DESIGN OF TOOL MANAGEMENT SYSTEMS FOR FLEXIBLE MANUFACTURING SYSTEMS

by

Mustafa Özbayrak

BSc, MSc

A Doctoral Thesis

submitted in partial fulfilment of the requirements

for the award of

Doctor of Philosophy

of the Loughborough University of Technology

Department of Manufacturing Engineering

June 1993

DECLARATION

No part of the work described in this thesis has been submitted in support of an application for any other degree or qualification of this or any other University, or the C.N.A.A. or other institute of learning.

ACKNOWLEDGEMENTS

My grateful thanks are made to my supervisor Professor R. Bell for his direction, support, suggestions, interest and help in this research; Dr. R. B. R. De Souza, for his help and collaborative efforts during the early stages of this research work. My gratitude to Dr. E. Roberts for his encouragement for the use of the Taguchi Method for the design of the experiments. My thanks also to my friends and colleagues in the FMS Research Group, GMP 4 and Factory Modelling Groups, especially to Dr. S. T. Newman, Dr R. I. M. Young, Dr. H. Jiao, Mr. A. Tavakoli, Mr. A. Al-Ashaab, Mr. S. Rahimifard, Mr. T. Ellis, Mr. P. Morrissey and Miss. B. Yu for the interesting discussions; Miss. M. Treasurer for her administrative support.

My special thanks go to Mr. P. Coleman for his collaborative efforts at the final stage of the research.

I am indebted to Rockwell International of Peterborough, which sadly closed later, particularly Mr. T. Stratton for providing the data.

Special thanks go to my sister Miss S. Bilgin for her inspiration and encouragement.

My special thanks also goes to the department's computer systems manager, Mr. D. Walters for his support in computer networking and maintenance during the life time of this work.

I wish to express my gratitude to the Sakarya University in Turkey and to Manufacturing Engineering Department for granting me during this research work.

Lastly, the author is very grateful to his wife, Mrs. Selma Özbayrak, who persevered and offered him warm encouragement and help over the past four years.

ABBREVIATIONS

AGV	Automated Guided Vehicle
AMS	Automated Manufacturing Systems
ATS	Auxilary Tool Store
ATC	Automatic Tool Changer
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
CTS	Factory Based Central Tool Store
C[n]	Tool-Oriented Computational Experiments
DCFK	Dynamic Cluster Full Kitting Strategy
DCDK	Dynamic Cluster Differential Kitting Strategy
DK	Differential Kitting Strategy
DNC	Direct Numerical Control
EDD	Earliest Due Date Scheduling Rule
F1	Part family I which contains 15 part type
F2	Part family II which contains 40 part type
F3	Part family III which contains 70 part type
FK	Full Kitting Strategy
FMC	Flexible Manufacturing Cell
FMF	Flexible Manufacturing Facility
FMS	Flexible Manufacturing Systems
GRP	Grouped Parts Scheduling Rule
GT	Group Technology
H	Hybrid Strategies
H[n]	Hybrid Computational Experiments
HSTK	Hybrid Single Tools Kitting Strategy
IS	Internal Scheduling
JIT	Just-In-Time
KBTMSS	Knowledge Based Tool Management Strategy Selection
KES	Knowledge Engineering Systems
LPT	Longest Processing Time Scheduling Rule
MRP	Material Requirements Planning
MRP II	Manufacturing Resource Planning
MU	Machine Utilization
OPT	Optimized Production Technology
PTS	Machine Based Primary Tool Store
PROC	Process Batch Size
SPT	Shortest Processing Time Scheduling Rule

STK	Single Tools Kitting Strategy
STS	Cell Based Secondary Tool Store
T[n]	Taguchi Method Suggested Computational Experiments
TMS	Tool Management Systems
TR	Tool Requirements
TT	Tool Traffic
TTR	Total Tool Requirements
TU	Tool Utilization
T-O	Tool Oriented Strategies
W[n]	Workpiece-Oriented Computational Experiments
WP-O	Workpiece-Oriented Strategies
WIP	Work-In-Process
X-Ref.	Cross Reference

NOMENCLATURE

T_s	Spent Tools
T_m	Minimum Tool Requirement
TI	Tool Inventory = TI_s
TI_m	Maximum Estimated Tool Inventory = TRP + T_s + T_m
TI_s	Tool Inventory Calculated = TRP + T_s
$(TI_s)_{fk}$	Maximum Tool Requirement (Full Kitting)
TRP	Tool Requirements Planning = $\sum_{i=1}^{n}$ (Operation Times x Batch Size) / Tool Life i=1,..,n number of jobs

SYNOPSIS

The objective of this thesis is to study the design and analysis of tool management system in the automated manufacturing systems.

The thesis is focused on two main areas, namely design and experiment. In the first part of the thesis, the design facility created has been reported. The model has been designed using a hybrid approach in which the power of both algorithmic and knowledge based approaches is utilised. Model permits detail, more accurate and complete solutions for the management of tools in a generic manufacturing system.

In the second part of the thesis, to add more understanding to the tool management problems, the interactions of the major tool management design parameters have been investigated using a well known design technique, the Taguchi method. For this purpose, a large number of design experiments have been configured where some have been suggested by the Taguchi method and some have been created by the author to add more confidence, using a large body of real industrial data. The experiments results give deeper understanding of TMS problems and allow design guide-lines to be drawn for the designers.

The design approach and the experiments have been proven to be an accurate and valid tool for the design of tool management systems for automated manufacturing systems. This is indicated in the conclusion of the thesis.

TABLE OF CONTENTS

Chapter 1
Introduction

Manufacturing industry has witnessed radical changes, especially in the last two decades, in the accelerating drive towards the fully automated factory. Advancements in electronic and mechanical engineering and the blend of other disciplines such as computer science and operation management have made the factory of the future virtually possible today.

An important step towards the automated factory is the implementation of a flexible manufacturing system (FMS). An FMS can be defined as a group of CNC workstations linked together by a work and/or tool transfer system and supported by auxiliary equipment and soft automation, all under a supervisory computer control.

Flexible manufacturing systems have been applied to many different kinds of technologies ranging from metal cutting to sheet metal forming and assembly. Although most of the hardware and software are standardized, still an important part of the system varies according to the technology applied. However, one strategic element of an FMS is common in all technologies regardless of the main interest of the system, which is tooling. The efficiency of the system largely depends on the availability of tools. A tool management system's primary interest is to supply tools to assure streamlined manufacturing. The main interest of this thesis is to study the design of tool management systems for a generic manufacturing system.

Many different parameters participate in the design of FMS and in particular the tool management system (TMS). Complex interactions are involved between the design parameters. An FMS will be very inefficient without a great deal of thought and planning going into design and operation of the tool management system.

The research reported in this thesis focuses on a generic manufacturing system. The research reported in this thesis is embedded in three main sections which are the background section up to chapter five, the design section which includes chapters six to ten, and the experiments and results section which includes from chapter eleven to chapter nineteen. The structure of the thesis is illustrated in Figure 1.1. The work commences with an extensive literature survey of automated manufacturing systems and the design, operation and control of tool management systems as well as the modelling and scheduling techniques implemented for system design and evaluation. The developments in four main machining technologies, namely prismatic, cylindrical, presswork and electrical machining technologies, with the emphasis placed on tool management system technologies and supporting systems have been discussed in Chapter 3. The parameter set involved in TMS design and analysis, rules and strategies have been presented in Chapter 4.

A new design platform which is the basis of this research work is introduced in Chapter 5. The importance of the approach adopted and its capability is highlighted. An external scheduling system has been built up using a knowledge-based modelling approach to study tool management in a more natural and balanced manner with regard to part and tool flow. This work is presented in Chapter 6. Tool requirement planning (TRP) modelling which is the core of the entire design work, contains the working mechanisms of the main tool issue strategies and the basis of the tool requirement calculations as well as the modelling capability and assumptions made have been introduced in Chapter 7. Chapters 8 and 9 have introduce the strategy selection and tool management output analysis modules respectively. Since this research work has employed a number of tooling strategies, each one has unique characteristics and the selection of the best strategy has a great importance for a successful manufacturing system. The output analysis is an interrogation system specifically designed to tackle tool management system problems. The system is supported by a fault detection ability which makes valuable contributions to complete the TMS design facility. Chapter 10 is the last chapter in design of TMS section in this thesis and summarizes the design facility presented in the previous four chapters and presents the entire modelling capability of the design facility.

Chapter 11 introduces the main research issues and highlights the TMS parameter interaction problems. Chapter 12 presents the method used for the initial design of computational experiments. After the initial results, in order to gain further understanding more effective computational experiments were found to be necessary and these experiments have been designed separately with the experience gained from the initial design method used.

Chapters 13 and 14 are devoted to the research into the workpiece-oriented approach which is one of the main approaches employed in this thesis. Chapter 13 presents the design of the experiments which use the workpiece-oriented approach. Chapter 13 further explains the rules and strategies applied to the design process to create a more efficient system. Chapter 14 presents the interpretation of results for the approach adopted in Chapter 13.

Chapters 15 and 16 introduce the tool-oriented approach which is the second major approach employed. Chapter 15 presents the tool-oriented approach design for TMS. The previous work done in the laboratory, cluster analysis, has been dramatically improved through new rule sets and strategies and further improved by introducing a dynamic approach through repeated clustering. A new strategy which has been invented through the experimental work, the dynamic clustering differential kitting strategy, is also introduced in this chapter. The rule set and the strategies are also presented in this chapter. Chapter 16 is in parallel to Chapter 14, and studies the tool-oriented approach experimental results using the same primary and secondary level criteria set.

Chapter 17 is the last chapter which presents one of the main design approaches. Another innovative approach, The Hybrid approach which is a composite of workpiece and tool-oriented approaches has been created. The rules and strategies, the design of the hybrid approach experiments as well as the interpretation of the results are presented in this chapter.

A broad comparison of the approaches and strategies employed in this thesis is presented in the concluding discussion chapter, Chapter 18. This chapter further considers a run of the computational experiment for a much longer time period, which introduces one of the crucial topics of discussion for factory level tool inventory organization.

Chapter 19 present the conclusions drawn from the research reported in this thesis and suggest further work.

The sample part data and the complete list of tools as well as the prototype software facility provided with a step by step approach experiment example are presented in the Appendices.

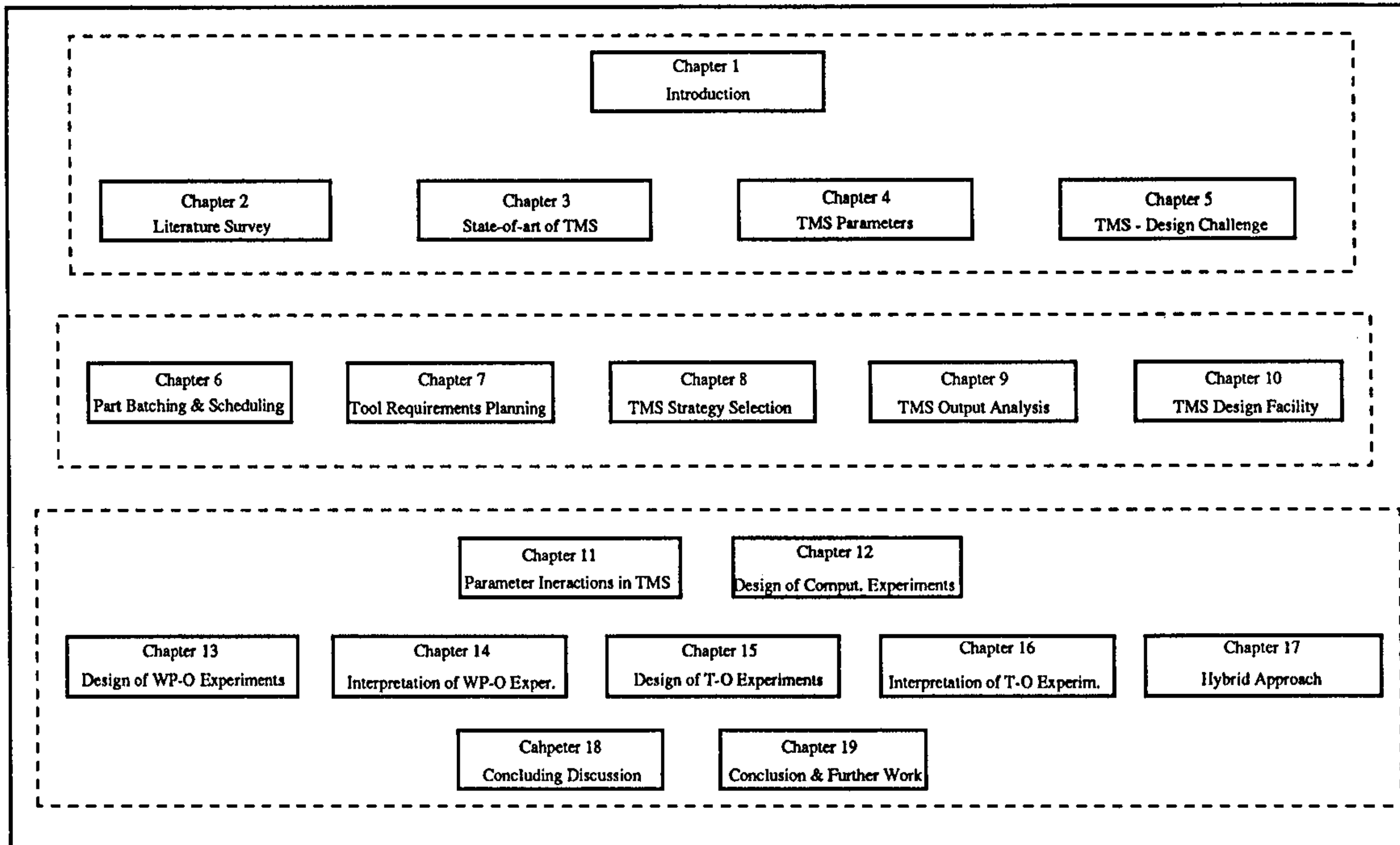


Figure 1.1	Layout of Thesis	LUT-FMS Research Group

Chapter Two
Literature Survey

2.1 Introduction

The scope of this literature survey is to provide a review of tool management system (TMS) within automated manufacturing systems (AMS) environments. The review covers the problems encountered, a discussion of related research works in this area, and the factors and influences on tool flow.

First, the concept, design approaches adopted and the application of AMS are presented, covering prismatic and cylindrical part machining, presswork and electrical discharge machining (EDM).

The concepts behind tool management (TM) are introduced and the structures and strategies in the design, operation and control of TMS are reviewed.

A cross-section of computer modelling techniques for AMS design and evaluation with the emphasis on tool management are reviewed. The factors in the control of AMS at cell level and material flow are encountered.

Finally, a brief survey of production scheduling in AMS is also given.

2.2 Automated Manufacturing System

2.2.1 Concepts of Automated Manufacturing Systems

Since Numerical Control (NC) machines appeared some 40 years ago, the concept of automated manufacturing has been developing constantly. Many engineering areas have been dramatically developed and evolved by both the increased use of computers and the introduction of new engineering and manufacturing concepts such as mechatronics [65] which considers close relations of mechanical and electronics engineering, technologies have had the greatest impact on developments in the manufacturing industry.

The phase of systems integration started in the late 1960s with direct numerical control (DNC), in which several individual machine tools were controlled by a central computer. Two kinds of DNC have been developed: DNC-BTR (behind the tape reader) and DNC-MTC (machine tool controller) [165]. In the latter, which was the original DNC, the central computer controls the individual machines. In the DNC-BTR system, each machine has its own control unit but receives its program instruction from a central computer, which is the program library for the machine system and supervises the individual machine operations by "go and no go" instructions. DNC-BTR thus has elements of distributed and centralised processing and control. In the early 1970s other computer based systems started to evolve; for example, computer aided design/computer aided manufacturing (CAD/CAM) systems and flexible manufacturing systems (FMS).

The ability to satisfy new market requirements, and to survive in a highly competitive market depends on producing cost effective but reliable products. In traditional manufacturing industry most of the cost derives from labour and non-manufacturing time [30]. To be competitive, a manufacturing organization needs to address such as areas as flexibility, work-in-process, inventory reduction, production cycle, throughput and lead time, quick production changeover, rapid reaction to product and market changes, quality of product and service, floor space and so on.

Developments in both computer technology and the electromechanical industry stimulated the solutions to all these manufacturing problems as well as providing the concepts and blocks of flexible automation. With the new technologies, manufacturing industry has been introduced to highly automated manufacturing workstations, with automatic part and tool changing, large tool magazine capacity, intelligent part and tool handling systems, large numbers of auxillary devices such as pallets, fixtures, gauges etc. giving true flexibility and advanced control systems. The first example of flexible manufacturing was the Molins System 24 introduced by Williamson [261]. By the early 70's only a few FMS had been installed throughout the world. The first fully automated factory was built in 1973 in the USA [191]. Early automated manufacturing systems mostly specialized in the metal cutting industry. Latterly, almost every section of manufacturing such as presswork, electrical machining, and assembly has been covered.

One of the most important implication of an automated system is the vast amount of data to be handled throughout the factory to keep system operable.

To understand the full potential of an FMS, the concepts behind FMS have to be understood [191]. A functional layout of a flexible manufacturing system is shown in Figure 2.1.

