134907	200	131873	200	130686	200
	0.3	**129098**	300	139594	300	133281	300	134907	300
	0.5	133281	500	139594	500	**129098**	500	**129098**	500
	0.7	133281	500	141388	500	130686	500	**129098**	500
	0.9	136353	500	139594	500	130686	500	**129098**	500
1.2	0.1	133281	200	131873	200	133281	400	137076	200
	0.3	133281	300	**129098**	300	134907	400	138522	300
	0.5	133281	500	131873	500	131873	400	139594	500
	0.7	131873	500	133281	500	130686	400	143815	500
	0.9	133281	500	137076	500	**129098**	500	141388	500
1.3	0.1	134907	200	136353	200	138522	200	131873	200
	0.3	133281	300	**129098**	300	137076	300	136353	300
	0.5	136353	500	131873	500	142967	500	**129098**	500
	0.7	139594	500	138522	500	145751	500	130686	500
	0.9	138522	500	131076	500	139594	500	131873	500
1.4	0.1	131873	200	136353	200	133281	200	134097	200
	0.3	**129098**	300	136353	300	134097	300	**129098**	300
	0.5	131873	500	**129098**	300	139594	500	133281	500
	0.7	130686	500	**129098**	300	138522	500	131873	500
	0.9	133281	500	130686	300	136353	500	130686	500
1.5	0.1	134907	200	131873	200	137076	200	131873	200
	0.3	133281	300	**129098**	300	142967	300	133281	300
	0.5	**129098**	500	**129098**	500	145751	500	**129098**	500
	0.7	130686	500	**129098**	500	143815	500	136353	500
	0.9	130686	500	130686	500	142967	500	139594	500

Table 5.53B Example Problem 8, Total FMS Tooling Cost of $129098, 93% Minimum Tooling System Reliability

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	143815	200	134907	200	138522	200	130686	200
	0.3	145751	300	**129098**	300	139594	300	131873	300
	0.5	141388	300	133281	500	141388	500	**129098**	500
	0.7	139594	500	131873	500	139594	500	139594	500
	0.9	138522	500	130686	500	139594	500	137076	500
1.7	0.1	133281	200	130686	200	136353	200	141388	200
	0.3	136353	300	**129098**	300	136353	300	142967	300
	0.5	136353	500	130686	500	137076	500	139594	500
	0.7	136353	500	131873	500	139594	500	138522	500
	0.9	134907	500	133281	500	137076	500	137076	500
1.8	0.1	137076	200	136353	400	134907	400	134907	200
	0.3	145751	200	133281	400	133281	400	137076	300
	0.5	138522	300	131873	400	130686	400	137076	300
	0.7	145751	500	130686	500	131873	400	138522	300
	0.9	136353	500	130686	500	131873	500		400
1.9	0.1	133281	200	137907	200	131873	400	131873	200
	0.3	131873	300	145751	200	134907	400	133281	300
	0.5	141388	500	142967	300	138522	400	133281	500
	0.7	137076	500	143815	400	137076	400	**129098**	500
	0.9	136353	500	142967	400	137076	400	**129098**	500

Table 5.54 Example Problem 8, Part Assignments with Tooling System Reliability Considerations, No Tool Sharing

	Op.	1	1	2	3	3	4	4			
	Tool	4	37	24	16	36	5	39			
Part 1	Mach.										
	1	*	*	10	*	*	x	x			
	2	x	x	x	x	x	8	8			
	3	x	x	x	x	x	*	*			
	4	7	9	6	8	8	x	x			
	Op.	1	1	2	3	3	4	4	5	5	
	Tool	7	33	5	39	21	25	27	1	17	
Part 4	Mach.										
	1	6	*	x	x	x	x	18	x	x	
	2	x	*	18	6	*	*	x	*	*	
	3	x	x	*	12	*	*	x	7	11	
	4	12	x	x	x	x	x	*	x	x	
	Op.	1	1	2	3	3	4	4	5		
	Tool	13	26	49	19	40	10	22	3		
Part 13	Mach.										
	1	*	x	7	x	x	x	x	6		
	2	6	*	5	x	x	*	*	x		
	3	x	6	x	*	*	12	*	x		
	4	x	x	x	12	*	x	x	6		
	Op.	1	1	2	3	3	4	4	5	5	6
	Tool	11	43	14	30	35	7	33	18	50	32
Part 15	Mach.										
	1	12	*	12	x	x	6	*	x	x	x
	2	x	x	x	*	12	x	*	*	*	12
	3	x	x	x	*	*	x	*	12	*	*
	4	*	*	*	x	x	6	*	x	x	x
	Op.	1	1	2	3	3	4	4			
	Tool	10	22	24	30	35	28	46			
Part 20	Mach.										
	1	x	x	6	x	x	x	x			
	2	*	*	x	*	16	*	8			
	3	16	*	x	*	*	8	*			
	4	x	x	10	x	x	x	x			

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.55 Example Problem 8, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, No Tool Sharing

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
91%	30	32	29	31	117452
92%	34	35	33	35	122223
93%	41	40	39	42	129098
> 93%	No Feasible Solution Found				

Table 5.56 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 1, No Tool Sharing

Tool #	3	7	11	14	24	27	49
Reliability Level							
91%	4	4	4	4	4	5	5
92%	5	5	5	4	5	5	5
93%	6	6	6	5	6	6	6
> 93%	No Feasible Solution Found						

Table 5.57 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 2, No Tool Sharing

Tool #	5	13	32	35	39	46	49
Reliability Level							
91%	5	4	4	5	6	4	4
92%	6	5	4	5	6	4	4
93%	7	5	5	6	7	5	5
> 93%	No Feasible Solution Found						

Table 5.58 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 3, No Tool Sharing

Tool #	1	10	17	18	26	28	39
Reliability Level							
91%	4	5	4	5	4	4	3
92%	4	6	5	5	4	5	4
93%	5	7	6	6	5	5	5
> 93%	No Feasible Solution Found						

Table 5.59 Example Problem 8, Redundancies Used vs. Required Tooling System Reliability on Machine 4, No Tool Sharing

Tool #	3	7	16	19	24	36	37
Reliability Level							
91%	4	4	5	4	5	4	5
92%	5	5	5	4	6	5	6
93%	6	6	6	5	7	6	7
> 93%	No Feasible Solution Found						

5.10 Comparison between MM Model and GA, No Tool Sharing

A comparison of the mathematical model (MM) with the genetic algorithm (GA) is presented in this section. The results of applying both models to the eight selected problems are summarized in Table 5.60 and illustrated graphically in Figures 5.5 and 5.6. For example problems 4 and 7; both models provide the same part assignment, tool loading and over all cost, however, processing time is superior for the GA. For the other six example problems considered (1, 2, 3, 5, 6 and 8), the GA showed superiority over the MM, not only in total cost but also in computational time.

Problem 1: It is clear that the GA outperforms the MM in both total cost and computational time. The total cost determined using the MM for reliability level of 99.7% is 98042 whereas, it is 97581 for the same tooling system reliability level. The time required for both GA and MM models was 0.16 vs. 23 seconds and 0.15 vs. 21 seconds for 99.7% and 99.3% minimum tooling system reliability respectively.

Problem 2: There is a clear difference between both models in solving this problem. the GA out performs the MM in both total cost and computational time. The total cost obtained by the GA for tooling system reliability of 90% is 136300 whereas, the total cost for MM is 140063. The GA showed better results in total cost and computational time. The time required for both GA and MM models was 2.47 vs. 53 seconds for 90% minimum tooling system reliability.

Example 3: The results show that the GA performed better than the MM in both total cost and computational time. Both models gave different part assignments and tool loading results as well a different tool spare allocation. Cost value obtained by GA was 132050 and for MM it was 135173. the GA obtained its best solution in 55.42 seconds and MM obtained its best solution in 180 seconds.

Problem 5: The GA out performed the MM in both total cost and computation time. The total cost value determined using the MM for a tooling system reliability of 96% is 136269; the value using the GA is 129565 for the same tooling system reliability of 96%, an 8% decrease. For GA, solution was obtained in 36.30 seconds and for MM, solution was obtained in 74 seconds.

Problem 6: The GA outperformed the MM in both total cost and computational time. For a minimum tooling system reliability level of 96%, the MM obtained a total cost value of 96449 and the GA was able to obtain a total cost of 95185 for the same minimum tooling system reliability and in less computational time. GA obtained its best cost value in 3.40 whereas the MM obtained its best cost value in 101 seconds, both for minimum tooling system reliability of 96%.

Problem 8: The GA outperformed the MM in both total cost and computational time. For minimum tooling system reliability level of 93%, the MM model obtained a total cost value of 138594 and the GA was able to obtain a total cost of 129098 for minimum tooling system reliability of 93%. The GA obtained its best cost value in 183.40 seconds whereas the MM obtained its bets cost value in 776 seconds.

Table 5.60 Comparison of GA and MM, No Tool Sharing Allowed

Example Problem NO.	Tooling System Reliability Level	CPU (sec)		Total Cost	
		MM	GA	MM	GA
1	99.3%	21	0.15	98567	94606
1	99.7%	23	0.16	102042	9581
2	89%	25	2.01	138563	133525
2	90%	53	2.47	145063	139300
3	92%	180	55.42	135173	132050
4	95%	26	1.26	128500	128500
5	94%	74	36.30	136269	129565
6	96%	101	3.40	96449	95185
7	98%	306	94.36	92772	92772
8	93%	776	183.40	138594	129098