There is as yet no internationally agreed definition of FMS. A number of different definitions have been made by several organizations, institutions and researchers to demonstrate the different aspects of FMS. In the late 1960s Dolezalek [68] introduced the use of the flexible manufacturing system term. His definition was " a number of machines interlinked through common control and handling system in a such a way that automatic manufacture of different workpieces requiring a variety of different operations could be carried out". One of the machine tool and FMS builders, Kearney & Trecker define FMS as " a group of NC-machine tools that can randomly process a group of parts having different process sequences and process cycles using automated material handling and central computer control to dynamically balance resource utilization so that the system can adapt automatically to changes in part production mixes and level of output" [126]. The Gidding & Lewis philosophy with regard to FMS is " two or more computer numerically controlled units interconnected with automated work handling equipment and supervised by an executive computer having random scheduling capabilities" [76]. The structure of FMS and its interconnection to other parts of the production system as envisaged by Gidding & Lewis is shown in Figure 2.2.

Beside these definitions, several other definitions have been given the researchers such as Bilalis [26] who has defined an FMS as "An FMS consists of a group of CNC machines interconnected by an automated material handling system and all under computer control." Also Groover [95], Merchant [163], Ranky [197] have given their definition and because of the wide research developments that have been undertaken on flexible manufacturing systems, it is difficult to give a strict definition. However, for the purpose of this thesis the following definition is suggested by the author, "An FMS is a production system which has highly automated CNC workstations which are linked by a fully or partially automated part and/or tool handling system all under control of a central computer".

An FMS automatically and completely processes many different kinds of workpieces simultaneously and randomly without human intervention. To do this, an FMS has to have some kind of special hardware and software configuration. CNC machine tools, transportation mechanism such as automated guided vehicle (AGV), robot, conveyor etc. and a central computer are the standard automated hardware configuration. However part programming, scheduling and control softwares are also common within the standard software configuration of an FMS. The term "flexible" is arguably used to indicate the capability of processing many different workpiece types but this flexibility always changes relatively from system to system. However current installations indicate that part type variety ranges from medium to relatively large size [108].

Thus an FMS requires relatively expensive investment, and is very difficult to control and operate . A current trend is to design an FMS as an integration of flexible manufacturing cells (FMC) [112] which comprise two or more machines, usually at least one CNC workstation, multi-pallet magazines and automatic pallet and tool changers for each machine. All machines as well as the operations carried out by the cell, are controlled by a DNC-computer.

The final phase of computer-based systems developments in the last decade of this century is perhaps the computer integrated factory which includes computer integrated manufacturing (CIM) systems as a major ingredient which all operations including planning organization, communication, manufacturing, inspection and marketing are controlled by computers. Figure 2.3 gives a more detailed description of the function and production processes which might be included in a CIM system.

The greatest improvement in manufacturing systems has been made in the area of planning and control of manufacturing systems. New methods, techniques and philosophies for planning and control have been developed and implemented such as group technology (GT) [31], product oriented manufacturing [31], just-in-time production (JIT) [31], optimised production technology (OPT)[31], material requirements planning (MRP) [31], material resource planning (MRP II) [31], and kanban information systems. In these new production organization methods, the main objectives are: the grouping of similar operations, line and production balancing and the achievement of short change-over times, short lead times and a high degree of flexibility within the production system. The introduction of FMS, accompanied by the new methods of production organization lead to significant reductions in lead time, stock level, work-in-process (WIP), entity requirements, floor space, labour, raw material etc. as well as leading to greater productivity, improved quality of product, and high equipment utilization [22][28].

2.2.2 Design of Automated Manufacturing Systems

Automated manufacturing system design is a difficult job and normally takes more time than conventional system design [253]. Fortunately as computer technology develops, this time consuming job is getting shorter, and systems design tools have become more sophisticated in the last decade.

One of the early and significant contributions to the development of automated manufacturing systems was made by the Charles Draper Laboratory Inc. [78]. A group of researchers in this laboratory produced a handbook to aid flexible manufacturing system design and implementation. They tried to answer the questions:

Why use an FMS?
Will FMS best serve your application?
What problem might be encountered?
How do you design an appropriate system?
What is required to operate a system?

Once it has been decided to use FMS technology then part types, machines, transportation mechanism and control and supervisory computer facilities can be selected. The next step is to describe the alternative design configurations and a number of issues relating to this point have been considered [78]:

* flexibility
* alternative material handling
* part machinability
* data and process plans
* system requirement
* ancillary functions such as inspection etc.

Kalkunte et al.[125] present a model classification scheme to provide a framework for systemizing the types of decisions identified with design, justification and operation of FMS. The discussion of the models is organized in four levels according to the level of management and length of planning horizon in which the associated decisions would typically be made. These four levels are designated as Strategic Analysis and Economic Justification (level 1), Facilities Designing (level 2), Intermediate Range Planning (level 3), and Dynamic Operations Planning (level 4).

The quantitative approaches that have been devised to aid decision making at each of these levels have been described in insufficient detail to provide an informed perspective of current capabilities and limitations.

Cutkosky et al. [59] founded a design philosophy on two principles:

1- The cell and its component parts and pieces must be modular,

2- The cell and its components fit in a structured hierarchy.

The modular component parts whether they are grippers, fixtures, lathes or software communication drivers, can be individually designed if care is taken to specify how the modules fit together. If a module is designed as something that can operate on an input and produce an output, then the input-output characteristics define the module.

The second principle provides the design with several important features, such as input-output characteristics of the cell and features of the cell.

Barash et al.[18] have divided the automated manufacturing systems processes into six steps. First step is: parts belonging to the same family are selected on the basis of production needs. The second step is to decide the machines and part batch size, third step is to decide some ancillary configuration and material handling system. Fourth step is to test the system performance. Fifth step is to identify the best system configuration and finally identify the operating rules for this system configuration.

Stecke [231] structured the FMS design problems in two stages: the initial specification and the subsequent implementation.

Kusiak [141] presents a structural approach to the design of FMS. He first classified the FMS design into two categories; system design and process planning. System design has been classified into two main categories: equipment selection and layout design. Some GT techniques are used to solve the design problem as well as to draw attention to product design consideration such as fabrication, machining, assembly and storage in FMS.

Banarjee and Al-Maliki [16] have proposed a structured approach to FMS design. They outlined a number of structured tools for FMS design using structured modelling techniques.

Wang & Bell [253] have developed a knowledge-based modelling system for the design of FMS. A series of flexible rules have been developed to help the design of FMS. The major advantages offered by their system are the capability to quickly design, modify and experiment with a model by manipulating icons and menus and modifying structure parameters and the selection of operational strategies.

Kwok and Carrie [145] have proposed another expert system approach to design of flexible manufacturing systems. They have attempted to combine several design tools such as analytical models and simulation techniques and have tried to integrate them in an expert system to create a better design approach for evaluating a number of different alternatives.

Fry and Smith [83] in their case study have proposed a systematic eight step procedure for the proper installation of an FMS.

* Identify the manufacturing requirements of the parts to be produced,
* Identify and evaluate alternative technologies,
* Choose the appropriate technology,
* Send out request for proposals,
* Evaluate and select the vendor,
* Installation of the FMS,
* Establish system operating procedures,
* Develop of on-going improvement.

Ganiyusufoglu [84] has presented a step-by-step cell design approach in his paper. He presented such an approach for the turning centre from the manufacturers point of view.

Eversheim [73] divides the specification and design of FMS into seven steps. These are analysis of machining requirements, choice of system structure, determination of the machining requirements, determination of the degree of automation, design of the transport system, concept of the organizational control and justification of the economic operation of the system.

Newman [176] has developed a range of modelling and design tools for flexible machining cells in his thesis. He developed a detailed simulation approach (emulation) to model a variety of faces of flexible machining cells. One interesting tool to model FMC is the static capacity analysis model (SCAN) which adds together the total amount of work load allocated to each resource, and estimates the performance from these totals or calculates the gross requirements for the resource. The areas of calculation of the model are: station requirements, transport requirements, manual requirements, work in process, job requirements and tooling requirements. Although the technique is static, it is still a valid tool to estimate the major or ancillary equipment such as number of workstation, tools, parts so on.

2.2.3 Applications of Automated Manufacturing Systems

Based on the arrangement of CNC-machines and materials handling system the following classification scheme for AMS can be obtained [30], Figure 2.4.

Flexible Manufacturing Cells: An FMC is formed generally by one or more CNC workstations with part buffers, tool changer and pallet changer and a material handling system all under a supervisory computer control [254] The large amount of initial investment, over complexity, difficult control and management and large size of FMSs have forced many users as well as manufacturers (vendors) to seek alternatives, which are, much cheaper, more flexible, and easily controllable. Especially nowadays it has been recognized and accepted that there is a need for greater automation coupled with greater flexibility in the manufacturing operation through the use of unattended or lightly attended cells for a fraction of the cost of a full scale of FMS [154].

Spur et al.[229] have described the cell concept for both cylindrical and prismatic part automated manufacturing and have made economic and technological evaluation. Cuthosky et al.[59] have designed a flexible machining cell for small batch manufacturing. They have proposed a range of solutions for the problems that could be faced in any flexible cell. These are basically the careful design of ancillary equipment such as grippers and fixtures to achieve accurate set-up with the aid of robots, the use of several sensors ranging from that for fixtures to vision systems to provide data for the status of cell; a cell host to control the cell which includes machine tool control, ancillary functions control, planning and control of production and communication of the entire system. Besides these, they have emphasized system flexibility.

In many cases the manufacturing cells do not need to be fully automated, but in order to obtain maximum benefit, computer integration is essential [66]. Low cost mini computers and sophisticated automation software create today's powerful cell control system at low risk. The cell approach makes possible improved productivity through limited automation while retaining maximum flexibility. Initial and further investment is minimized and further cells can be created or expanded as the need arises. One of the few examples of a genuinely unmanned machining cell in the UK, working 24-hour day and 7-day week is the disk plant of IBM at Havant [10]. This cell has three Cincinnatti Milacron type T-10 horizontal CNC machining centres, each with a twin pallet changer and each machine is loaded and unloaded by a Cincinnatti Milacron robot. Which also transfers the finished machined parts.

Flexible Manufacturing Systems (FMS):

FMS are usually capable of unmanned, continuous production for at least one shift. This can dramatically increase machine utilisation and productivity. FMS use very sophisticated support facilities. Different part programs must be identified and downloaded to different machine tools automatically. Components need to be loaded, unloaded and transported automatically as appropriate. Swarf needs to be cleared from the machining area and disposed automatically. Automatic washing and inspection facilities may also have to be provided [121].

The ability to release components to the manufacturing system is made by the ability to call up different part programs at different CNC machines very quickly, with the ability to automatically select, transport and load components. Queueing, work-in-process (WIP) and large stock levels are largely eliminated. One of the most important benefits of FMS is to release parts randomly. The term "*flexible manufacturing*" does not necessarily mean flexible enough to produce a large variety of components, but flexible enough to produce components as and when they are required [17] [121].

Another important feature of FMS is the capability of selecting, transporting and changing the cutting tools and components. Many CNC workstation tool magazines comprise up to 220 [135] tools that can be changed automatically. Components have to be delivered to the workstations, loaded and unloaded and when finished transported away to other machines for operations, washing/inspection stations, or storage locations. Robots and/or automated guided vehicle systems are common elements of most FMS installations.

An important factor in the control and operation of an FMS is computer software [154]. Unmanned and unsupervised operation is difficult and unpractical and requires a well-defined and intelligent software system. Software for the purpose of controlling the FMS is responsible for managing the following points: CNC machine tools, NC part programs, material/tool handling, robots, adaptive control or torque control, tool inventories and storage position, tool monitoring, part scheduling and release, finished part storage, tool and data files as well as the warehouse system. Once the system is modelled it may be possible to alter the software should the manufacturing requirements change.

The present developmental status of FMS can be illustrated by examples which are currently in operation. One of the latest examples was built in Worcester, UK, in 1987, by the Japanese machine tool builder, Yamazaki. This plant is the sister plant of Minokamo in Japan and Kentucky in the USA [140][10]. In this plant, the workpiece machining is carried out on three FMS lines and a number of single CNC machines. Materials are transported from the warehouse by two Automated Guided Vehicles (AGV), in the main aisle, instructed by a central production control unit and supplied to and from the FMS lines the sheet metal processing line [140], Figure 2.5.

The FMS lines are the rotational parts machining line, the small prismatic part machining line, and the large prismatic part machining line. The rotational parts line consists of three mill centre lathes which are supported by a robot, automatic jaw changing and an 80 tool magazine and are linked to a Micro Vax computer. The small prismatic parts line consist of seven machining centres and components are fed from a 2 tier stacker on fixtures mounted on pallets. Each machine is equipped with an 80 tool magazine, and a 150 pallet stocker. Additionally the line has two auto stocking cranes, a washing station, 3 co-ordinate measuring machine, an automatic workpiece loading unit, automatic tool replacement system. The large prismatic parts line has three machining centres each again with an 80 tool magazine; 36 pallets are stored holding fixtures and workpieces and transfer is carried out by an automatic stacker crane and five machining centre each with 120 tool magazine and automatic tool replacement system.

2.3. Tool Management Systems in Automated Manufacturing Systems - An Overview.

2.3.1 Tool Management System Concept

Flexible manufacturing systems are designed to produce a medium to large variety of parts with a small batch size in the most economical manner possible. However, the versatility of these systems can be limited by the availability and variety of cutting tools. Especially when the number of machines is increased and interconnected, then the return of used tools, refurbishment and disposal, storage and flow of tools between tool stores becomes a vital element in operating on FMS successfully. Thus, the design and development of a versatile and efficient tool management system becomes a key factor in FMS design to maximize flexibility and utilisation.

The development and improvement of cutting tool design has resulted in improved CNC workstations efficiency [272]. On one hand, new cutting tool materials and advanced tool making technologies which permit higher metal removing capacity and indexable tool tips result in a shorter economic tool life, which has shortened cutting time. On the other hand, new tool management design technologies on the workstations such as modular tool design [127], block tooling systems [205], flexible tooling system and tooling cassette systems [259], as well as improvement in tool changing technology ease the tool storage and handling system greatly.

Hammer [104] stresses the importance of tool management and states several prerequisites for automated manufacturing,

* automatic tool changing and adequate tool magazine,

* automatic tool replacement at job changeover and worn tool exchange through immediate access to a tool pool,

* integrated workpiece cleaning and chip disposal,

* direct monitoring of workpieces, tools and machining process, including error diagnosis.

The essence of successful manufacturing is having tools in the right quantity, in the right place, at the right time as well as having the workpieces. There are mainly three approaches to tool management; manual tooling systems, automated tooling systems and hybrid-mixed manual & automated-tooling systems.

In a manual tool management system, an operator carries the tools to the workstation and manually inserts them into the workstations tool store, namely, a magazine. To keep the human interference to a minimum and to increase the efficiency a tool transporter and workstation magazine capacity should be of the order of 120 tools [233].

As part of fully automated manufacturing, tool management systems are designed to ease tool flow between workstations, by storage in either STS or PTS, and the loading of magazines and transporters. The human interference is eradicated. The best example of a fully automated tool management system is Yamazaki's Worcester plant in the UK. All the workstations have a 80 tool magazine and additionally each FMS line has a 160 tool secondary tool store. Tools are transported to and from the secondary tool store and magazine by two tool transport systems using overhead monorails [140]. The system consists of several modules which operate and control the TMS. These are tool data management and adaptive feed rate control, tool breakage detection system, tool stocker, tool transport robot, tool presetter, tool reader/writer, and a control system which eliminates human error.

Hybrid systems are operable in many installations. The system is designed for fully automated operation but because of the lack of control or lack of true hardware configuration, human interference is advisable at some points, especially for tool loading and unloading and sometimes tool transportation.

The problems that originate in a tool management system are mostly not because of a lack of technology or hardware, but rather because of not truly applying the technology and not truly integrating the tool management system technology and software to other parts of the entire system. The poor organization and management and incompatibility between hardware configuration are the main reasons for unsuccessful tool management systems.

In the literature, complete tool management systems for automated manufacturing systems are few. Researchers usually propose the solution for part of the entire system. These research areas are indeed the basic requirements of any tool management system and may be classified in several groups:.

1- Tool storage, either machine based or cell based [140][131][70][3]
2- Tool Distribution, [4][5]
3- Tool Identification/Recognition [131][27][140][120][262]
4- Tool assembly and preparation [200]
5- Tool Changing [19][136]
6- Tool Scheduling [3][162][273]
7- Tool Standardization [70]

Rhodes [200] has suggested a complete tool management system for FMS and has demonstrated several examples in metal cutting industries. He has described basic FMS tool management parameters as well as emphasizing the functions of those parameters in an FMS. Another early tool management example in flexible manufacturing is described in ElMaraghy's paper [70], in which the framework has been drawn for an automated tool management system which ranges from storing, loading and unloading to sensing cutting tool failure.

A comprehensive and efficient tool management system should contain some key features. Well designed, a computerized system makes easier the tooling planning and control in which the features are embedded.

This starts in the store room [110] then contains every step of physical production until returning tools to the tool room. Tool storage, preparation, loading and unloading, tool identification and recognition, tool transfer, tool scheduling, tool requirements planning and rationalization, tool changing, refurbishing and tool disposal are the elements that should be considered in any tool management system.

The large number of tools in any medium sized manufacturing facility make a tool management database advisable [197]. A comprehensive and reliable tool database is very useful not only to run the tool management but also to run the entire manufacturing system [70]. The tool database controls the tool inventory, satisfies the tool requirements of the system, standardizes the cutting tools, eliminates human error, [140], helps the tool tracking and monitoring. A satisfactory database should contain the features to support the several activities in an FMS. These are the part scheduling, part programming, tool room activities, tool requirements planning and system information. Figure 2.6.

2.3.2. Tool Management System Structure and Strategies.

Hankins et al. [106] described the tool management system by classifying five major components; tool room support, tool allocation, tool distribution, fault detection and tool data flow. They have evaluated several tooling strategies on the configuration of an FMS. These are:

1. Bulk exchange which removes all the tools in each machine at the completion of specific production requirement and replaces them with new requirement.

2. Tool sharing which permits the common tools sharing.

3. Tool migration strategy basically mixture of first two strategies and once magazine loaded, keeps the tools throughout the production period and shares the same tools as much as possible, and exchanges when they become worn.

4. Resident tools assume tools are assigned first and then parts are allocated to machines according to group technology principles which bring the parts together which have the identical operations.

Tomek [245] has defined three basic tooling strategies which are:

1. Batch of parts - group of tools, that copies the conventional job shop approach. For each batch of parts a group of tools are delivered to the workstations and possible tool sharing between succeeding batches is ignored.

2. Several parts batches - one group of tools - based on group technology and sharing identical tools among several batches.

3. Common tool inventory shared by a group of machines - this strategy ensures the ability to respond to any unexpected situations. Tools are preloaded to minimise the migration of tools between machines. Most often required tools reside in the magazines. Tool sharing among machines is permitted .

Luggen [154] have described four strategies. These are mass-exchange which is a similar strategy to Tomek's batch of parts - group of tools and Hankins et al, bulk exchange strategy. Tool sharing which is improved form of bulk exchange and shares the tools between succeeding batches, migration at the completion of workpiece type which takes the concept of sharing one step further than the previous strategy. This strategy further reduces the tool inventory through sharing between batches. Finally assigned tools strategy which aims to respond to the need of flexibility. The strategy first identifies the high usage tools for the entire production mix, and those tools reside in each machine magazine for the entire production period. Migration can then be used with the remaining pockets.

DeSouza [66] has classified tool management strategies first at two levels: workpiece-oriented strategies, and tool-oriented strategies. Then workpiece-oriented strategies are classified, complete duplication strategy, limited duplication strategy and continuous replenishment strategy. However tool-oriented strategies are classified as work tool clustering strategy, restricted clustering strategy and random flow strategy.

Additionally, De Souza [66] has classified tool issue strategies to distinguish from tool management strategies. Tool issue strategies are:

- Total tool changeover
- Tool kitting strategy
- Differential or modified tool kitting
- Single tools
- Tool cluster sets
- Resident kits, and
- Functional tool number issue

Several other researchers have suggested and implemented several tooling strategies under different names but basically the working mechanisms of the strategies are similar. These are; AMAZON [8], Gyampah et. al [99], Graver and McGinnis [94].

Borghi et. al. [27] have developed a tool resource management philosophy which involves bar coding, and the management of each physical tool from the tool room to the spindle and vice-versa; management of tool transfer from one machining centre to another while maintaining the data intact; tool change management in hidden time from primary to secondary tool magazine in a machining centre.

CIMTOOL [46] has designed and developed another tool management system especially for the control of high value tooling such as, jigs and gauges. The system consists of eight modules which are, tool and gauge monitoring, tool kitting, tool stock control, tool life analysis, interface to manufacturing, tool status reporting, tool costing and tool maintenance.

2.3.3. Tool Management System Design, Operation and Control

Several tool management design and implementation researchers include De Souza and Bell [67], Carrie and Perara [36], Carrie and Bititci [35], Giardini [88], Syan [237], Happersberger [107], Lynee [156] and software companies have designed tool management systems either for a specific manufacturing system or for generic systems. One of the early tool management design paper was presented by Rhodes [200].

Rhodes described the basic FMS tool management parameters such as number of workpieces, operation time, number of tools, magazine capacity etc. and presented several tool management system implementation examples in several metal cutting industries.

ElMaraghy [70] described an automated tool management in flexible manufacturing and emphasized tool transfer, tool storage, loading and unloading, tool control systems, tool cutting failure and tool database.

Kurimoto et.al. [140] and Kurimoto [139] outlined the design, layout and operation of a fully integrated tool management system for a fully automated manufacturing system from the manufacturers point of view and they have illustrated one fully automated system as an example.

Bell and De Souza [23] have presented another tool management design facility for a highly automated manufacturing system. They focused especially on tool flow in the system, and related technologies such as tool transfer, tool storage, tool exchange, tool refurbishment and control. An algorithmic model has been developed to aid the design work. De Souza [65] has designed another algorithmic model for the system where prismatic parts are produced.

Zhang [272] developed another tool management design facility for rotational parts. He developed an algorithmic model to design tool management for systems where rotational parts are produced. He tried a range of part scheduling algorithms to determine the tool requirements in different working conditions. Some detailed outputs for tools, chuck jaws and ancillary equipments have been obtained.

Silva [220] has designed a simulation tool to design tool management in FMS and obtained some very detailed outputs.

Some of the mathematical programming and heuristic approaches to tool management design and operation problems include the studies of Bard [19] who developed a heuristic to minimize the total number of tool switches on a flexible machine and his model is based on part variety. Tang and Denardo [242] [243] developed another heuristic mathematical model to minimize the total number of tool changing instants. Co et al. [53] deal with batching, loading and tool configuration problems in FMS and have built a mathematical model to overcome tooling and related problems. Their model is based on minimizing difference in workload between two stations in a batch. Koulamas [136] presented several methods to compute the tool requirements in multi-level systems. He calculated tool requirements by using the Bill-Of-Materials (BOM) matrix and a tool data matrix and presented another algorithm to minimize tool requirements which was based on slower machine speed. Finally, Koulamas presented a search technique to find out the optimum tool requirements solution. These methods are valid, but the algorithm based on slower machine speed totally ignores the effect on throughput time. This fundamental measure of manufacturing performance is severely increased in this case. Acaccia et al. [4] have developed an expert-simulation of tool distribution for factory automation and they discussed tooling integration in flexible manufacturing for a short term manufacturing period. Acaccia et al. [3] again have another expert system approach that provides an expert scheduling system for tool stock to satisfy long term production requirements.

A number of tool management systems have been installed throughout the world and to describe even some of them is far beyond this thesis.

2.4 Modelling of Automated Manufacturing Systems

Automated manufacturing systems are very complex systems in which a lot of entities are involved in either the design stage or the operation stage, and are needed to make careful decision at each stage. In today's competitive manufacturing world, careful planning and analysis of alternative strategies and design is essential.

To experiment on hardware is sometimes simply impossible and always too expensive to coup. Modelling tools are very useful to analyse systems both in the design stage and the operation stage. There are many different kinds of decisions to be made, and therefore, there are many different ways to model the system, depending on the emphasis given to different aspects.

The key step in modelling is to build up a model which expresses the behaviour of the system. The objective of the model building is to track the model behaviour as well as estimating the possible changing result. It is important for the designer/engineer to recognize that the model can include only some features of the system and it can only focus on those features of the system which may determine the performance and identify the influence of the various factors which interest the designer/engineers [137]. The model has to be a simplification of reality. There are several reasons for this. Firstly, a more complex model takes more time to build up. Secondly, a more complex model is difficult to understand, in the sense that the way in which the various parameters influence performance can involve complex interactions that are hard to perceive. On the other hand, if the model is too simple its reflection of performance could be entirely inaccurate and the model may not represent all the key design and operating decisions.

It is desirable to be involved in modelling starting when the original concept for the system is defined and carrying through the entire planning, design, installation and operation. It is essential that the modellers use a model development strategy that ensures that the models are flexible and able to be either used as they stand or modified easily as the requirements of the modelling exercise change. However, besides this goal, the model has to be able to demonstrate and convince the user that the model represents correctly the way in which the system will be operated. Further, the model has to be efficient in its use of the resources required to develop and use it. Finally, the model should have a user interface that will enable it to be used without the modeller being present, that is, the model has to be easy to use, display results in a clear and well organized manner, and force the user to specify data inputs in an unambiguous manner [33].

Classification of models, as a result, can be conducted in several ways [234]. Solberg [224] has classified models according to form, the system objective, the time nature and the variability. Wilhelm and Sarins' [260] classifications on the models is presented by Doumeingts et al. [69] based on the level of abstraction, the nature of the model and the various steps of the life cycle. For the purpose of this thesis only the major modelling methodologies are explained. Some broad classification of modelling can be found in Ref. [254].

2.4.1. Analytical Modelling

Analytical Models are constructed at the beginning of the modelling stage to predict the system behaviour quickly. Analytical models do not describe detailed events but rather allow rapid evaluation about the system. By omitting detail and simplifying the assumptions, the model can be constructed quickly but these models are often criticised for lack of realism and their simplicity [33].

Analytical modelling can be done using several techniques which include static capacity analysis, queueing networks, mathematical programming, heuristic algorithms, semi-Markov processes and Petri-Nets [254].

Mathematical programming is often used to model automated manufacturing systems because of the quick construction and less computational effort requirements as well as very quick response to the modelling effort. The primary techniques available include linear programming, non-linear programming and dynamic programming [231]. The main disadvantages of mathematical modelling are the limited level of output provided, the original system has been too simplified and sometimes it is very difficult to model several entities in a manufacturing system, thus, the reliability is not so good. However, they are still valuable tools for modelling the manufacturing systems in order to gain a quick response.

The preliminary theory of queueing networks was established by Jackson [119] where he identifies the criteria for the construction of a network of queues. These type of models can provide approximate solutions with a certain degree of detail and accuracy. The queueing models applied to automated manufacturing modelling including the studies of Solot and Bastos [228], Baskett et al., [21], Gordon and Well [91] and Schweitzer [213]. Solberg [225][226][227] developed the first model for FMS design based on closed queueing networks. The CAN-Q (Computer Analysis of Queueing of Networks) model allows the user to calculate a number of system performance figures such as production rate, machine utilization, queue length distribution, flow time and output sensitivity.

MVA (Mean Value Analysis) is another queueing network model which provides steady-state mean performance measures [199][20]. It can model some more detail features than CAN-Q but it is still unrealistic in some assumptions, like the probabilistic entry of parts and exponential processing times.

Suri and Hildebrant [236] developed the MVAQ model for FMS design. The MVAQ modelling tool has proven to be an efficient model to determine the optimum number of machines in each machine group, the minimum number of pallets/fixtures, the best configuration for multi part types and many other entities.

SCAN (Static Capacity Analysis) [176] has been developed by Newman to compute the gross requirements of the production for flexible machining cells. These areas of calculation of the model are:

- station requirements,
- transport requirements,
- works in process,
- job requirements, and
- tool requirements

Lenz [150] developed a design tool which is called SPAR used for aggregate capacity planning of a manufacturing system. Typical model output includes the number of machines, transporters and pallets.

Another analytical modelling approach was Petri Nets which model the dynamic behaviour of discrete concurrent systems [7]. Manufacturing systems can be described in a graphical form and this allows easy visualisation and communication of the complex interactions among different components. The other important feature is that Petri Nets based models are executable, i.e. the simulation code can be generated automatically from the specification of the net. Therefore, the performance measures are obtained by direct simulation of the net, without the need to write additional software.

2.4.2 Simulation Modelling

There has been a dramatic increase in the use of simulation for manufacturing systems modelling and analysis during the past decade. Due to the complexity and the large amount of entities that are involved in the design of flexible manufacturing facilities, simulation has become the most widely used modelling tool for manufacturing design. Since automated manufacturing systems are far more complex in terms of hardware and planning than traditional job shop manufacturing systems, a simulation model with great detail and extensive computer support is an effective and reliable tool. Although a wide range modelling approaches such as mathematical and analytical models, artificial intelligence techniques and heuristic models, (used preferably in the development of preliminary design and more appropriate to solve specific problems- such as scheduling and machine loading-) are available for manufacturing system design, simulation can provide more detail and more precise modelling output as well as envisaging the dynamic behaviour of a manufacturing system. The development of simulation techniques and their application in manufacturing has been studied by Carrie [34], Law [147], Schorer and Tseng [211], Newman [176], Wang [254].

Events such as part and tool flow, machine breakdown, transportation activities, labour and other work forces like robots are very significant events in any automated manufacturing system and the ability to include them in the model is significant [72].

Emulation models are the ultimate development of the simulation concept. They provide a detailed insight into the complete system, to such an extent that they can be used as the foundation for the control software of the finished installation. Conversely, although simulation or emulation models provide a more realistic picture of the entire system, simulation basically is not an optimization technique and the number of controllable variables in designing any automated manufacturing system is usually very large. Hence, the analysis procedure of simulation models is cumbersome and the analyst can sometimes leave the optimal and near-optimal alternatives untested. Further simulation models require considerable expertise and experience.

Simulation languages have been classified according to their simulation approaches to the real system by Zhang [272]. Those are:

1. Discrete-Event, three phase system which are time increment, Scans the activities, and terminating to finish.

2. Discrete-Event, two phase systems which is a combination of the previous two phases.

3. Continuous systems that use a process type description of the activities.

Simulation languages such as GPSS (General Purpose Simulation System) [212] which is a discrete-event simulation, SIMAN [192], and SLAM [186], have made easier the simulation of large and complex systems. Commonality in these simulation languages makes them easier to learn, less flexible, most of them are data driven and largely support report, graphics and animation facilities.

Tens of new commercial simulations have been released to assist the non simulationist and simulationist alike to model either manufacturing systems or non manufacturing systems in a relatively short period of time. These packages include TESS [92] Map/1 [203], Simple-1 [55], MAST [149], XCELL [57].

The SIMAN simulation language was developed by Pedgen [192]. It is a FORTRAN based language designed to run on large and minicomputers as well as on micro computers. The SIMAN model framework is built up of two basic components, the model itself and the experimental framework. It may be constructed to model discrete, continuous and discrete-continuous systems. The language used is a general purpose simulation language but has a very detailed manufacturing system modelling capability with special purpose system blocks such as AGV, Conveyor, Station, etc. SIMAN is supported by a powerful graphical animation package CINEMA which consists of two parts. The first, called CINEMA, is used to define the graphical images used in the animation. The second, called CSIMAN is used to execute the animation. Both programs have a user-friendly graphical interface which does not require any programming. The three main benefits of animation may be summarised as follows [164]:

1. Model Verification, which visually verifies that the model is behaving like the actual system.

2. Bottleneck analysis which makes it easier to understand the system status and any bottlenecks that occur.

3. Presentation & Communication.

Traditional simulation languages can provide adequate quantitative representation and analysis. They do not always provide enough information to the user for high level decisions [239].

The most recent developments in simulation studies involve the combination of simulation and artificial intelligence methods to create a more intelligent simulation output and statistical analysis [102].

To overcome the difficulties of interpretation of large amounts of output and to eliminate the weakness mentioned above, expert systems and other AI techniques have been incorporated within simulation power. This incorporation has led to new approaches as well as increasing the feasibility and flexibility of simulation modelling for automated manufacturing design. Such work has been reported by Norrie et al. [179] under the FLEXES project. Several design and analysis modules have been built successfully using both AI and simulation tools [187][215][184][148].

2.4.3. Algorithmic Modelling

The algorithmic approach is another approach to modelling manufacturing systems in detail and efficiently which is feasible and acceptable [232].

The algorithms deal with the scheduling of chains of events and form the basis for the modelling of the systems. The use of the algorithmic approach provides a powerful tool to design, control and operate manufacturing systems in a practical manner. This approach, unlike simulation, has the ability to record, manipulate and output considerable amounts of user specific data on the operation of manufacturing systems, other than the normal statistical based outputs obtained from simulation [272].

Stecke and Kim [232] studied part type selection, machine grouping, production ratio, resource allocation and loading problems for FMS using several heuristic algorithms. Rajagopalan [195] applied the algorithmic approach to the formulation of solutions for part grouping and tool loading problems in FMS. The same approach was employed by Suri & Whitney [235] to solve several FMS problems, including batching, balancing, scheduling and dispatching, transportation and tooling. Co et al. [53] have studied part batching under tooling constraints for FMS applying the algorithmic approach.

Mukhopadhyay et al. [170], suggested several heuristic solutions to scheduling problems in FMS. A wide range of researchers have proposed several modelling and solutions procedures for scheduling problems in FMS including, Hutchison et al. [115], Kusiak & Jaekyoung [143], Sycara, et al. [238], Chan and Bedworth [40] , Gupta & Tunc [97]. Algorithms deal with machine tools, buffer storages, part and tool transportations. The following points are the common problems which are to be solved: part scheduling, tool allocation, pallet scheduling, and machine scheduling.

De Souza [66], Zhang [272] both used algorithmic approaches to investigate the modelling of tool flows in automated manufacturing systems for prismatic and cylindrical parts respectively. As shown in Figure 2.7, the total tool flow in a manufacturing system has been presented as a hierarchy of tool supply. For the defined machine, cell and factory levels, the primary tool store, the secondary tool store and the central tool store are the corresponding focal points.