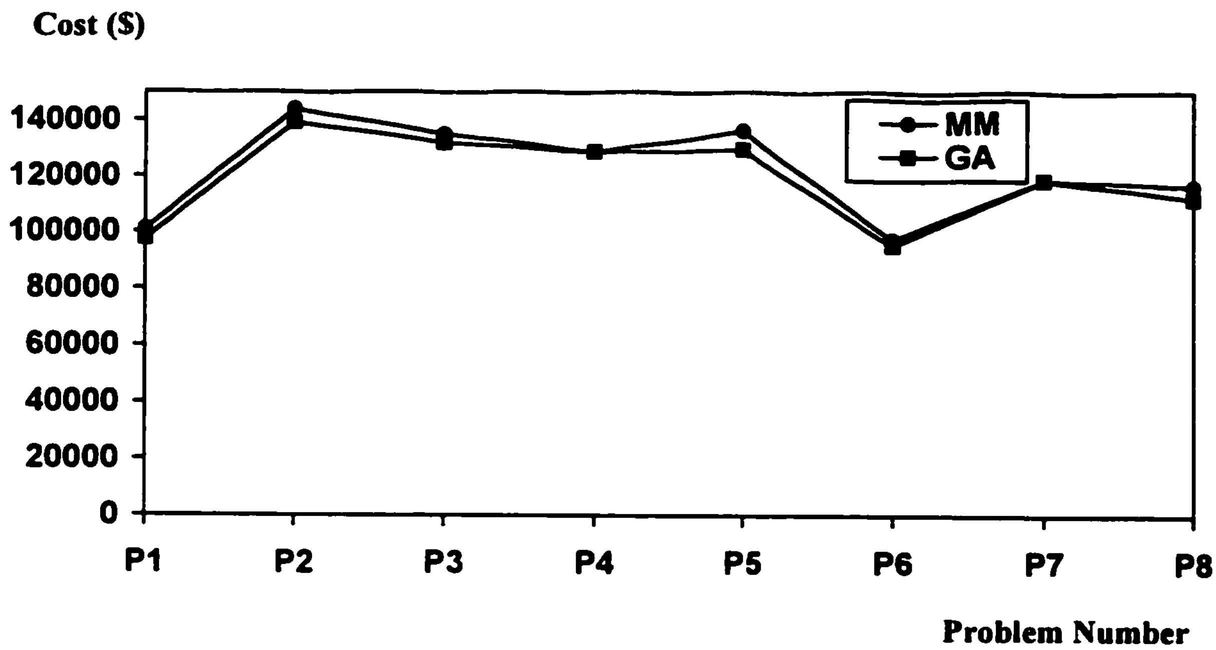

Figure 5.5 Optimal Total Cost Values Obtained by both Models, No Tool Sharing

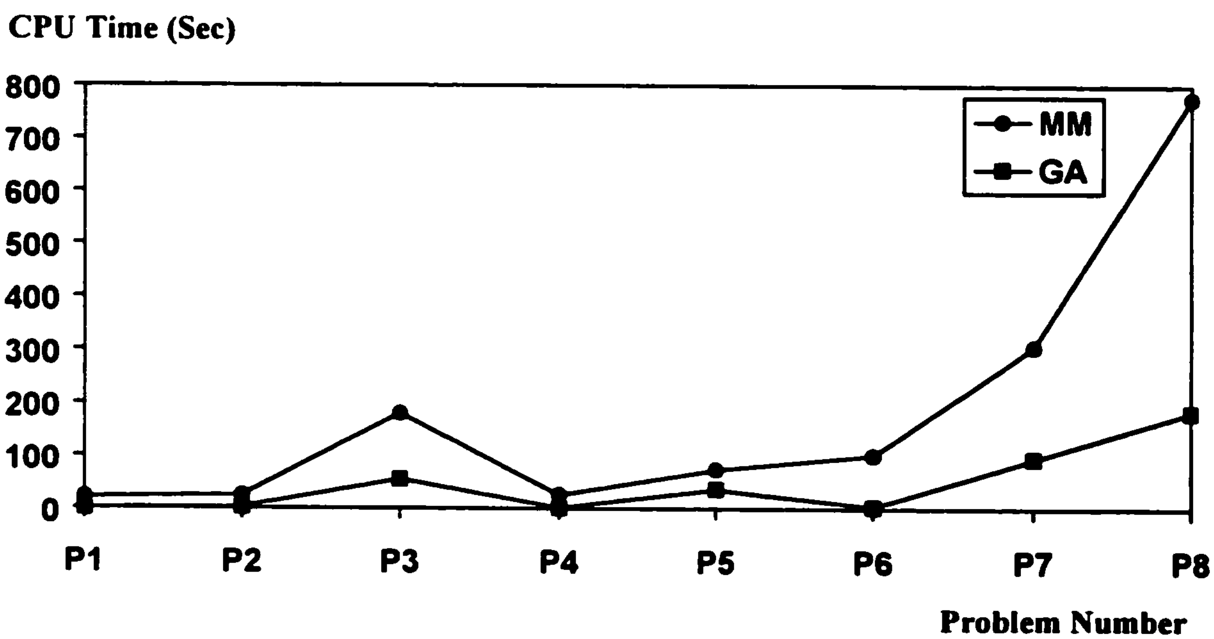

Figure 5.6 Optimal Computational Time Required for both Models, No Tool Sharing

5.11 Example Problem 1, Tool Sharing Allowed

Again and for illustration purposes, this example problem is analyzed in detail. Problem in part taken from Leung and Maheshwari (1992), consists of four different part types. Each part type requires four operations. The production requirements of the four part types are 60, 60, 40, 40 respectively. Each machining center carries a tool magazine of size 50. There are 20 different types of tools. Table 3.1 of chapter 3, provides part-operation-tool compatibility matrix. Machine-tool compatibility matrix and number of tools available for each tool type are given by Table 3.2. Processing times (minutes) and cost (dollars) of each operation of a part on a machine using different tools are shown in Table 3.3 and Table 3.4 respectively.

The selection of best combination of genetic algorithm parameters is the most difficult and time consuming. In this problem the genetic algorithm parameters are population size (PSIZE), selection bias (SELBIAS) and (AMUT) which represents the adaptive mutation rate. Different combinations of these parameters were tested in order to arrive at a suitable set for the tooling system reliability problem. Population sizes of 40 and up to 70 with an increment of 10 were used. SELBIAS ranging from 1.1 to 1.9 and incremented by 0.1; the mutation rates varied from 0.1 to 0.9 in a step of 0.2, and between 200 and 500 generations were used. Table 5.1 gives parameters values for GA calculations for example problem one with four parts, four operations, twenty tool types and several tool copies for each tool type.

Example problem 1 was run for different combinations of population size, selection bias and mutation rate. The performance measure is cost minimization for various minimum tooling system reliability. The search process begins with the proper representation in the form of a feasible solution and evaluation of each solution in the population, and the application of genetic operators to this population for improved solutions. The process continues for a specified number of generations. The results for reliability levels of 99.3% and 99.5% are given in Tables 5.54 to Table 5.56 respectively.

The population size was varied from 40 to 70 with an interval of 10. The selection bias was varied from 1.1 to 1.9 in a step of 0.1 and mutation rate was varied from 0.1 to 0.9 in a step of 0.2. The number of generations was varied between 200 to 500.

Table 5.61A Example Problem 1, Total FMS Tooling Cost of $98150, 99.5% Minimum Tooling System Reliability, Tool Sharing Allowed

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	101115	200	99259	200	101115	200	105167	200
	0.3	103166	300	99259	300	100512	300	100512	300
	0.5	99259	500	101974	500	106290	500	**98150**	500
	0.7	**98150**	500	100512	500	104368	500	**98150**	500
	0.9	99259	500	101974	500	101974	500	101974	500
1.2	0.1	104368	200	101974	200	101115	200	101115	200
	0.3	101115	300	103166	300	103695	300	99259	300
	0.5	99259	400	101974	400	**98150**	500	101115	500
	0.7	100512	400	**98150**	500	102696	500	100512	500
	0.9	99259	500	104368	500	103166	500	100512	500
1.3	0.1	101974	200	100512	200	103166	200	**98150**	200
	0.3	**98150**	300	103695	300	102696	300	100512	300
	0.5	**98150**	500	101115	300	**98150**	500	**98150**	500
	0.7	**98150**	500	100512	400	**98150**	500	101115	500
	0.9	103166	500	103695	400	**98150**	500	100512	500
1.4	0.1	104368	200	**98150**	200	102696	200	104368	200
	0.3	105167	300	**98150**	300	101115	300	103166	200
	0.5	106290	500	**98150**	400	99259	400	100512	300
	0.7	105167	500	101115	400	**98150**	400	101115	400
	0.9	105167	500	100512	500	99259	400	101115	400
1.5	0.1	100512	200	99259	200	101512	200	100512	200
	0.3	100512	300	101115	300	100512	300	102696	300
	0.5	100512	500	103695	500	103166	500	103695	300
	0.7	101974	500	102696	500	100512	500	101115	300
	0.9	100512	500	104368	500	103695	500	100512	400

Table 5.61B Example Problem 1, Total FMS Tooling Cost of $98150, 99.5% Minimum Tooling System Reliability, Tool Sharing Allowed

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	**98150**	400	102696	200	104880	200	109220	200
	0.3	**98150**	400	103166	300	106290	300	108119	300
	0.5	**98150**	400	103695	500	103166	500	105167	500
	0.7	103166	400	100512	500	101974	500	106290	500
	0.9	101350	400	99259	500	102696	500	105167	500
1.7	0.1	100512	200	108119	200	104368	200	108119	200
	0.3	103166	300	105167	300	100512	300	105167	300
	0.5	103166	500	**98150**	500	100512	500	104368	500
	0.7	101115	500	103166	500	103166	500	101350	500
	0.9	106290	500	104368	500	100512	500	105167	500
1.8	0.1	104368	200	104368	200	101350	200	100512	200
	0.3	108119	200	101115	300	101350	300	106290	200
	0.5	103166	300	109220	400	102978	500	109220	300
	0.7	101974	300	108119	400	109220	500	108119	400
	0.9	105167	400	102696	500	106290	500	103166	400
1.9	0.1	103166	200	104368	400	98150	200	102696	200
	0.3	102696	200	**98150**	500	102696	300	101115	300
	0.5	101350	300	100512	500	**98150**	500	99259	400
	0.7	101974	300	98150	500	106290	500	104368	400
	0.9	101974	400	98150	500	105167	500	103166	500