Zhang's thesis [272] has focused on turning automation and tool flow. He has examined the tool flow problems and using the same model, labour requirement and machine utilization, which are time related and complement the main stream tool flow modelling to produce a balanced modelling tool.

The modelling of activities incorporates the full range of tool assignment, issue, storage, and transfer strategies. The operating of turning cells from manually operated, manually supported, to highly automated cells has been modelled. The turning model at the central tool store (CTS) level models the CTS tool issue, tool preparation and disposal. Fig.2.8.

2.4.4. Knowledge Based Modelling

Artificial Intelligence (AI) is a branch of computer science that uses computers to mimic behaviour usually associated with human intelligence. The primary concern is to find an effective way to understand and apply intelligent problem solving, planning and communication skills to a wide range of practical problems. In spite of the variety of problems addressed in AI research, a number of important features emerge that seem common to all divisions of the field; these include [155]

- the use of computers to do symbolic reasoning,

- a focus on problems that do not respond to algorithmic solutions,

- problem solving using inexact, missing, or poorly defined information and the use of representational formalism that enables the programmer to compensate for these problems,

- an effort to capture and manipulate the significant qualitative features of a situation rather than relying on numeric methods,

- answers that are neither exact nor optimal, but in some sense "sufficient",

- the use of a large amount of domain-spesific knowledge in solving problems,

- the use of meta-level knowledge to effect more sophisticated control of problem solving strategies.

This new exiting technique has become the new frontier of practical applications of computers and has attracted researchers who work in manufacturing system modelling and analysis.

One significant branch of AI, expert systems (ES) produce intelligence behaviour by operating on the knowledge of a human expert in a well-defined application domain. The ability to operate on knowledge gives the expert system the capability to perform its task at a skill level usually associated with the expert. Because knowledge is the key ingredient in an expert system, such systems are often called knowledge-based systems [174] . The basic structure of an expert system is shown in Figure 2.9.

Application of Knowledge-Based modelling technology to improve manufacturing system modelling and analysis has become a widely used tool among the researchers. Show & Whinston [218] have suggested AI techniques to solve the planning and scheduling problems in FMS. They have used a knowledge-based system to identify the planning and scheduling issues in FMS, and developed a four step nonlinear planning scheme.

Fox & Smith developed a factory scheduling system which is called ISIS, using a knowledge-based approach [81]. ISIS has focused on constructing a knowledge representation that captures the requisite knowledge of the job shop environment and its constraint-directed search and developing a search architecture.

Pan et al. [189] have drawn a broad framework for a CIM environment including the modelling of processes, equipment, facilities and operational procedures using knowledge-based systems.

Mellicham & Wahab, [160]have developed an expert system for FMS design. The expert system was developed to analyse the output from an FMS simulation model to determine whether operational and financial objectives were met.

Clarke [52] has used a knowledge-based system for the configuration of industrial automation systems and has developed a knowledge-based system called PROKERN-XPS emulating the configuration engineer's approach.

Caselli et al. [38] have discussed the integration of structural, functional and control knowledge in manufacturing workcell modelling, simulation and design.

Recent developments in computer technology have led to several approaches being used for particular situations. The integration of knowledge-based systems, simulations and graphical output presentation has made the AI based systems more powerful focussing on explanatory output and natural language input [161]. Additionally, traditional simulation model processing has employed the forward chaining mode, whereas the AI systems can run under both forward and backward chaining control. Time ordering and dynamic processes have been at the core of simulation modelling but AI integrates traditional dynamic modelling with other symbolic forms of state transition representation such as casual inferencing [187][215].

A large number of research studies including: Ford and Schreer,[80], Haddock [101], O'Keefe [184], Fan and Sackett [74] and Lenz [148] have covered the design and analysis of FMS and it is beyond this thesis to include all studies done.

2.5. Control of Automated Manufacturing Systems

Since the involvement of computers in manufacturing industry, new control and planning methods and techniques such as MRPI, MRPII, JIT, MPS, CRP have been implemented in manufacturing to reduce costs, inventories, lead time, work-in-processes and improve product quality, production capacity, productivity, production cycle time and customer service [241].

Due to the large amount of complex tasks in automated manufacturing systems, the control philosophy is implemented through the hierarchical architecture [124][43].

Jones & McLean [124] have proposed a five level control architecture which comprises facility, shop, cell, workstation and equipment control. This five level control mechanism supplies a top-down control hierarchy and each level has its own functionality.

Huang and Chang [112] have proposed a four level control hierarchy of FMS. This is split into (1) Factory level:includes control of factory, production scheduling, information management and manufacturing engineering; (2) plant level: includes control of task analysis, resource allocation, dispatching and monitoring; (3) cell level: includes control of set-up workstations and overall cell control which may include stock, manufacturing, transport, packing, inspection, shipment etc., (4) workstation level: includes control of material handling, software buffer and machining which may include robots, CNC machines, conveyors etc.

Warnecke & Dangelmaier [255], have pointed out five major places where production control is necessary,

1- existing production area,

2- on entering the production area in question,

3- where the material flow is divided because of multiple use and splitting

4- where material flows merge after splitting and in assembly,

5- where working speed is changed.

Stecke [230] defined the control problems to be those associated with the continuous monitoring of the system, i.e. the keeping track of production to be certain that the production requirement and due dates are being met as scheduled and they listed four points which have to be specified:

1) Determine a policy to handle machine tool and other breakdowns.

2) Determine scheduled, periodic, preventive maintenance policies

3) Determine in-process and/or finished goods inspection policies.

4) Determine procedures for tool life and process monitoring and data collection, as well as for updating the estimation of tool life.

2.5.1. Cell Control

A cell consist of one or more CNC workstations, a robot, material and/or tool handling system and the major operations are load/unload of parts and tools, machining scheduling of parts, tools and machine, set-up, transfer of parts and tools. It is obvious that even a very small size cell involves many activities and they must be controlled and co-ordinated to operate the manufacturing cell. A requirement is that the cell controller should function in real-time [183]. O'Grady & Seshadri have developed such a cell control mechanism with three main functions which are job scheduling, operation dispatching and monitoring.

In Jones & McLean's [124] hierarchical control paper, cell control is responsible for sequencing batch jobs of similar parts through workstations and supervising various other support services, such as material handling or calibration.

The required functions of a cell control system can vary and depend on the size and the facilities of the cell, and the degree of decision-making capability given to it. However, for a cell control system, a decentralized control structure is preferred [182]. In this type of control structure, since decisions are made as low as possible in the hierarchy to be commensurate with overall efficiency, the cell level can take over much of the responsibility of running the cell.

The major functions of the cell control system are to schedule the jobs, workstations, pallets, tools and other resources in the cell so as to achieve the goals from the shop level by using the resources within the cell efficiently [100].

Das & Sarin [62] have reported a planning and control system not specifically for cells but for any computer integrated system, in which they developed a relational network of modules and their macro decisions, while the architecture consists of the algorithms and procedures forming those modules and their micro-decisions. Control functions are used for planning, performance, material procurements, quality, production order, production items and tools.

Rogers & Williams [202] have developed a knowledge-based control system for manufacturing automation. They have offered a control system to tackle three significant problems having two elements. Problems are the integration of a wide range of devices, from the cell where a number of machines must cooperate and the whole manufacturing system must be coordinated, making automated systems more capable of reacting to their current situations and automating the programming of the system. The control elements are logical which acts to satisfy ordering constraints on event sequences and geometric control that ensures the position, path and motion of all elements of the system. The cell controller coordinates the operation of the devices according to a set of control rules based on the contents of a state table representing the current state of the cell.

2.5.2. Part Flow Control

Parts are the main entity in flexible manufacturing and have several operations until they become finished parts. These are batching, sequencing, cutting, inspection and washing. During these operations a number of other entities are needed to complete the operations. Every relation with other entities makes the part flow more complex and hence the control is rather difficult. At the same time as parts one of the main entities of the integrated system the control must be synchronised or simultaneously done with the other entities.

Bell & Bilalis [24] have separated the control mechanism into three level 1) pre-release planning, 2) release or input control, and 3) operation control. At the pre-release phase, parts which are to be machined by the system are identified, and individual batches are given a priority. The second level, input involves control for determining the timing and sequence of the release of jobs to the system. The sequence of release is controlled by priority rules which may be static or dynamic. They will always release a batch and in the case of more than one batch being required, the sequential release principle is followed. There are five rules for input control. Those are:

- Release the batch which occupies for the longest time the machine tool with the minimum assigned workload.
- Release the batch which will result in a minimum difference of work-load between the machines, with the maximum and minimum assigned workload.
- Release the batch with the maximum total operation time.
- Release the batch with the minimum total operation time.
- Random release of orders.

At the operational control level, the movement of the parts between the machine tools and the central store is resolved. Three simple rules were examined:

- First come first served (FCFS),
- Select the part with the minimum operation time,
- Select the part with the maximum operation time.

Parts, especially before physical transformation are processed at a time through batching, sequencing and scheduling in FMS. An enormous number of algorithms have been developed for batching, sequencing and scheduling of parts. The next main section gives a more detailed survey of sequencing and scheduling from a number of disciplines including operation research, control theory, simulation, algorithmic approaches and artificial intelligence techniques.

2.5.3 Tool Flow Control

As one of the main physical entities that flow in a manufacturing plant, tools have a significant effect on FMS performance. Although most of the decision rules for tool flow are formulated at the design stage, it is equally important to formulate and execute the operational rules along with manufacturing operations. Since tool flow has significant interrelations with a wide range of FMS entities such as part scheduling/loading, machine allocation/ grouping, tool/part transferring, batching etc. it has to be treated as one of the main FMS issues. Most of the research work in FMS primarily deal with a part scheduling, machine loading/grouping, material handling and tool flow is incorporated as a secondary issue.

Ventura et al.[252] have studied the grouping of parts and tools in FMS and formulated a 0-1 integer program to maximize the system efficiency. They have grouped parts and associated tool sets simultaneously, incorporating tool magazine constraints using an extensive mathematical programming technique to formulate and solve the model. Although the model has given relatively better results when compared with similar other research work reported in the paper it needs substantial mathematical effort to build and solve the algorithm.

Sarin and Chen [209] have formulated a similar problem that considers machine loading and tool allocation using 0-1 linear integer programming. In order to minimize machining cost, an operation is assumed to depend on the tool-machine combination that processes it. In particular, magazine capacity and tool life are both assumed to be limited.

Sarin and Chen's problem was addressed and gave rise another solution approach by Balasubramanian et al.[15]. The problem has been modelled and solved using discrete generalized networks which is a variation of linear programming. Both models are complex because of consideration is given to a limited number of machines, limited magazine capacity and limited tool life.

Chung [45] has developed another tool requirements planning model using mathematical models. His approach is two fold. In the first stage which is the higher level, a rough cut tool planning model is developed. In the second stage, which is lower and more detailed level, a tool requirements planning model developed is developed. The two models are integrated through a manufacturing planning and control system.

Graver and Mc Ginnis [94] again calculated tool requirements in their tool previsioning paper. They are more concerned with the problem of establishing the inventory of tools and classified the provisioning problem as static assignment where the production period and part list is fixed, machines are pooled and within each pool, operation and tooling assignment are identical; and dynamic assignment where additionally tool refurbishments and reassignments to machines are permitted.

Gyampah et al.[99] have compared tool management strategies and part selection rules. They have described four tool management strategies as discussed in Section 2.3.2 and three part selection rules of where two concentrate on tooling and other is EDD. They have developed a simulation model and used five performance measures. Although the paper deals with primarily tool management in FMS all the performance measures focus on the part and general system spectrum and major tool management performance criteria such as tool requirements and tool inventory level have been omitted.

Zavenella and Bugini [270] have developed an analytical approach to solve the tool requirements planning problem. The tooling problem is coupled with the fixture resource and solved by experimenting with various size of batches. First, an analytical model using queueing theory has been developed and then the model has been given detail simulation.

Reddy et al.[198] have applied the Petri Nets approach, considering high machine utilization which leads to maximum production rate as the performance criteria to evaluate tool management strategies. Their approach is to group machines and to generalize the tool management to analyze the tool sharing among machines and non-sharing.

Melnyk et al.[162] and Gosh et al.[87] have studied scheduling under tooling constraints using a simulation model. In the second study they extended the previous study by adding the machine constraint. In both studies the same four tool issue strategies have been used. In both studies they concluded that tool issue strategies have a formidable effect on the shop floor.

Leung et al.[151] have studied the concurrent assignment of parts and allocation of tools with the material handling consideration. They have formulated a linear integer model with the objective of minimizing machine processing cost. Alternatively using the same limitations, they have developed time and machine workload minimization models. Magazine capacity, tool type on a specific machine, machine operation time, capacity of the material handling system and the utilization of the material handling system are the constraints in main as well as alternative models. All the models are complex with considerable computational considerations. The material handling system influence on system performance was specifically studied using up to four vehicles alongside part routeing and tool allocations. Further analytical model has been practised in a simulation model and given several performance criteria based on material handling performance.

Some more studies may be found on tool management system problems either in design or operation stage in literature [273][217][39][6][146][246][247][173] and quoting all the research work done is beyond the purpose of this thesis.

2.6 Production Scheduling in Automated Manufacturing Systems

Production scheduling is concerned with allocating a particular set of jobs to a set of processing resources subject to a set of constraints. The need to schedule automated manufacturing systems for maximum effectiveness is very important due to the very expensive investment, and the great time and effort involved. Scheduling is critical because such as machines, pallets, buffers, tools and other ancillary entities are limited. The objective of an automated manufacturing system is to respond quickly to changes in demands without carrying large finished or semi-finished goods inventory. The major role played by scheduling is to adapt to such a change in an automated manufacturing system and the effectiveness of the system entirely depends on the scheduling.

Early scheduling systems were designed for job shop systems. Conway et al. [58], Jones,[123], Baker [14], Simmons [221], provided very good examples of job shop dispatching rules and the general scheduling problems.

In recent years, a vast number of approaches including quantitative, simulation, algorithmic and heuristic approaches, to several important types of scheduling problems have been proposed by several researchers. Gershwin [85] has proposed a hierarchical flow control for discrete event manufacturing. Gupta [96] has used the branch and bound algorithm to solve the scheduling problems. The extensive usage of mathematical programming to solve scheduling problems may be found in Johnson and Montgomery [122], Ryzin et al. [204] Gupta & Tunc [97], Pourbabai [193], Daoud and Purcheck [61] and many more.

The scheduling of an automated manufacturing system, specifically FMS, is similar to that of scheduling a job-shop, since the processing of various components on a common set of workstations requires effective methods to reduce the problems associated with competition for resources. Various differences in the FMS environment require new and different approaches in solving FMS scheduling problems [98].

Nof et al.[178] proposed a network approach to scheduling automatic manufacturing systems. They present an Evaluation-net (E-net) approach, a network-type knowledge representation, for hierarchical planning in this environment. This paper provides a general conceptual discussion of the FMS planning and scheduling problem and suggests the use of the modified Petri-Nets for decision making.

Carrie and Pestopoulos [37] identified the important management decisions that have to be made prior to the design and implementation of actual FMS. These include: the product range problem, the transportation problem, the machine capacity problem, the fixture problem, the pallet problem, and the process planning problem.

The FMS Scheduling problem has broadly been discussed and given an overview by Stecke [231]. Two parts of the scheduling problem are solved by linearised mixed integer programming methods in the second paper. Stecke solves the grouping problem, allocating operations and tools among the machine groups to maximize performance for data from a metal-cutting FMS.

Mukhopadhiyay et al. [170] have proposed a heuristic solution method considering tool allocation, part scheduling, pallet scheduling, machine scheduling and transport equipment scheduling simultaneously. They attempted to get an optimum production rate identified in terms of minimum time or maximum production rate. Chan and Bedworth [40] have designed a scheduling system for FMC to minimize the mean flow time for the n-job/m-machine problem in static and dynamic environments.

Since all the systems have finite resources and capacities, to avoid a bottleneck a careful and intelligent scheduling is vitally important for FMS, to avoid bottleneck occurring.

The decisions to be made in scheduling include: [64]

- What part should be loaded next?
- When should it be loaded?
- Once loaded into the system, how should it be routed?

In the same paper a three-step scheduling approach is used, part loading, part launching and sequencing. A similar approach has been used by number of researchers including Chan et al [41] Aanen et al. [1] and Toczylowski [244]

2.6.1. Loading Algorithms

A number of problems have to be addressed for the successful planning in an operation of FMS. Stecke [231] describes five decision problems that must be solved in setting up an FMS. These are:

1- Selecting the set of part types to be simultaneously manufactured,
2- Setting the production ratio for the selected part types,
3- Allocating the limited pallets and fixtures to part types,
4- Partitioning machines into groups of identically tooled machines, and
5- Loading machine groups by assigning part operations and required tools.

The loading problem is to allocate the operations and associated cutting tools of the selected set of part types among the machine groups subject to the technological and capacity constraints of the manufacturing systems.

Stecke [231] again proposed six objectives which could be used to formulate the loading problem:

1- Balance the assigned machine processing times,
2- Minimize the number of movements from machine to machine,
3- Balance the workload per machine for a system of groups of pooled machines of equal

sizes,

4- Unbalance the workload per machine for a system of groups of pooled machines of unequal sizes,

5- Fill the tool magazine as much as possible

6- Maximize the number of operating assignment

Sarin and Chen [209] have considered the minimum cost approach while solving the machine loading and tool allocation problem using 0-1 integer programming to get optimum tool allocation. Mukhopadyay et al. [171] have attempted to solve a similar problem to get an optimum production rate identified in terms of minimum time or maximum production rate. They also considered the machine loading, pallet loading flexibility and status of material handling equipment.

O'Grady and Menon [181] have studied the loading problem for an FMS and they attempted to solve the tool requirements and constraints, process times and routing and candidate job considered problems, using a mathematical programming model.

A number of objectives are considered when addressing the loading problem.
Chen & Askin [44] have considered the following objectives:

- difference between machine utilization,
- intermachine part movements,
- routing flexibility
- tool investment
- machine utilization

Sarin and Chen's [209] objective is to minimize the total machining costs corresponding to cutting tools and machine utilization. A variety of approaches have been applied to loading problems in FMS. The traditional operations that have been applied to loading applications are simulation and queue network analysis which has been used extensively and is often used in conjunction with a 0-1 mixed integer optimization model [231] [144], combinatorial procedures and heuristic approaches.

2.6.2. FMS Scheduling Algorithms

Scheduling is performed as part of the production planning and control function. Schedules serve as a guide for production and for establishing manufacturing resource requirements in terms of manpower, facilities, tooling and machine capacity. It is obvious from the wide range of tasks controlled through scheduling that the quality of schedules produced is a major influence on the effectiveness of a manufacturing system.

Scheduling within a manufacturing system ranges from detailed short-term to long term scheduling. The function of long-term scheduling emphasises planning for production and plant operations over extended periods of time. The short-term detailed schedule controls demand over the course of each day. The objectives of short-term scheduling include meeting due date, minimising work-in-process inventory, minimising manufacturing lead time and maximising machine and other resource utilisation.

The complexity of the scheduling task increases when it is applied in a flexible manufacturing system which is an integrated system, that is each function somewhat depends on other functions as well as the decisions made elsewhere in the system.

The complexity of automated manufacturing systems gives rise to many unique objectives which must be considered simultaneously. Often these objectives can be conflicting in certain circumstances [272].

Smith et al. [222] surveyed US FMS operators and observed the following objectives to be most importance:

1- Meeting due dates,
2- Maximising system/machine utilisation,
3- Minimising in-process inventories,
4- Maximising production rates
5- Minimising set-up and tool set-up changes times,
6- Minimising mean flow times,
7- Balancing machine utilisation.

A number of approaches have been applied to scheduling and sequencing problems. These range from mathematical modelling to knowledge-based scheduling systems but any scheduling system must be robust enough to handle exceptions and be efficient in terms of meeting due dates and production economy. Gershwin and Akella [86] provide a list for building a good scheduling system,

- Operating rules must be clearly defined,
- Capacity constraints must be known to keep resource demand within reasonable limits,
- Hierarchical schedules must be used to account for the many time scales over which planning and scheduling decisions must be made,
- The system's capacity must be addressed because of uncertainty and randomness,
- Feedback indicating the current state of the system must be available for appropriate, timely decisions under uncertainty.

Bestwick and Lockyear [25] provide several characteristics required for a scheduling system to be most useful. The system must be able to:

- Produce feasible schedules in real time,
- Accommodate schedule revisions in a timely manner,
- Direct priority or partial priority in scheduling,
- Perform due-date scheduling,
- Handle parallel processing workcentres,
- Accept previously committed capacity,
- Be clear enough for both administrators and system operators to understand and use.

The most widely used technique in scheduling is the operation research (OR) techniques such as linear programming, non-linear programming and dynamic programming which has traditionally been applied to scheduling and is defined as mathematical programming in the literature. Dagli [60] used a line balancing technique to generate production alternatives in scheduling assembly operations of electronic components. He investigated minimising cell operation cost under three types of constraints namely, satisfaction of demand, available capacity limits and machine hour requirements of products.

Shanker and Tzen [214] addressed the bi-criterion scheduling problem in a random FMS. They investigated two types of problems: (1) a single criterion problem, i.e. balancing of the work load, and (2) a bi-criterion problem i.e. balancing of the workload among the work stations and meeting the due dates of the jobs. They considered an FMS with n-machines where each machine has a known tool magazine capacity. The optimization models are formulated under the constraints on tool slots, unique job routing, non-splitting of the job, machine capacity and integration of the decision variables. They have proposed a mix-integer models that contain non-linear functions.

Escudero [71] has addressed part loading sequencing and processing routes in FMS. A mathematical programming model was formulated which consisted of objectives:

- the loading ordering of the set jobs in the FMS,
- the execution ordering of the operation per part type,
- the processing route of each part along the FMS.

Operation research provides powerful mathematical techniques which appear to be of little use for practical scheduling problems. The combinational nature of the scheduling problem precludes the computation of a solution in a realistic time. In addition to computational difficulties, inability to react to events on the shop floor and the need to include unrealistic simplifying assumptions make the mathematical programming models less useful and mostly unrealistic.

The complexity and uncertainty of the manufacturing environment has led researchers and scientists to look for easy to apply, realistic and smaller size models which need less computational time. Existing computer based scheduling systems do not meet the requirements of making effective decisions dynamically and it is difficult to capture in these scheduling systems any intuitive insight [210]. Due to these reasons, artificial intelligence techniques have become a new tool to solve these problems in production scheduling.

A number of formalisms are used in knowledge-based systems (KBS) to represent and reason with each type of knowledge. These include first order logic, production rules, semantic nets and frames. Among these, production rules and frames have been extensively used in applications of KBS in production scheduling [75].

The principal advantage of the KBS approach is related to the ability of human experts to circumvent mathematically complex problems by the use of 'heuristics' or rules of thumb. Shaw and Whinston [218] have addressed the following points which a knowledge-based system should be capable of achieving:

1- providing on-line decision support,
2- scheduling operations dynamically,
3- coordinating manufacturing resources,
4- synchronising processes for different jobs,
5- monitoring the plan execution.

They have built a knowledge-based scheduling system to schedule n-parts concurrently to minimise makespan while avoiding any conflicts arising from assigning parts to busy machines. Fox and Smith [81] have design a knowledge-based system for factory scheduling, ISIS. This is one of the early examples of a scheduling system, and is capable of scheduling a large scale job shop. The system has focused on constructing a knowledge representation that captures the requisite knowledge of the job shop environment and its constraints to support constraint-directed search, and developing a search architecture capable of exploiting this constraint knowledge to effectively control the combinatories of the underlying search space.

Kusiak and Ahn [142] have developed an intelligent scheduler for automated machining systems. They have introduced the Most Dissimilar Resources (MDR) dispatching rule and scheduling algorithm for automated machining. MDR has been developed for efficient scheduling of operations in an automated machining system where the maximisation of the utilisation rate of manufacturing resources is a major concern. The system has been designed by incorporating operations research and artificial intelligence techniques.

Most practical scheduling involves the use of heuristic rules for dispatching orders to resources. These dispatch rules are based on a body of expertise which has been built up through a process of trial and error during practical experience. Dispatch rules compromise the problem-solving process by only considering factors which are local to the dispatching decisions.

Chandra and Talavage [42] have addressed real-time machine loading and dispatching in FMS where parts are assumed to be dynamically scheduled. The main objective is to develop an intelligent dispatching strategy for FMS using an opportunistic reasoning approach rather than a static dispatching rule.

Knowledge-Based systems have formed the basis of the 'heuristic algorithms' in computer based solutions and these heuristics are the kind of knowledge which rule based KBS are designed to handle.

The PLANIT project [93] evaluated the use of KBS techniques in process planning, project planning and job shop scheduling and developed a prototype system covering all three application areas. The PLANIT approach makes a distinction between hard and soft constraints. Hard constraints are those that the planner is unable to relax, whereas soft constraints are viewed as preferences and therefore amenable to relaxation by the planner.

Schelam [180] is an expert system kernel produced by IBM Japan. It is designed for scheduling steel making processes. Typical constraints in this domain are:

- fixed process plans,
- no machine conflicts among products,
- low queueing time,
- continuous use of some machines and an idle time requirement for others.

This system does not aim to produce optimal schedules. The designers of the system take the view that it is better to get a feasible solution efficiently rather than confront the combinatorics of optimization. A knowledge-based approach was chosen for flexibility in expressing constraints and for its ability to incorporate expert heuristics.

The research reported in this thesis focuses on a generic manufacturing system. The research is embedded in three main sections which are the background section up to chapter five, the design section which includes chapters six to ten, and the experiments and results section which includes from chapter eleven to chapter nineteen. The developments in four main machining technologies, namely prismatic, cylindrical, presswork and electrical machining technologies, with the emphasis placed on tool management system technologies and supporting systems are discussed in Chapter 3. The parameter set involved in TMS design and analysis, rules and strategies are presented in Chapter 4.

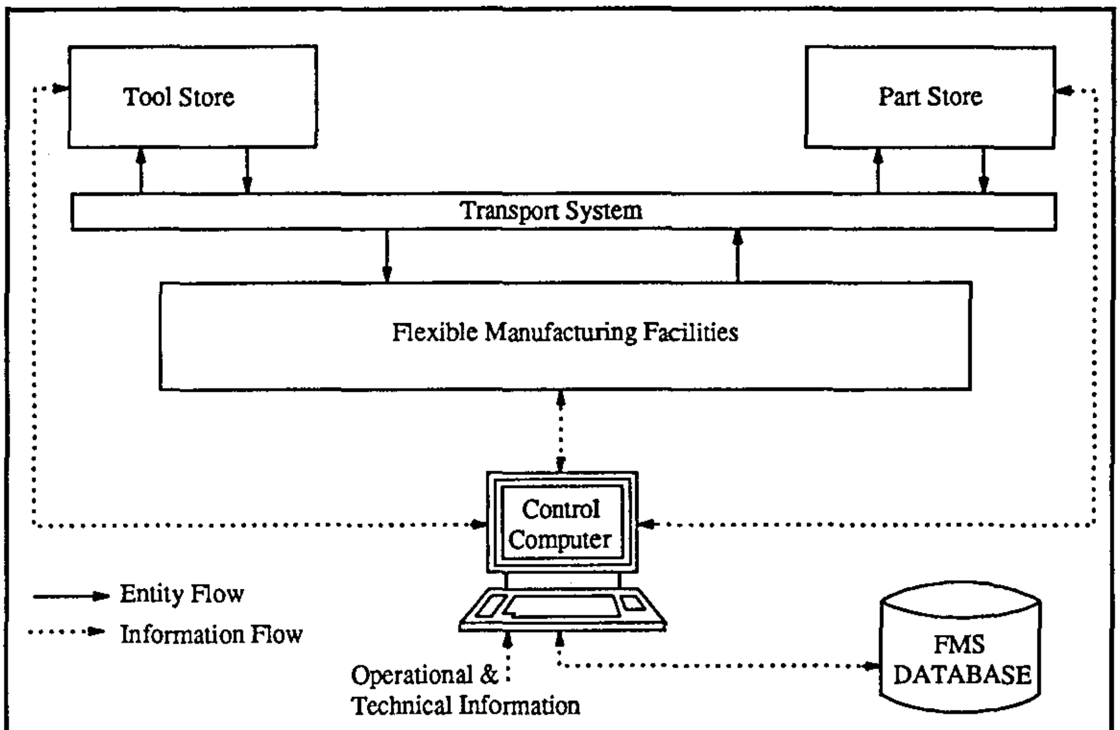


Figure 2.1	Functional Layout of FMS	LUT-FMS Research Group

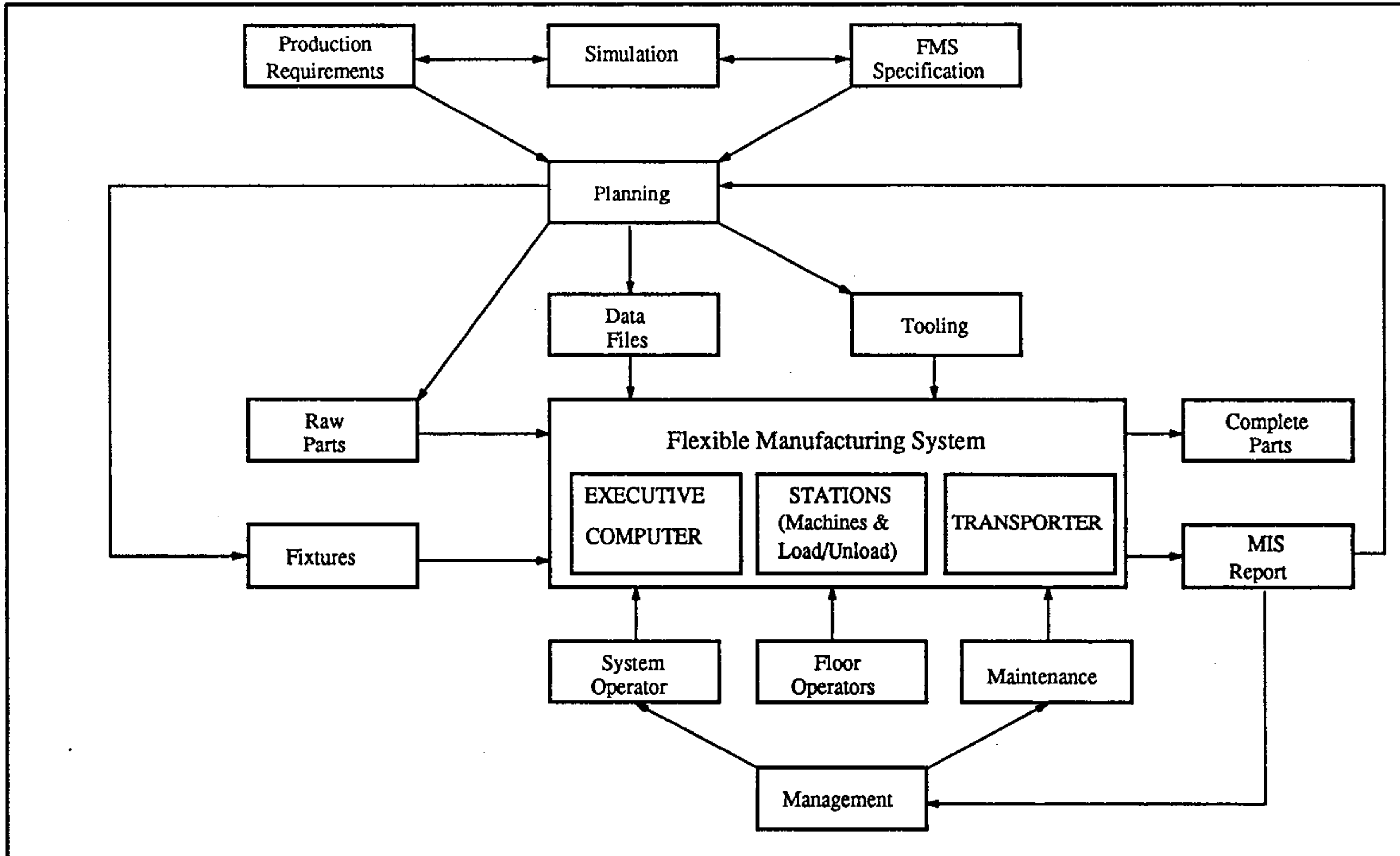


Figure 2.2	Interconnection of an FMS (Ref. 76)	FMS Research Group

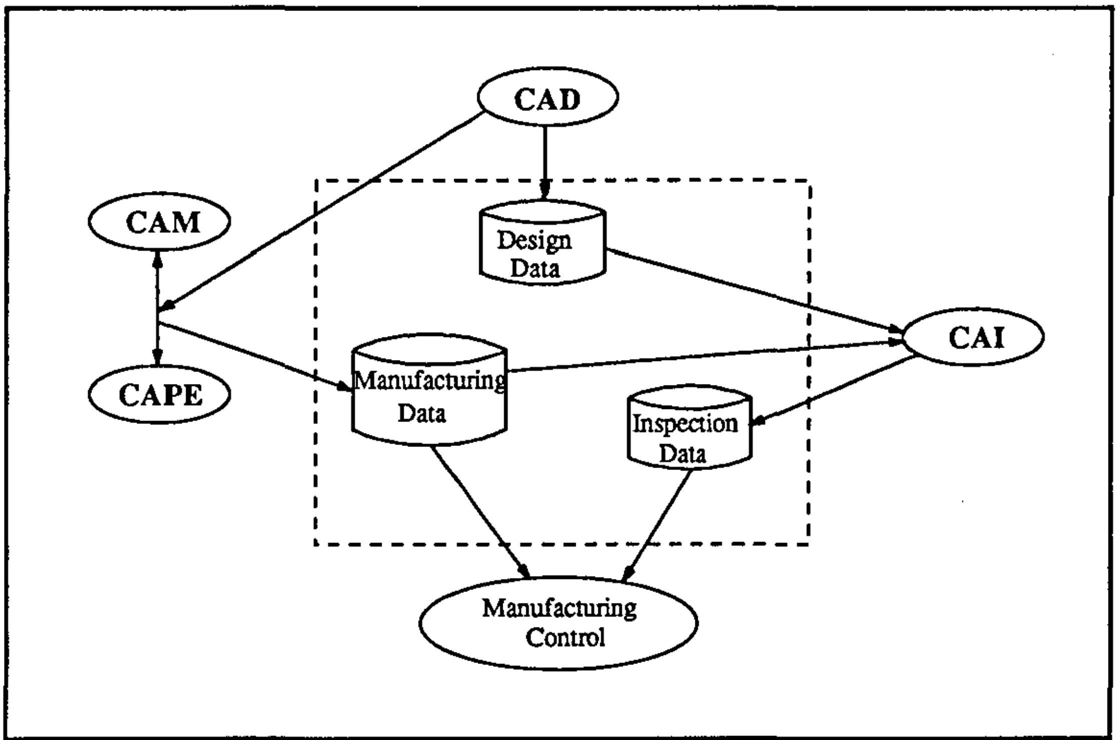


Figure 2.3	A Company View of Computer Integrated Manufacturing (Ref. 272)	LUT-FMS Research Group