Table 5.62 Example Problem 1, Part Routing of the Different Part Types and Required Operations, Tool Sharing Allowed

	Part Type 1				Part Type 2				Part Type 3				Part Type 4			
	Operation number				Operation number				Operation number				Operation number			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Machine																
1	0	60	*	0	53	48	50	48	24	*	*	40	*	10	*	0
2	15	0	40	53	7	*	0	0	*	*	20	0	0	15	0	40
3	45	0	20	*	*	12	10	12	0	17	*	*	40	*	*	0
4	*	*	*	7	*	*	*	*	16	23	20	*	*	15	40	*

Table 5.63 Example Problem 1, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, Tool Sharing Allowed

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
90%	42	34	34	34	84374
93%	45	36	36	36	86624
97%	50	41	41	41	91624
98%	50	48	44	44	94974
99.3%	50	50	46	48	96974
99.5%	50	50	49	50	98150

Table 5.64 Example Problem 1, Redundancies Used, v/s Required Reliability, Tool Sharing Allowed

M/C #	Tool #	90%	93%	97%	98%	99.3%	99.5%
MACHINE 1	1	5	5	5	6	6	6
	3	5	5	6	6	6	6
	5	5	5	6	6	7	7
	7	4	5	5	6	6	6
	10	7	8	9	9	10	10
	12	9	10	10	8	6	5
	16	7	7	9	9	9	10
MACHINE 2	1	5	5	5	6	6	6
	6	4	4	5	5	6	6
	7	4	5	5	6	6	6
	10	5	5	6	6	6	6
	11	6	6	7	8	8	8
	19	5	6	7	7	7	8
	20	5	5	6	6	7	7
	3	0	0	0	4	4	3
MACHINE 3	2	5	5	6	6	7	8
	4	5	5	5	6	6	6
	6	5	5	6	6	7	7
	8	5	6	6	7	7	7
	9	5	5	6	6	6	7
	12	5	5	6	7	7	7
	17	4	5	6	6	6	6
MACHINE 4	5	5	6	7	7	7	8
	9	4	5	6	6	6	6
	11	4	5	5	5	5	6
	13	4	4	4	5	5	5
	14	5	5	6	6	7	7
	15	7	6	7	8	8	8
	18	5	5	6	7	7	7

5.12 Example Problem 2, Tool Sharing Allowed

Example problem two consists of five part types (parts 2, 4, 13, 17 and 18). The demand for these 5 part types is 20, 18, 12, 20 and 22 respectively. Again tool magazine capacity was restricted t0 50 tool slots for all machines. Table 2 of the appendix, provides machine and cutting tool compatibility as well as number of tools available in the system for each tool type. Table 3 and Table 4 of the appendix, gives operation times (min) of parts on different machines for different tools and operation cost ($) of parts on machines using different tools.

When tool sharing is permitted, all tools within the system are available to all other machines in the entire system. However, tools will need to be passed back and forth between machines as required and to serve as means of reducing overall tooling system cost. Tools transportation from one machine to the other involves lost production time, for both donor and recipient machines. This effect is quantified as a penalty cost of borrowing and is included in the objective function. This system configuration includes tool transporter as a new piece of hardware. Each time a tool is transported from one machine to the other, tool transporter carries away the worn tool into a specified location on the tool transporter device. Therefore, tool magazine capacity of any tool is not violated at any given time. Each tool on any given machine is actually backed-up by all other tools in the system, this in turn reduces the required number of tools in the system. In such case and for reliability analysis, the aggregate processing time is independent of the machine on which any given tool is loaded. The tooling reliability in this case is a function of cumulative hazard rates and total number of spares for each tool type. The model was solved for various values of minimum required tooling system reliability. The total cost was observed for different values of minimum tooling system reliability levels. A tool transporter is ready to transport tools form tool storage room to different machines as well as to exchange tools amongst machines. If a particular tool is 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 model assigns parts to machines for different required operations and allocates tool and tool spares to different machines while minimizing total cost of operation. In order to force tool sharing between machines, tool life was reduced by one half. To be able to compare the two cases no tool sharing and with tool sharing, model was reworked on the modified problem and results were compared.

Table 5.65A Example Problem 2, Total FMS Tooling Cost of $143581, 90% Minimum Tooling System Reliability, Tool Sharing Allowed

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.1	0.1	145735	200	146320	200	144873	400	**143581**	200
	0.3	144873	300	146662	300	145735	400	146320	300
	0.5	144873	500	152730	500	145735	400	145735	500
	0.7	147127	500	150077	500	149620	400	**143581**	500
	0.9	149620	500	147127	500	150077	500	**143581**	500
1.2	0.1	146662	200	147127	200	153108	200	145735	200
	0.3	150825	300	144873	300	151994	300	146320	300
	0.5	148662	300	**143581**	500	146320	400	146320	400
	0.7	146320	500	**143581**	500	149620	500	149620	400
	0.9	146320	500	144873	500	148662	500	152730	500
1.3	0.1	147127	200	144873	200	149620	200	144873	200
	0.3	151389	300	144873	300	147127	300	145735	300
	0.5	146320	300	144873	500	144873	500	**143581**	300
	0.7	151994	400	145735	500	**143581**	500	148662	300
	0.9	153108	400	148662	500	145735	500	**143581**	400
1.4	0.1	150077	200	**143581**	200	147127	200	145735	200
	0.3	149620	300	145735	300	149620	300	145735	300
	0.5	152730	400	**143581**	500	150077	500	147127	400
	0.7	153108	500	**143581**	500	146662	500	151389	400
	0.9		500	144873	500	147127	500	148662	400
1.5	0.1	145735	200	146320	200	145735	200	146320	200
	0.3	151994	300	144873	300	146320	300	151994	300
	0.5	153108	300	147127	500	151389	500	150077	400
	0.7	149620	500	150077	500	147127	500	152730	500
	0.9	147127	500	147127	500	145735	500	147127	500

Table 5.65B Example Problem 2, Total FMS Tooling Cost of $143581, 90% Minimum Tooling System Reliability, Tool Sharing Allowed