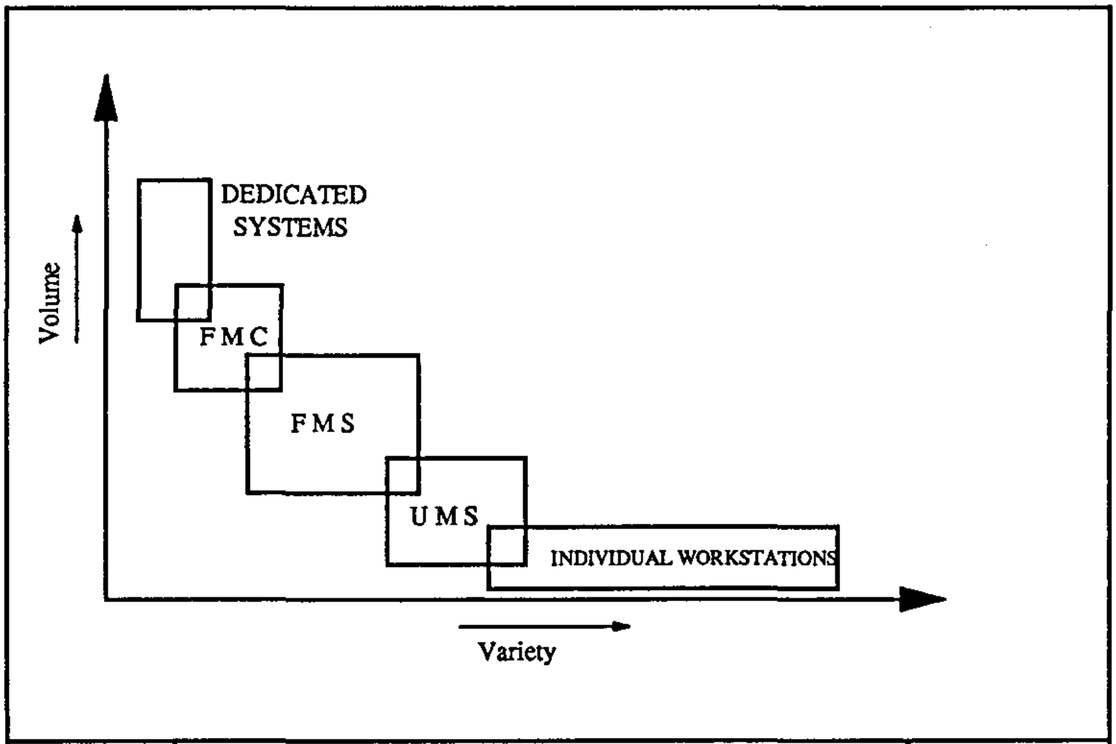


Figure 2.4	Automated Manufacturing System Classification	LUT-FMS Research Group

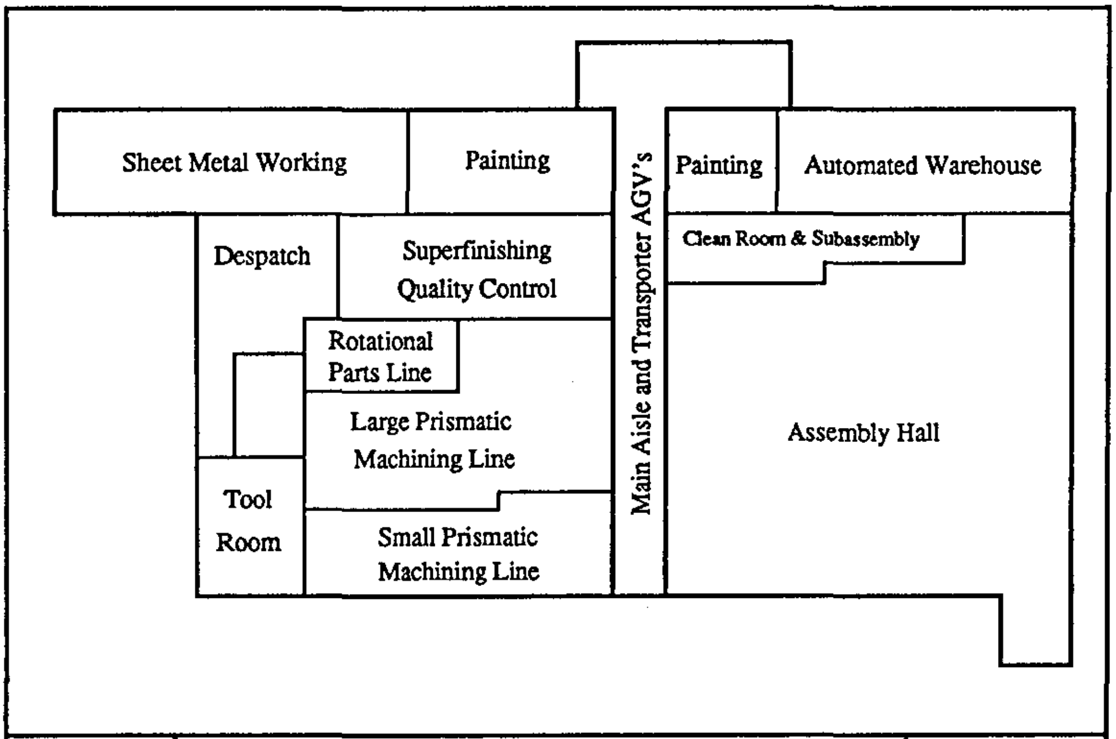


Figure 2.5	Yamazaki Parellel Multi-Cell FMS (Ref. 140)	LUT-FMS Research Group

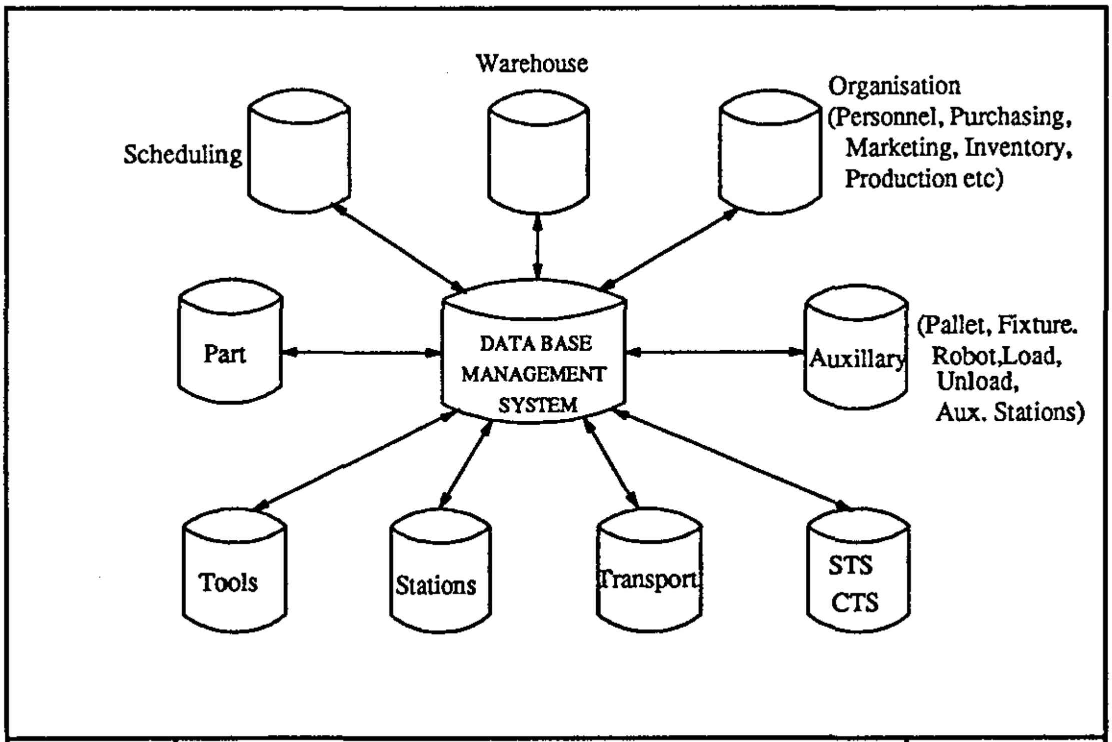


Figure 2.6	Structure of FMS Database System	LUT-FMS Research Group

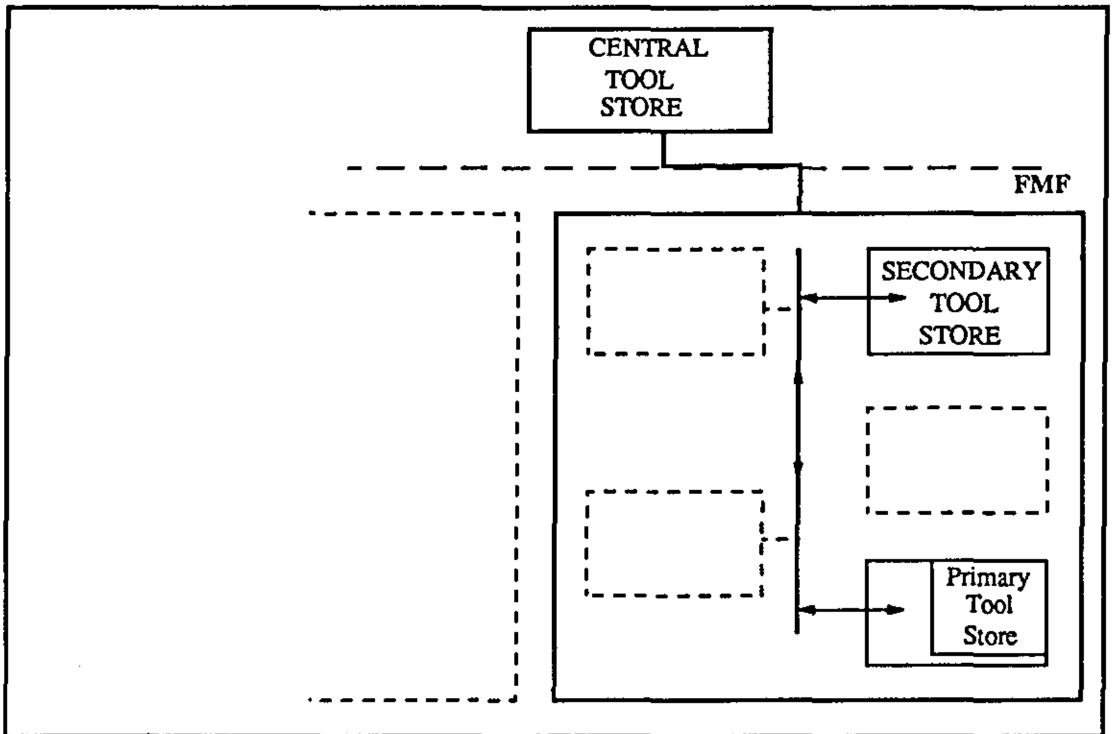


Figure 2.7	Hierarchical Tool Management System	LUT-FMS Research Group

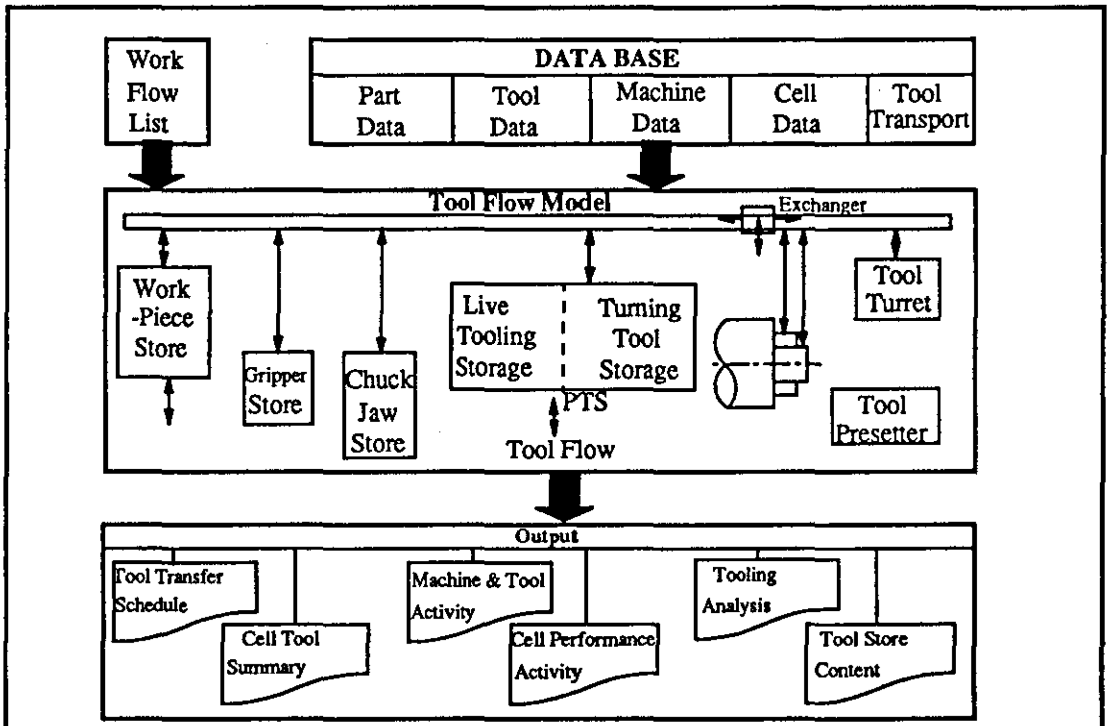


Figure 2.8	Turning System Tool Flow Model (Ref. 272)	LUT-FMS Research Group

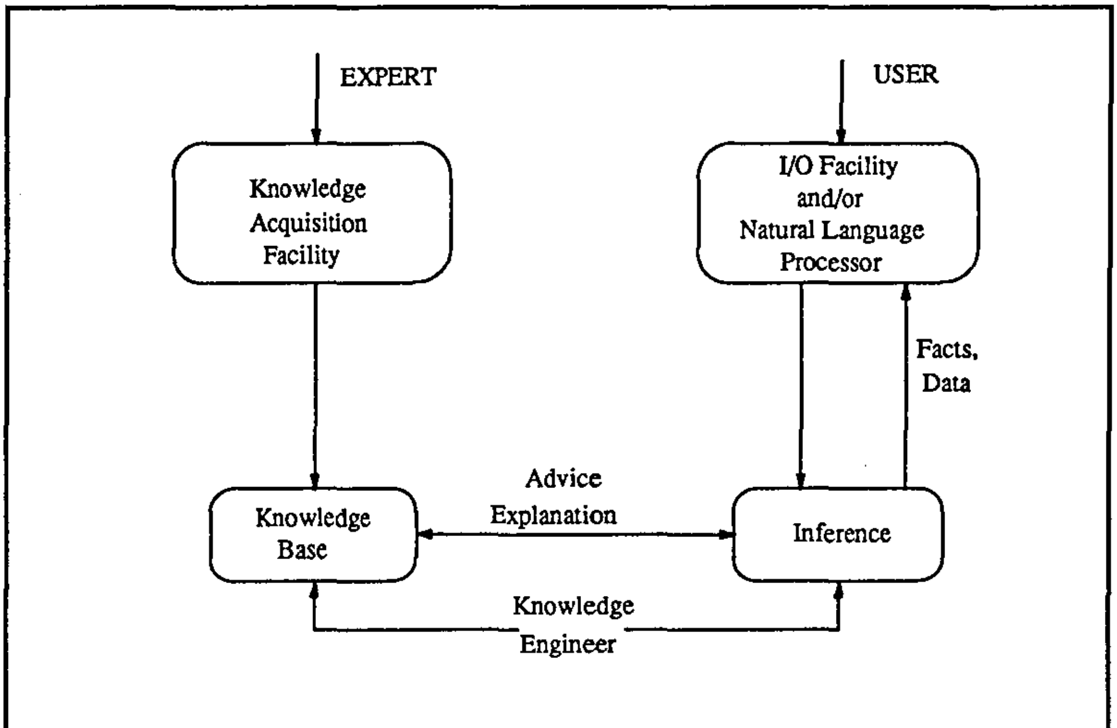


Figure 2.9 | Basic Structure of Expert Systems (Ref.130) | LUT-FMS Research Group

Chapter 3
Developments In The Tool Management Concepts For Automated Manufacturing Systems - State Of The Art

3.1. Introduction

In this chapter, the state of the art in tool management systems and automated manufacturing systems is presented. A discussion on new tool management design technologies including tool exchange systems, tool storage systems and functions is highlighted. A framework for tool flow system design and operating strategy is also presented.