		Population Size							
		PSIZE = 40		PSIZE = 50		PSIZE = 60		PSIZE = 70	
SBIAS	AMUT	Value	GEN	Value	GEN	Value	GEN	Value	GEN
1.6	0.1	146320	200	144873	200	148662	200	148662	200
	0.3	146320	300	145735	300	145735	300	144873	300
	0.5	149620	500	143581	500	144873	500	145735	500
	0.7	147127	500	146320	500	146662	500	150077	500
	0.9	145735	500	147127	500	147127	500	149620	500
1.7	0.1	146320	200	145735	200	146662	200	146320	200
	0.3	146320	300	144873	300	146320	300	153108	300
	0.5	151994	500	147127	500	145735	500	144873	500
	0.7	148662	500	149620	500	147127	500	145735	500
	0.9	146662	500	151389	500	149620	500	144873	500
1.8	0.1	144873	200	143581	200	144873	200	145735	200
	0.3	152730	400	150077	300	143581	300	147127	300
	0.5	143581	400	143581	300	153108	500	150825	500
	0.7	143581	400	143581	400	151994	500	148662	500
	0.9	147127	400	145735	400	151389	500	146662	500
1.9	0.1	149620	400	143581	400	152730	200	151994	200
	0.3	148662	400	143581	400	150825	200	150825	300
	0.5	143581	500	149620	400	144873	300	144873	300
	0.7	146320	500	144873	500	147127	500	144873	300
	0.9	143581	500	144873	500	145735	500	148662	400

Table 5.66 Example Problem 2, Part Assignments, Tool Sharing Allowed

	Op.	1	1	2	2	3	3	4	4	5	5		
	Tool	16	36	2	12	4	37	7	33	16	36		
Part 2	Mach.												
	1	16	*	10	*	13	*	13	7	10	*		
	2	x	x	10	*	x	x	x	x	x	x		
	3	x	x	x	x	x	x	x	x	x	x		
	4	4	*	x	x	*	7	*	*	10	*		
	Op.	1	1	2	2	3	3	4	5	5			
	Tool	7	33	5	39	21	25	27	1	17			
Part 4	Mach.												
	1	*	8	x	x	x	x	18	x	x			
	2	x	x	*	6	12	*	x	*	*			
	3	x	x	12	*	6	*	x	11	7			
	4	10	*	x	x	x	x	*	x	x			
	Op.	1	1	2	3	3	4	4	5				
	Tool	13	26	49	19	40	10	22	3				
Part 13	Mach.												
	1	x	x	12	x	x	x	x	*				
	2	*	*	*	x	x	*	7	x				
	3	*	12	x	*	*	*	5	x				
	4	x	x	x	*	12	x	x	12				
	Op.	1	1	2	2	3	3	4	4	5	5	6	6
	Tool	42	48	10	22	13	26	34	47	1	17	11	43
Part 17	Mach.												
	1	*	8	x	x	x	x	x	x	x	x	13	*
	2	x	x	*	10	*	11	*	9	*	*	x	x
	3	x	x	*	10	*	9	*	11	9	11	x	x
	4	12	*	x	x	x	x	x	x	x	x	*	7
	Op.	1	1	2	3	3	4	4	5	5	6		
	Tool	19	40	32	16	36	4	37	28	46	20		
Part 18	Mach.												
	1	x	x	x	8	*	*	10	x	x	x		
	2	x	x	14	x	x	x	x	*	12	22		
	3	*	*	8	x	x	x	x	*	10	*		
	4	10	12	x	14	*	*	12	x	x	x		

x denotes combination of machine and cutting tool is not feasible.

* denotes combination of machine & cutting tool is feasible but no assignment was made.

Table 5.67 Example Problem 2, Effect of Tooling System Required Reliability on Magazine Occupancy and Total Cost, Tool Sharing Allowed

Min. Required Reliability	Number of Tools in Magazine				Total Cost
	M/C 1	M/C 2	M/C 3	M/C 4	
88%	42	40	40	40	134129
89%	46	44	43	43	137452
90%	50	50	50	49	143581

Table 5.68 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 1, Tool Sharing Allowed

Tool #	2	4	7	11	16	27	33	48	49
Reliability Level									
88%	4	5	5	4	6	4	4	6	4
89%	4	5	4	6	7	5	4	6	5
90%	5	6	5	6	7	5	5	6	5
> 90%	No Feasible Solution Found								

Table 5.69 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 2, Tool Sharing Allowed

Tool #	2	20	21	22	26	32	39	46	47
Reliability Level									
88%	5	5	3	4	4	5	5	4	5
89%	5	6	4	4	5	6	5	4	5
90%	6	6	5	5	6	6	6	5	6
> 90%	No Feasible Solution Found								

Table 5.70 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 3, Tool Sharing Allowed

Tool #	1	5	17	21	22	26	32	46	47
Reliability Level									
88%	5	4	3	5	4	4	4	4	3
89%	5	4	4	5	5	4	4	4	3
90%	5	5	5	6	5	5	5	5	4
> 90%	No Feasible Solution Found								

Table 5.71 Example Problem 2, Redundancies Used, vs. Required Tooling System Reliability on Machine 4, Tool Sharing Allowed

Tool #	3	7	16	19	37	40	42	43
Reliability Level								
88%	5	4	6	4	5	7	5	4
89%	6	5	7	4	5	6	5	5
90%	7	6	7	4	6	7	6	6
> 90%	No Feasible Solution Found							

5.13 Advantages and Disadvantages of Model I and II

This section presents the advantages of the developed models. The mathematical and GA models have several advantages and disadvantages.

5.13.1 Advantages

The advantages of the developed models can be summarized as follows:

The developed models incorporate reliability into the part assignment and tool-loading problem.

It does not require conversion of the original decision variables into binary variables, unlike Misra and Sharama (1991).

The developed models are easy to understand and use since the only input data are the number of parts, operations, machines, tools and tool copies, processing time, processing cost of each tool type on different machines for different operations and reliability parameters of tool types on different machines.

4. The developed models allow for alternative routs for different operations in case of abnormal situations such as machine breakdowns and capacity problems.

5. The GA model explains the procedures to obtain the best values for the GA parameters (population size, selection bias, adaptive mutation and number of generations).

6. The developed models return with part assignment and tool allocation along with redundancies required for minimum overall tooling system cost while guaranteeing a pre-set tooling system reliability.