3.2 Tool Management Framework

Although their importance changes from one design facility to another, the fundamental criteria required to analyse the performance of a tool management system and to determine the combinations as well as the interactions of the design parameters, can be classified in three levels. These are hardware utilisation, time and cost. In a tool management system design effort, two fundamental hardware components are important, these are workstations and the transporters.

The hardware utilisation is an indication of the cell performance. Since tool load, unload, exchange and set-up is required, a workstation or machine is often engaged in non-cutting operations and this affects the level of utilisation. A well designed tool management system should support high machine utilisation, eliminating unnecessary machine downtime, long and frequent tool changes and set-ups. Similarly, the transportation system must also be supported by the tool management system to allow for the timely provision of tools as required. Therefore, a transportation system with a well balanced capacity and speed of delivery is also a fundamental indication of a successful design.

In today's highly competitive manufacturing industry, a great deal of the technological developments and improvements is dedicated to reducing production cycle time and lead time. Tool management is one of the major factors affecting the production cycle time. Because of the close relationship and interactions between tool flow and production cycle time, throughput time is used as a major factor in the analysis of the TMS performance.

Finally, the most important factor is cost, not only for a tool management system but also for overall manufacturing performance analysis. Since every single tool required costs a certain amount of money, an important TMS design effort is to reduce the total tooling cost in a flexible manufacturing facility. This may be achieved by keeping the captive tool size to a minimum and by effective use of the available tool life, even to using the same tool many times providing a low cost refurbishment facility is present.

Flexible manufacturing facility design efforts are focused mostly on isolated design problems and usually the interactions between design parameters are omitted. The interactions between design parameters affect the design as much as individual design parameters do. These influences may happen both positively or negatively, but the interactions need careful exploration in several configurations. A number of TMS configurations have been designed to explore a number of issues as well as to explore the possible design parameter interactions and trends (Ref.to Chapters 11 and 12). The output of the design configurations is presented in an through Appendices II to VII, and the major research issues have been explained in detail in through chapters 10 and 17.

In particular, the latest machine tool technology has made a valuable contribution to flexible manufacturing cell planning and control efforts. As a major part of cell control, tool flow control as well as effective tool life utilisation control has benefited from these developments. Large magazine capacity has been provided to store a large amount of tools on the machine and intelligent tool monitoring systems make the major contribution to the effective usage of tools. These developments lead to the use of the same tool for several jobs, as long as enough tool life is available. This extensive tool life sharing between several batches saves on the number of sister tools, the machine downtime, the amount of tool load/unload, tool set-up time, tool changing, kit size, total captive tool size and most importantly, cost. Although the use of tool issue strategies is another fundamental factor to use tool life effectively, to practice such strategies needs a certain hardware configuration. In such cases, the true combination of hardware emerges as a major design challenge. Thus tool life utilisation, tool monitoring, tool flow control, magazine capacity, tool issue strategy, part batching and scheduling are the fundamental design parameters and need careful exploration individually as well as in combination (Ref.to Chapters 6, 7, 8 and 9).

For a medium size flexible manufacturing facility, the average tool inventory is about 2000 tools and the capital tied-up sometimes reaches up to 8 percent of overall investment [245]. This relatively high initial investment, again relatively high operating cost and strategic importance of tooling has forced manufacturing managers to consider tool inventory and tooling economy as fundamental issues. The true determination of permissible tool life, the provision of low cost refurbishment for recycleable tools, the correct selection of tool technology and the good control and management of tool inventory are the fundamental design factors to be considered in any design. As stated earlier, the interactions of the design factors have an important impact on the tool management system and a major subject of this research.

The tool transportation is the final issue to be explored in this context. In a multi-cell environment tool traffic is highly intensive between tool stores, and inelegant solutions sometimes create serious problems. Intelligent and fast transportation, when associated with good control and planning, solves the major part of the tool management design problem.

3.3 Tool Management System Approaches

There are three main approaches to tool management : manual tooling systems, automated tooling systems or mixed tooling systems. A broad classification of these systems can be found in reference [66]. These systems are represented schematically where possible using symbols in Figure 3.1.

3.3.1 Manual Tooling Systems

Manual tooling systems are usually applied in a narrow environment that includes machine based primary tool stores (PTS). However, there are some novel concepts to increase the number of tools available at the machine level. Werner's chain or cassette magazine type TC series workstations can provide up to 225 tool with 6 second tool changing time for long term non-stop machining [256]. The Mori Seiki MH-50 range machine, however, can accommodate up to 240 tools [168].

De Souza [66] has summarized the approach adopted by machine tool manufacturers into five categories:

1. A standard single integrated PTS
2. A non-standard integrated PTS

3. An interchangeable or transferable PTS
4. Two or more integrated PTSs
5. An integrated cassette system

Deckel has employed a dual tool magazine on its DC series machining centre [63]. Twin chain magazines can accommodate up to 160 tools to support long range unmanned machining. A second tool changer arm is located behind the dual chain magazine that handles the exchange of tools between the two chain magazines. The standard tool changing mechanism changes the tools between the main chain magazine and the spindle. The second chain magazine can be loaded and unloaded while the machine is in operation. Later, the needed tools may be transferred from the second magazine to the main magazine. Figure 3.2.

3.3.2 Auxiliary Tool Store System

The auxiliary tool store system (ATS) may be in several forms ranging from a single supporting turret system to a large capacity fully automated tool store system.

Mazak has developed a tool storage system, the Tool Hive System, which can be used either as an ATS to support one machine or as a secondary tool store (STS) to support a two or more machine cells. Tools are stored in a honey-comb arrangement and are moved by a tool robot. The minimum tool storage capacity of the Tool Hive is 160 tools which can be expanded incrementally to a maximum of 480 tools. The tool storage area is protected and when the door is open, tool robot motion is inhibited. The tool robot automatically loads and unloads tools from their designated pockets and transfers them to the automatic tool changer (ATC) position. After a tool has been used, the tool robot will remove it from the ATC transfer pocket and transfer it back to its designated storage position. In order to prevent interference between the tool change arm, the angle heads and the touch sensor couplings, tools are rotated through 180 degrees in the tool hive transfer pocket. A nylon brush rotates and an air blast cleans the taper shank during this operation [268] Figure 3.3.

Kolb has employed an auxiliary head magazine on a CUBIMAT HC 1500 machine. The machine is normally supported by a 72 tool capacity rack type magazine. Additionally, three head magazines are employed, each with a 12 tool capacity. Both systems are supported by a robot tool changer Figure 3.4 [135].

3.3.3 Secondary Tool Store Systems

A secondary tool store (STS) basically has the same function as an ATS, but it is designed to support more than one machine and is not attached to any individual machine. STSs are widely used tool storage systems throughout multi-cell flexible manufacturing systems as well as in single cells and it is possible to see many different examples in several installations including [139],[249],[152],[51],[48],[185],[133].

The Yamazaki Worcester plant employs a "tool highway" to transfer new or used tools individually between the cell level secondary tool store and the machine level PTS in three FMS lines. A very fast tool robot of single tool capacity loads and transports tools from the STS into the PTS of any machine in the cell or FMS line. Each machine is supported by an 80 tool capacity magazine separately Figure 3.5 [139].

A similar system also employing a "tool highway" or overhead gantry is the two machine Cincinnatti Milacron T10 cell. The two T10 horizontal machining centres each have a capacity of 90 tools in two 45 tool chains, supported by an STS of four chains, each with a 170 tool capacity Figure 3.6 [49].

3.3.4 Central Tool Store

The selection of appropriate tool storage facilities, tool exchange mechanisms and their location are major problems in the design of a tool management system in FMS. For a multi-cell installation, as well as each cell's own local tool store, a location for the tool preparation, presetting, refurbishing and disposition becomes a necessity. This hierarchical system makes the tool flow more organized and prevents the local tool stores from becoming overcrowded as well as increasing the system flexibility. At the same time, however, the capital tied up in whole tooling system increases.

British Aerospace at Preston [29] employ a central tool store (CTS) that contains 4000 tools, which would include several hundred different tool types. The tools are stored in two parallel racks each 21 rows high. In between the two racks a robot travels up and down picking up the required tools and placing them in a crate. The crate is then delivered to shopfloor level, removed from the paternoster and taken by AGV to a machine tool Figure 3.7 [133].

Although it is relatively an old system, the TOS Olomouc plant [271][249] is still a state-of-art example in terms of tool management system. The central tool store for palletised workpieces has 240 cells placed in two parallel racks. Each machine has its own buffer store for 5 palletised workpieces. The tool store is composed of ten magazines each with a maximum capacity of 144 tools. Of these 1440 tools, 288 can be placed in two magazines in the tool room and 1152 in eight magazines near the machining centres. All magazines are interconnected by a tool transport cart with transport cells for five tools. The tool transporter unit regroups the tool transport or unloads them from the manual tool cart. It also places the cell with the tool for the next coming operation into the spindle station, where it waits exchange into the spindle. Figure 3.8 shows the TOS Olomouc tool management system.

3.4 Overview of Flexible Manufacturing System Technologies

Modern machine tool technology incorporated with computer technology, has taken classical NC machines beyond conventional limited operations. A typical CNC workstation today has a workpiece handling facility, tool exchanging system, large tool magazine with automatic indexing, tool monitoring system, contact probes and intelligent CNC controller [48]. Due to their central position between machining processes and the machine tools, the basic conditions relating to the use of tools have also changed [73].

Tools are directly involved in the machining processes and hence are the first elements that require adaptation when technology changes. Against the background of these developments relating to tool technology, tool cost and quantity and in conjunction with the accompanying rise in the cost of automated manufacturing facilities, the importance of the tools becomes clear [73].

These systems are categorised into installations with:

1. Primary Tool Store,
2. Secondary tool store systems,
3. Central tool store systems.

3.4.1 Single Machine Installation Examples

3.4.1.1 Machining Centre

Machining centres are the most widely accepted and used machines in metal cutting industry [154].

Yamazaki Mazak has built up a highly automated horizontal machining centre, the Mazatech H-1000, which can machine up to 1800x1500x1000 mm dimensions and up to 3000 kg weight. The machine is supported by sophisticated functions such as automatic workpiece handling, a high speed ATC system with approximately 16 seconds chip-to-chip tool changing time and a fast control unit with 32-bit processing. The simultaneous operation of different units such as the machine table indexing and ATC or the pallet changer and ATC can be performed to reduce non cutting times. The machine is supported by an 80 or 120 tool chain type magazine which permits long term unmanned production. Tool breakage detection, a tool transfer robot and a pallet management sensor are other functions included [264].

Werner has built the horizontal machining centre TC2-Series, which is a good example of state of the art engineering. The basic equipment includes a pallet changing device for 2 workpiece carriers with left-front/right-front transfer. The machine has a chain type 72 tool magazine on a separate stand with compact attachment to the side of the bed. The swivelling tool changer with double gripper is mounted directly on the tool magazine. The loading/un-loading station with an intelligent tool terminal permits tool changes while a program is being executed. Tools can be inserted or removed into the magazine with both hands since the unlocking mechanism is actuated by a foot switch. An automatic tool changer changes the tools in a matter of seconds [256] Figure 3.9.

Werner has developed a tool supply system with a cassette magazine on the TC range of workstations. A stationary tool cassette magazine accommodates 105 tool storage locations and a changing cassette accommodates 12 tool holding locations. Tools can be changed by changing the cassette while the machine is in operation. Tools are transported by a 2-axis linear gantry mounted manipulator with an integrated drive, bearing and measuring system. The gripper unit of the manipulator is used to load the tool changer, magazine and changing cassette (2x6 locations). After the front side has been worked through, the changing cassette is turned so that this side can be manually loaded and unloaded by the gantry robot while the machine is in operation. Tools are monitored before and after spindle operation and during tool exchange by an optical tool monitoring system. A taper cleaner installed on the tool changer cleans the tools prior to use in the spindle. This consists of an hydraulically moveable sleeve with rotating brush blades and spray nozzle driven by coolant pressure [257] [105]

Cincinnatti's Nighthawk [50] is a multipurpose processing centre which has both milling and turning functions on a single machine. Although it is not constructed like a traditional CNC machining centre it can mill, drill and tap. The machine is supported by automatic workpiece and tool changers as well as a 12 station live or fixed tooling turret.

Other examples of highly automated machining centres from different suppliers are given by Heller [109], Fraser Amca Int., [82], KTM, [138], Mori Seiki, [168], Huron Graffenstaden [114].

3.4.1.2 Turning Centre

Some of the most common workstations in manufacturing industry are modern turning centres. These are commonly preferred due to their increased capability and flexibility, especially after the incorporation of secondary operations such as milling and drilling. Although principally designed for large workpieces, turning centres have considerably advanced state of the art CNC machine and control unit technology [154].

One of the turning systems pioneers, Traub, has developed a high production, highly automated turning centre, the TNS 65D. Two turrets can accommodate 20 turning, drilling and milling tools. The Traub FHS1 CNC gantry loader can load and unload chuck-held and shaft-type workpieces. The machine is supported by sophisticated technology such as process monitoring and quick chuck jaw changing, a conveyor with multiple part pallet for blanks and finished parts and workpiece indexing milling in two set-ups, in fully automatic production Figure 3.10 [250].

Another compact system for turning, milling and drilling has been built by Yamazaki. The Mazak Multiplex 620 completes all operations in one set-up. This highly automated, twin turret machine can operate on both spindles continuously and simultaneously and both have the same machining capability. After the completion of the first process on one spindle, the workpiece is automatically transferred to the other spindle and automatically re-chucked. The machine is equipped with identical turrets, each with a storage capacity of 12 tools for both right and left spindles. Tool layout flexibility permits rotary tools to be mounted at any turret position. After mounting a tool on a turret, a tool eye sensor can check tool wear and data is recorded in CNC memory. Tool changes are performed by changing tool holders and to process different diameter bars, the solid collet chuck can be quickly changed [266].

The Gildemeister Max Muller MDW 7 [90] turning centre is equipped with a 60 tool capacity chain type magazine and is another example of a modern turning centres. The machine is equipped with a tool changing magazine (MDW) which automatically transfers tools from the magazine to the tool clamping head. The changer consists of :
- tool magazine;
- tool changing mechanism;
- tool holster changing mechanism.

The tool changing and toolholder clamping mechanism are identical in principle but the magazine itself is arranged to suit the particular working requirements. The magazine contains a pre-selection facility so that the next tool coded for use is taken to a change position prior to the actual change. The travelling chain magazine has 12 positions in which the tools are placed at random. The 13th tool is held in the tool clamp in the machine. The stationary chain magazine with 40 or 60 tool positions is used for more comprehensive turning, drilling and milling operations and for storing larger numbers of tools.

Some detailed explanations of some other highly automated turning system examples from different suppliers can be found in references [116], [267], [5] [223][248].

3.4.1.3 Presswork

Hot and cold working of metals is of great importance in engineering manufacture. Processes such as punching and forging predominate in the primary stages of manufacture and have been perfected largely through electronic developments.

A press is equipped with dies and punches designed for producing parts in press-working operations. These tools are necessary for forming, ironing, punching, blanking, slotting and the many operations that use press-working equipment. One modern example of a press machines is the Shape Sigma Index CNC Punch Press [216] machine which is equipped with turret styles to suit thick or thin turret tooling. The servo driven turret rotation is bidirectional for fast and precise indexing. The tooling systems used is designed for high speed CNC punch press production. The tools are self-aligning and self-stripping with each punch assembly fully guided over its length. This reduces the need for special drops into the correct turret station and with the dies held into the bottom of the turret by quick release die locks then complete tool changes can be performed in a short time.

3.4.1.4 Electrical Discharge Machines (EDM)

Spark erosion or Electrical Discharge Machining (EDM) is a relatively new production process. When the spark is discharged, material is removed from the workpiece surface by an electrothermal process, through melting, instead of by the mechanical action of a tool on the workpiece. Modern spark erosion centres are equipped with computerised numerical control systems that assist the machine operator in performing numerous jobs. The CNC unit also helps the operator produce shapes and contours, guiding the electrode through in straight lines and circular paths and making sure that the electrode does not move beyond a specified target point. An example for EDM is the DECKEL DE25-C [63] which has the latest developments in spark erosion. An automatic tool changer is available and electrode change is controlled by the spark erosion program. The tool changer and a magazine for 16 tools is attached to the machine frame. The tool magazine accommodates larger and heavy electrodes when adjacent positions are vacant. A robot loads and unloads workpieces as well as tools.

3.4.2 Cellular Installation Examples

A cell can take a number of configurations, but it generally has more than one machine tool with some form of pallet changing equipment, such as a robot or other specialised material handling device. In most cases, the grouping of machines is small and often uses a common pallet or part fixturing device as well as a tool store. Part variety is generally low and batch size is medium to high [254].