7. The final solution is complete and does not require manipulation or explanation.

8. The developed GA model has the ability to solve large-scale problems in a reasonable amount of time.

9. Where sophisticated equipment is available. Tool sharing can easily and cost effectively be applied.

5.13.2 Disadvantages

The developed models have the following disadvantages:

1. The mathematical model requires a long computational time to solve large-scale problems.
2. The developed models also do not consider other input factors such as machine breakdowns, tool transporter breakdowns and switch failures.
3. Where sensing devices for tracking tool life is not available, tool sharing becomes an expensive option.

5.14 Disadvantages of Genetic Algorithms

Genetic algorithms and like any other solution technique has certain disadvantges associated with it, these are as follows:

- GA's are problem specific which means that there are no packages available that can solve different real life problems.
- Like all other search algorithms, some time is required to develop and test a GA for a specific problem in order to optimize the GA parameters.
- GAs and like other search algorithm do not guarantee optimal solution.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Earlier work in FMS was limited to the part assignment and tool-loading problem and ignored tooling system reliability as another limiting resource. The research related to FMS part assignment and tool allocation to date is also limited to analytical techniques and simulation techniques as well as heuristics. The main criticism to using analytical techniques is that for large-size problems, no optimal solution can be found in a reasonable amount of time. Simulation can potentially be expensive and time consuming to develop, debug and run for FMS planing. The accuracy of any simulation model is limited by the judgement and skill of the programmer. The other drawback is the large amount of time this search approach takes (compared to genetic algorithm) to reach an optimal or near optimal solution because of its experimental nature. The basic problem of using heuristics for part assignment, tool loading and tooling system reliability requirements is that they represent a set of locally greedy strategies that ignore the possibility for global optimization.

In the past, planning models on part assignment and tool allocation did not consider tooling system reliability levels. However, results from this research work show that the tooling system reliability level has significant impact on part assignment and tool allocation decisions in FMS. Therefore, disregarding tooling system reliability considerations at the planning level may result in unrealistic solutions.

As Reliability gets considered at the early stages of the design process, changes can easily and economically be made. Necessary improvements and trade-offs can be considered early in the design stage. Once the weaknesses in the tooling system are identified, solutions may include addition of spares, providing better quality tools or increasing reliability by shortening the predefined tool life. The objective of this research has been to use existing theory to develop a methodology that quantifies and incorporates reliability within the design of flexible manufacturing tooling systems and one that evaluates their performance during their operation. Consequently, the main contribution of this research is both methodological and practical. This is to say that the models and procedures developed constitute tools that can be used by designers and analysts of automated manufacturing systems. The constructed models are capable of describing/predicting the output of FMSs and permitting the user to establish, a prior, desired tooling system reliability parameter levels, as well as other FMS operational parameter levels, within the design and/or operational phases of FMS activity.

It was realized that solutions obtained through the "LINGO" optimization software were time consuming, thus genetic algorithm was developed for the part assignment and tool loading in FMS with tooling system reliability considerations. The results indicated that the developed genetic algorithm obtained solutions to the various example problems in shorter times than results obtained by a mathematical model using "LINGO" optimization software for the same example problems. Cost values obtained by the genetic algorithm were slightly better in most cases or similar cost values as those obtained by the mathematical model using "LINGO" optimization software. Genetic algorithms have been successfully implemented for solving different optimization problems.

Results from example problems show that the tooling system reliability level has significant impact on part assignment and tool allocation decisions in FMS. Therefore, disregarding tooling system reliability considerations at the planning level may result in unrealistic solutions.

In terms of reliability assessment, the tooling system of FMS can be treated as a series system with standby redundancies. The proposed models can provide the number and location of required spares for desired overall tooling system reliability with minimum overall cost as an objective. Two types of systems were modeled and solved for minimum cost with certain tooling system reliability levels. The first system was obtained in part from the literature and both models were applied namely; tool sharing allowed, and no tool sharing allowed. The second case considered a flexible manufacturing cell in a stamping environment, required weld caps for minimum tooling system reliability levels were determined with minimum cost as the objective.

6.2 Research Contributions

The present work contributes to the area of flexible manufacturing systems (FMS) by introducing a cost minimzation model that assigns parts to machines, tools to different machines for processing parts while satisfying a minimum level of tooling system reliability. The contributions of this research are summarized as follows:

1. An integer programming model for the part assignment, tool loading problem in FMS with tooling system reliability considerations has been developed.

2. A genetic algorithm model to solve developed models has been developed.

3. The developed model was extended to consider tool sharing.

4. Models were applied to real-life stamping flexible manufacturing cell, the theme was determining number of weld caps required in order for the cell to run at specific reliability level throughout the production period. Cost minimzation was the objective.

6.3 Recommendations for Further Research

Following are some potential directions for further research:

- In this work, some important factors such as tooling reliability were considered. However, machine reliability was not considered as a factor. The analysis of the FMS assumed that there are no random failures of the machines or the tool transporters. In real life such breakdowns are common and do occur.
- The developed model considers only processing time and cost. It would be interesting to consider other factors such as material handling cost as well as fixture cost.
- Another interesting direction for further research would be to use other search techniques such as simulated annealing and TABU search to solve the developed model and compare the results with those obtained by using the GA.

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APPENDIX

Table 1 Problem Sets

Prob. No.	Number of Parts	Part Number				
1	4	1	2	3	4	
2	5	2	4	13	17	18
3	5	4	9	10	11	14
4	3	5	14	18		
5	3	2	13	14	17	18
6	4	1	3	19	20	
7	4	1	6	8	14	
8	5	1	4	13	18	20

Table 2 Machine and Cutting-Tool Compatibility Matrix

Tool No.	Mac. 1	Mach. 2	Mach. 3	Mach. 4	Inventory
1	0	1	1	0	30
2	1	1	0	0	120
3	1	0	0	1	30
4	1	0	0	1	40
5	0	1	1	0	30
6	0	0	1	1	25
7	1	0	0	1	30
8	0	0	1	1	25
9	1	1	0	0	30
10	0	1	1	0	35
11	1	0	0	1	120
12	1	1	0	0	30
13	0	1	1	0	40
14	1	0	0	1	120
15	1	0	0	1	20
16	1	0	0	0	35
17	0	1	1	0	30
18	0	1	1	0	40
19	0	0	1	1	20
20	0	1	1	0	120
21	0	1	1	0	30
22	0	1	1	0	25
23	0	0	1	1	45
24	1	0	0	1	50
25	0	1	1	0	50
26	0	1	1	0	35
27	1	0	0	1	40
28	0	1	1	0	35
29	1	0	0	1	50
30	0	1	1	0	35
31	0	0	1	1	20
32	0	1	1	0	25
33	1	0	0	1	120
34	0	1	1	0	30
35	0	1	1	0	30
36	1	0	0	1	25
37	1	0	0	1	40
38	0	1	1	0	20
39	0	1	1	0	30
40	0	0	1	1	35
41	0	0	1	1	34
42	1	0	0	1	37
43	1	0	0	1	52
44	1	0	0	1	45
45	1	1	0	0	20
46	0	1	1	0	39
47	0	1	1	0	47
48	1	0	0	1	55
49	1	1	0	0	42
50	0	1	1	0	33

Table 3 Operation Times (min) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination									
1		1	1	2	3	3	4	4			
		4	37	24	16	36	5	39			
	1	4	3	8	14	22	0	0			
	2	0	0	0	0	0	13	9			
	3	0	0	0	0	0	17	12			
	4	4	5	10	19	30	0	0			
2		1	1	2	2	3	3	4	4	5	5
		16	36	2	12	4	37	7	33	16	36
	1	6	9	18	14	15	11	7	12	11	16
	2	0	0	23	19	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0
	4	9	15	0	0	23	16	11	18	18	26
3		1	2	3	3	4	4	5	5	6	6
		20	6	21	25	19	40	18	50	7	33
	1	0	0	0	0	0	0	0	0	5	6
		18	0	7	10	0	0	13	17	0	0
		24	13	10	14	3	5	16	22	0	0
		0	17	0	0	4	7	0	0	6	8
4		1	1	2	2	3	3	4	5	5	
		7	33	5	39	21	25	27	1	17	
	1	6	8	0	0	0	0	8	0	8	
	2	0	0	11	16	15	21	0	4	7	
	3	0	0	14	24	23	32	0	7	11	
	4	8	11	0	0	0	0	12	0	9	
5		1	1	2	3	3	4	4	5	5	6
		4	37	49	18	50	9	45	21	25	14
	1	20	13	4	0	0	3	4	0	0	18
	2	0	0	6	17	12	5	6	11	16	0
	3	0	0	0	23	16	0	0	18	26	0
	4	33	20	0	0	0	0	0	0	0	26

Table 3 Operation Times (min) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination												
6		1	1	2	2									
		18	50	31	41									
	1	0	0	0	0									
	2	14	11	17	28									
	3	23	17	28	46									
	4	0	0	0	0									
7		1	2	2	3	3	4	5	5	6	6			
		49	10	22	42	48	44	31	41	15	29			
	1	7	0	0	14	19	4	0	0	16	21			
	2	10	22	18	0	0	0	6	8	0	0			
	3	0	37	29	0	0	0	10	12	0	0			
	4	0	0	0	19	25	7	0	0	22	30			
8		1	2	3	4	4	5	5	6					
		6	44	24	15	29	8	23	14					
	1	0	13	17	14	21	0	0	3					
	2	0	15	0	0	0	12	16	0					
	3	17	0	0	0	0	19	27	0					
	4	25	22	26	21	32	0	17	5					
9		1	2	3	3									
		27	24	8	23									
	1	7	3	0	0									
	2	0	0	0	0									
	3	0	0	8	12									
	4	10	5	12	17									
10		1	1	2	2	3	4	5	5	6	6	7	8	8
		42	48	18	50	49	14	7	33	5	39	38	9	5
	1	16	25	0	0	3	3	9	12	0	0	0	16	25
	2	0	0	15	9	4	0	0	0	21	15	3	24	37
	3	0	0	23	24	0	0	0	0	28	20	4	0	0
	4	24	38	10	0	0	4	15	19	0	0	0	0	0

Table 3 Operation Times (min) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination													
11		1	1	2	3	4	4	5	6	7	7				
		10	22	38	27	28	46	49	3	9	45				
	1	0	0	0	7	0	0	12	12	11	16				
	2	5	3	9	0	11	15	16	0	14	21				
	3	6	5	14	0	17	22	0	0	0	0				
	4	0	0	0	9	0	0	0	19	0	0				
12		1	1	2	2	3	4	5	5	6	6	7	7	8	9
		34	47	2	12	14	44	15	29	31	41	19	40	38	14
	1	0	0	10	8	5	16	9	13	0	0	0	0	0	16
	2	15	21	14	11	0	0	0	0	0	0	0	0	8	0
	3	21	30	0	0	0	0	0	0	7	11	11	17	12	0
	4	0	0	0	0	7	21	12	18	10	14	15	22	0	20
13		1	1	2	3	3	4	4	5						
		13	26	49	19	40	10	22	3						
	1	0	0	3	0	0	0	0	15						
	2	4	3	5	0	0	7	5	0						
	3	6	4	0	15	20	10	7	0						
	4	0	0	0	20	28	0	0	22						
14		1	1	2	2	3	3								
		4	37	28	46	16	36								
	1	6	4	0	0	12	18								
	2	0	0	8	11	0	0								
	3	0	0	12	16	0	0								
	4	8	6	0	0	20	29								
15		1	1	2	3	3	4	4	5	5	6				
		11	43	14	30	35	7	33	18	50	12				
	1	17	13	7	0	0	16	24	0	0	0				
	2	0	0	0	26	17	0	20	20	12	12				
	3	0	0	0	33	22	0	21	30	18	17				
	4	25	19	9	0	0	23	35	0	0	0				

Table 3 Operation Times (min) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination											
16		1	1	2	2	3	3						
		7	33	28	46	1	17						
	1	4	5	0	0	0	0						
	2	0	0	4	7	8	12						
	3	0	0	7	10	11	18						
	4	5	7	0	0	0	0						
17		1	1	2	2	3	3	4	4	5	5	6	6
		42	48	10	22	13	26	34	47	1	17	11	43
	1	18	27	0	0	0	0	0	0	0	0	12	17
	2	0	0	4	5	6	4	6	9	8	12	0	0
	3	0	0	7	6	9	6	8	12	13	20	0	0
	4	27	40	0	0	0	0	0	0	0	0	19	24
18		1	1	2	3	3	4	4	5	5	6		
		19	40	32	16	36	4	37	28	46	20		
	1	0	0	11	8	12	11	7	0	0	0		
	2	0	0	13	0	0	0	0	12	16	16		
	3	6	8	18	0	0	0	0	17	23	24		
	4	8	10	0	11	16	18	12	0	0	0		
19		1	1	2	3	3	4						
		21	25	14	5	39	38						
	1	0	0	6	0	0	0						
	2	10	13	0	16	11	12						
	3	16	20	0	23	16	16						
	4	0	0	7	0	0	0						
20		1	1	2	3	3	4	4					
		10	22	24	30	35	28	46					
	1	0	0	10	0	0	0	0					
	2	7	4	0	25	17	14	23					
	3	9	6	0	34	23	22	35					
	4	0	0	14	0	0	0	0					

Table 4 Operation cost ($) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination									
1		1	1	2	3	3	4	4			
		4	37	24	16	36	5	39			
	1	23	14	17	26	22	0	0			
	2	0	0	0	0	0	32	21			
	3	0	0	0	0	0	35	18			
	4	24	25	34	19	15	0	0			
2		1	1	2	2	3	3	4	4	5	5
		16	36	2	12	4	37	7	33	16	36
	1	17	14	35	10	25	14	8	32	16	34
	2	0	0	25	32	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0
	4	22	25	0	0	30	29	13	36	19	24
3		1	2	3	3	4	4	5	5	6	6
		20	6	21	25	19	40	18	50	7	33
	1	0	0	0	0	0	0	0	0	20	28
		27	0	15	21	0	0	29	33	0	0
		18	22	23	17	12	8	35	26	0	0
		0	20	0	0	7	14	0	0	27	33
4		1	1	2	2	3	3	4	5	5	
		7	33	5	39	21	25	27	1	17	
	1	15	22	0	0	0	0	8	0	9	
	2	0	0	31	27	25	27	0	7	27	
	3	0	0	34	31	37	31	0	12	35	
	4	17	28	0	0	0	0	18	0	13	
5		1	1	2	3	3	4	4	5	5	6
		4	37	49	18	50	9	45	21	25	14
	1	31	19	21	0	0	32	17	0	0	21
	2	0	0	17	33	19	29	19	25	28	0
	3	0	0	0	25	21	0	0	13	39	0
	4	22	24	0	0	0	0	0	0	0	25

Table 4 Operation cost ($) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination												
6		1	1	2	2									
		18	50	31	41									
	1	0	0	0	0									
	2	20	19	27	22									
	3	18	23	20	14									
	4	0	0	0	0									
7		1	2	2	3	3	4	5	5	6	6			
		49	10	22	42	48	44	31	41	15	29			
	1	14	0	0	11	25	25	0	0	25	24			
	2	21	28	20	0	0	0	18	18	0	0			
	3	0	16	29	0	0	0	21	15	0	0			
	4	0	0	0	15	19	17	0	0	30	25			
8		1	2	3	4	4	5	5	6					
		6	44	24	15	29	8	23	14					
	1	0	17	27	31	23	0	0	28					
	2	0	13	0	0	0	25	35	0					
	3	30	0	0	0	0	21	21	0					
	4	32	34	15	17	19	0	14	27					
9		1	2	3	3									
		27	24	8	23									
	1	26	41	0	0									
	2	0	0	0	0									
	3	0	0	23	26									
	4	22	29	21	16									
10		1	1	2	2	3	4	5	5	6	6	7	8	8
		42	48	18	50	49	14	7	33	5	39	38	9	5
	1	20	19	0	0	25	27	15	23	0	0	0	22	29
	2	0	0	33	41	24	0	0	0	17	22	25	23	29
	3	0	0	25	25	0	0	0	0	17	18	24	0	0
	4	17	14	0	0	0	30	13	21	0	0	0	0	0

Table 4 Operation cost ($) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination													
11		1	1	2	3	4	4	5	6	7	7				
		10	22	38	27	28	46	49	3	9	45				
	1	0	0	0	20	0	0	14	11	17	18				
	2	12	15	11	0	21	13	20	0	12	25				
	3	16	17	9	0	15	12	0	0	0	0				
	4	0	0	0	18	0	0	0	9	0	0				
12		1	1	2	2	3	4	5	5	6	6	7	7	8	9
		34	47	2	12	14	44	15	29	31	41	19	40	38	14
	1	0	0	13	15	34	12	13	14	0	0	0	0	0	9
	2	13	11	14	17	0	0	0	0	0	0	0	0	23	0
	3	12	9	0	0	0	0	0	0	17	13	18	10	18	0
	4	0	0	0	0	29	17	11	11	25	11	15	8	0	7
13		1	1	2	3	3	4	4	5						
		13	26	49	19	40	10	22	3						
	1	0	0	35	0	0	0	0	16						
	2	31	34	33	0	0	30	25	0						
	3	30	29	0	11	11	18	27	0						
	4	15	0	0	10	4	0	0	9						
14		1	1	2	2	3	3								
		4	37	28	46	16	36								
	1	15	20	0	0	13	12								
	2	0	0	17	11	0	0								
	3	0	0	12	10	0	0								
	4	18	6	0	0	5	3								
15		1	1	2	3	3	4	4	5	5	6				
		11	43	14	30	35	7	33	18	50	12				
	1	14	13	21	0	0	12	17	0	0	0				
	2	0	0	0	5	11	0	13	9	11	12				
	3	0	0	0	4	29	0	12	3	15	13				
	4	5	8	16	0	0	14	34	0	0	0				

Table 4 Operation cost ($) of Parts on Machines Using Different Tools

Part	Mach.	Operation-Tool Combination											
16		1	1	2	2	3	3						
		7	33	28	46	1	17						
	1	32	29	0	0	0	0						
	2	0	0	22	21	12	15						
	3	0	0	19	18	13	13						
	4	21	25	0	0	0	0						
17		1	1	2	2	3	3	4	4	5	5	6	6
		42	48	10	22	13	26	34	47	1	17	11	43
	1	12	9	0	0	0	0	0	0	0	0	14	15
	2	0	0	30	30	28	27	20	25	27	11	0	0
	3	0	0	27	22	21	20	21	13	11	9	0	0
	4	10	3	0	0	0	0	0	0	0	0	12	8
18		1	1	2	3	3	4	4	5	5	6		
		19	40	32	16	36	4	37	28	46	20		
	1	0	0	16	17	14	21	23	0	0	0		
	2	0	0	15	0	0	0	0	12	13	12		
	3	33	16	14	0	0	0	0	11	10	10		
	4	26	27	0	19	11	12	13	0	0	0		
19		1	1	2	3	3	4						
		21	25	14	5	39	38						
	1	0	0	15	0	0	0						
	2	21	18	0	11	23	15						
	3	15	10	0	9	13	12						
	4	0	0	18	0	0	0						
20		1	1	2	3	3	4	4					
		10	22	24	30	35	28	46					
	1	0	0	25	0	0	0	0					
	2	26	30	0	10	11	13	12					
	3	25	28	0	4	9	10	3					
	4	0	0	21	0	0	0	0					

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