In many cases, the manufacturing cell does not need to be fully automated, but in order to derive maximum benefit, computer integration is essential. The lower cost of today's generation of mini computers, coupled with the availability of FMS software packages makes it possible to install powerful cell control systems at low risk [12].

Substantial evidence may be found that CNC workstations have been integrated into flexible manufacturing cells. These can be highly automated cells with automatic tool and workpiece flow or a series of manually operated CNC workstations.

One of the many examples of a genuinely unmanned machining cell working 24 hours per day and 7 days per week is the disk file plant of IBM at Havant, in the UK [13]. This cell has three Cincinnatti Milacron type T-10 horizontal CNC machining centres, each with a twin pallet changer and each machine is loaded and unloaded by a Cincinnatti Milacron Robot. The robot also transfers the finished parts.

Two FMCs were built for Remington Arm Co. [77] plant. One has ten Cincinnatti Milacron T-10 and ET-10 machining centres and the other cell has eight Cincinnatti T-10 and ET-10 machining centres. The first FMC has a 12 station automatic work changer and a tool management area. Remington's processes require some 300 different tools per day. A strategic control system plan for tool management was developed to meet tool kit planning and preparation requirements. CNC controller enhancements were made to optimize tool selection and tool life on the machining centres [47]. The machining centres resident tool selection priority is based on each tool's usable life and not the position in the tool chain. Also, tool wear compensation has been added to maximize the usable life of tools.

The German machine tool builder, KOLB [134], has developed a range of FMCs which incorporate 2, 3 and 4 workstations. The cells are equipped with an automatic tool changer; double pallet rail guided vehicle for workpiece transport; workpiece clamping and unloading stations; measuring, testing and monitoring equipment for tools and workpieces; automatic auxiliary head change; tool magazine for each machine and a cell tool store as standard. The cells are designed specifically for the manufacture of several types of component such as crankcases, textile machinery and machine tools. The cells are equipped with a large expandable tool cassette system (80 to 200 tools), where each cassette is freely changeable and transportable and may be kitted out for particular jobs. Also, a robot served tool store of hidden tool shelves, each containing 48 tools, can be incorporated into the cells when required.

Yamazaki [263] has developed a complete FMC for unmanned production. The cell consists of up to 8 machines, a tool presetter, tool stocker, tool transport system, stacker crane robot, pallet changer, pallet stacker, load/unload robot, loading station and pallet management system. A pallet with a finished workpiece is automatically unloaded and the pallet with the next workpiece is immediately loaded by the pallet changer. The pallet stacker temporarily stores pallets with loaded workpieces. The tool presetter measures the tool diameter and length and automatically transmits this data to the tool management computer. The tool stocker which has a tool storage capacity of 120 to 960 tools, supplies tools from the tool store to the individual machines by a tool transport system. Figure 3.11.

A vast number of CNC workstation cells have been installed throughout the world's major industrialised countries as well as some developing countries and it is beyond the scope of this thesis to list all of them. Some of these can be seen in the literature [269],[177],[56],[153].

3.5 Tool Flow System Configuration

Individual machine level, cell level and factory level tool management systems are linked by a tool flow network which comprises of transportation systems between a hierarchy of tool stores where tool exchange take place Figures 3.12 and 3.13. The tool flow network has been defined based on the previous sections.

The tool flow network has been defined hierarchically between three levels: the central tool storage (CTS), cell level storage (STS) and standalone workstation level storage (PTS).

3.5.1 Central Tool Store - Functions and Tool Presetting

The plant level central tool store (CTS) is one of the core places where the main tooling activities take place. The activity of the tool stores and their inventory are a major problem faced in automated manufacturing systems. To supply the required tools in the desired condition to the desired place greatly depends on the success of central tool store management. The basic function of a tool store is to keep tools and supply them whenever they are required, to a machine or machine group on the shop floor. [110] The central store normally interacts with the individual machines in the system through a cell level secondary tool store. The main activities which take place in the central tool store are, Figure 3.14, [66]:

1. To receive tool requirements for different machines, jobs or batches;

2. Advanced preparation of tools and fixtures to support scheduled production, including presetting, tool assembly build-up and grouping of tools into kits for transfer to individual machining cells;

3. Assessing the disposition of the assemblies which have been returned from the cell;

4. Teardown of the tool assemblies which require refurbishment and storage of the reusable tool assemblies in appropriate locations;

5. Responding to unexpected tool requests due to sudden tool breakage;

6. Maintenace of relevant tool characteristics and tool usage data for future reference,

reporting and inventory control;

7. Replenishing the tool stores in an orderly and timely manner according to predefined criteria.

Amazon [8] technology has developed a computerised tool management system which is mostly based on the central tool store activities. The central tool store system manages and individually tracks both disposable and refurbishable tooling items throughout the factory. The central tool store has the following functions to control tools in the system:

- search by description;
- store functions;
- record creation and amendment;
- purchasing functions;
- management functions.

Kennametal Erickson's [128] computerised tool location management system, ToolPro, provides a comprehensive tool store and inventory control system. The system consists of several integrated modules that each activate one function of the total tool management system including inventory control, monitoring, tracking, location specification, kitting, costing etc.

A software company, ISIS [118] Informatics, has developed a tool management system called Toolware. Toolware is basically a tool inventory control system, additionally capable of planning, programming and kitting. Gauges and fixtures are included in the inventory control. The system can communicate with other FMS software such as CAD/CAM and tool identification or recognition systems and can produce detailed reports Figure 3.15.

A tool production company, Sandvik,[207] has developed tool management software, CoroTas, that basically deals with tool storage, preparation, measurement and coding, transportation, inspection and identification. The system contains comprehensive stock control functions with tool location, tool code and search facilities as well as tool kit, usage statistics and purchasing lists, Figure 3.16.

One of the central store functions is tool presetting. Kennametal has developed a presetting system which is based on two co-ordinate measuring machines. Tools are inserted to the adapter

and their images will be displayed on the screen. A micro computer based electronic system ensures rapid and accurate measurement and data processing with the necessary interface [128]
.

3.5.2 Cell Secondary Tool Storage

A flexible manufacturing cell consists of one or more CNC workstations and employs a secondary tool store to feed the individual machine magazines. The main activities include tool exchange, tool transportation and tool load and unload between the STS and CNC workstations. The transportation system may be either dedicated to the movement of tools or shared with the movement of parts. An STS is used in either one of the following two modes:

1. As a transient tool buffer store linking an FMC to the CTS, or
2. As a major tool store with a large capacity to hold all the tools required by the cell for a planned production period [272].

The size and capacity of an STS mostly depends on the machine magazine capacity and the production period as well as the workpieces manufactured in the cell. Machine tool builder Yamazaki has developed the "Tool Hive", a compact tool storage system which is used as a secondary tool store to serve two or more machines. The Tool Hive can store up to 480 tools and replaces the magazine or drum on a machine tool. A tool handling robot transfers tools from the Tool Hive to the changer [268].

3.5.3 Machine Based Primary Tool Store

All modern manufacturing workstations are equipped with a primary tool store. PTS capacity ranges from 20 to 240 tools as standard. The requirements of a wide variety of work-pieces can be met and additionally some spare tools can be stored for extended periods of unmanned operation.

Various types of different complexity are found in practice. DeSouza has listed eleven different types of magazine [66]. In addition to his list, new types of magazine have emerged recently. Werner has employed a stationary cassette type magazine which consists of two tool cassettes with a total of 80 storage positions and one changing cassette with 12 positions on its TC-Series workstations. The magazine may be expanded up to 160 + 12 tool positions. Tools are handled via a 2-axis linear gantry robot with integrated drive, bearing and measuring system. The gripper unit of the manipulator is used to load the tool changer as well as the magazine and the changing cassette [256].

SHW has developed a golf-ball like tool store which is used at a machine as a primary tool store or remotely as an auxiliary tool store. A segment within the robot accessed golf-ball permits the supply or removal of a tool set in addition to the supply/removal of a single tool. The ball presents tools to the robot in a telescopic fashion [219].

Smaller magazine capacities have emerged as inadequate for machining tasks which use large batches and require relatively large numbers of tools, causing frequent down time and load and unload requirements. Larger magazine capacities, despite an initially higher investment can accommodate larger numbers of tools and more adequately support continuous and unmanned production.

3.6 Tool Exchanging Systems

The introduction of secondary operations in machining centres and turning systems results in the requirement of a large variety of tools on the same machine. To accommodate the variety of tools, a reasonably large magazine is necessary. Due to the need for worn tool replacement and tool changing for different cutting operations, a fast tool changing system plays a crucial role for the efficiency of the machine tool. The exchange mechanisms employed on CNC workstations include those used in ATC systems and are as follows [66]

- overhead gantry system;
- shuttle mechanisms;
- robotic exchange;
- gripper exchange.

Werner has employed fast tool change mechanisms for its TC-series flexible machining system. The tools are loaded or removed by a gantry mounted gripper. The machine column and vertical slide move to the changing position at the end of a machining operation. The tool changer swivels to the spindle at the same time. The used tool is first deposited in the free gripper. The spindle then moves to the transfer position and takes the new tool from the second gripper. The tool changer then swivels back to the initial position with the used tool. The vertical lift door to the working space of the machine is then closed. The tool changer is protected from coolant and chips by the vertical lift door. The complete operation takes five seconds and the machine operation can begin immediately after the changing process is completed. At the same time, the gripper returns the used tool to its proper position in the machine magazine and loads the changer with the next tool required [256][103].

3.7 Modular Tool Design

Since the use of computer technology in machine tool construction a radical change has taken place in both machine tool capability and ancillary equipment functions. Machine tools have been developed with great efficiency and which are capable of higher cutting speeds. This in turn requires cutting tools that do not limit these capabilities. Various tool materials and tooling systems have been developed to meet these requirements. New cutting tool materials such as carbides, ceramics, armet and polychrystalline diamonds which are highly durable under very high heat and various chemical reactions have been developed so that tools are very reliable. In addition to tool material developments and indexable inserts, modular tooling systems are another new feature in cutting tools design and implementation for FMS [188].

The use of modular tooling systems has increased the storage capacity of magazines and the availability of tools. They enhance the standardisation of tooling system design, and facilitate central tool store tool component storage and assembly [272].

Karl Hertel have introduced a tooling system, the Flexible Tooling System (FTS), as an alternative tool changing concept which uses a single clamping unit to handle any conceivable cutter type providing a universal and flexible facility [111]. The FTS is based on a Hirt coupling with the cutter and clamping unit which gives better accuracy and torque transmission. The cutter head is locked back to the adaptor by means of a collet and drawbar and coolant is carried internally through the coupling, thereby rinsing the coupling from inside and protecting the Hirt serrations from contamination. Hertel provides two types of gauging heads for in process gauging. One type uses inductive transmission and the other uses optical transmission of signals. Hertel provides a standard drum type magazine of 60 and 120 tool pockets. A twin shuttle type is also available with 120 (2x60) tool positions, which allows one magazine to be serviced for the next part family while the second is being used for the current processing.

Sandvik Coromant has developed a tooling system for Turning systems, the Tool Block System (BTS) [206]. The BTS consists of:

- an accurate and stable coupling;
- small light cutting units;

- manual or automatically operated clamping devices;
- a tool changer and tool magazine;
- measuring probes for tool and workpiece;
- a comprehensive programme of external and internal tool units.

The unique coupling offers no play in any direction when in the clamped position. The force on the drawbolt makes the Block Tool as rigid as a solid tool. The tool is supported underneath so that stability is ensured. The plain contact faces and high precision between the unit and holder help to maintain the stability of the coupling. The system includes methods and equipment for automatic gauging. Measuring probes are available with the BTS coupling for measuring workpieces in the machine and also with the fixed mounting in the machine tool for setting. The small cutting units can be accommodated in large numbers in magazines or stores and do not take up much room.

Kennametal has designed the KV tooling system which combines three proven tooling systems. Firstly, standard tools have been incorporated wherever possibly. Secondly, a modified V-flange adapter has been used for accurate location, ease of insertion or removal and to provide a gripping point for automated tool changing and finally, a Ball-Lock clamping mechanism is folded inside for compactness. The KV tooling system offers two options for outside diameter turning tools. For larger machines, the KV tool adapters accept ANSI standard toolholders or cartridges whereas when a more compact turning system is required, integral shank KV turning tools can be utilised [128][156].

3.8 Tool Identification and Recognition

It is desirable that the right tools are at the right machine and are properly presetted in the correct magazine pockets. A facility to check a tool's identity when it arrives at a workstation, again when it is removed from the magazine to the spindle and also when unloaded from the magazine is important [13].

Data to allow correct identification of a tool can be stored in a tool database system and may include a tool's individual identification code; current information on preset dimensions; insert specifications; assigned job and kit number; cutting speeds and feed rates for the job; the time that the tool has been cutting and the expected remaining hours of cutter life.

Employing the latest electronic technology, this vast amount of data can easily flow between machines, tool rooms and offices. All tool identification systems fall into two categories [194]: Read-only (RO) and Read-write(WR). In RO systems, the tags carry fixed codes only. Updating of tool data is performed in the system computer database. RW systems, on the other hand, use tags containing EEPROM (electronically eraseable, programmable read-only memory) chips that can be written to. Within these two categories, four types of system based on distinct technologies have emerged. These are:

1. Bar coded tags and laser scanners;
2. Microchip tags with air-induction coils;
3. Microchip tags with radio frequency (RF) transceivers;
4. Microchip tags with mechanical contacts.

Yamazaki Mazak has employed an intelligent chip which is mounted in each tool's retention stud, to read and write the tool ID, diameter and length. The chip activates the tool management computer to generate a graphic display on its monitor indicating which tool is in progress [139].

Kennametal has developed a chip identification system which reads and writes through electromagnetic induction without physically contacting the tool. Kennametal's chip contains a fixed code and cannot be reprogrammed [128].

Giddings and Lewis (G&L) has developed a vision system consisting of a small solid state camera and CRT display that identifies various cutting tools by type and dimension [89].

Sandvik Coromant's tool management system, CoroTas, has a facility to support tool identification and recognition. The system supports both RO and RW categories. The read only system utilizes tags containing a fixed multi-digit code. The system operates with a central processor which stores and processes the data related to the tool identity code. The read only system basically comprises: a read only code tag installed in each tool and a reading head and interface unit at each reading position as well as a suitable software package. Figure 3.17. The read/write data tag can store up to 2 KB of tool data. Existing data can be updated and new data entered as well as displayed or transferred. The system utilizes an independent station which can be located anywhere [206][208].

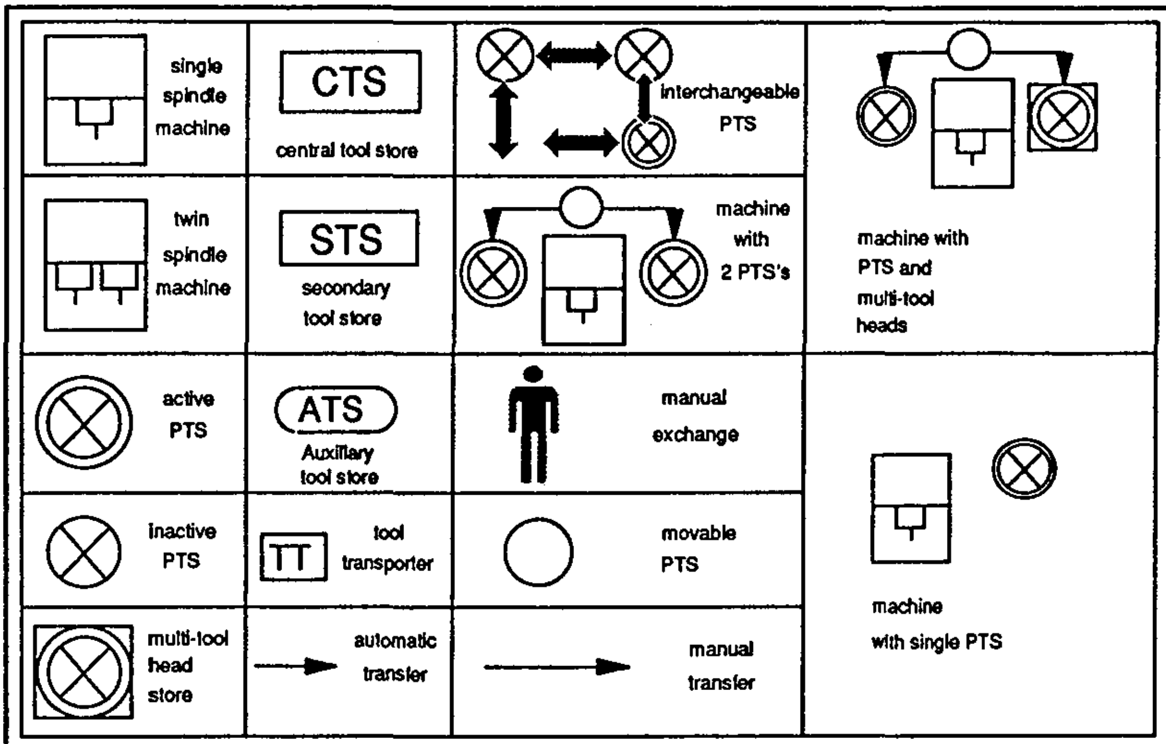


Figure 3.1 (Ref.66)	Tool Flow Systems - Shematic Representation	LUT-FMS Research Group

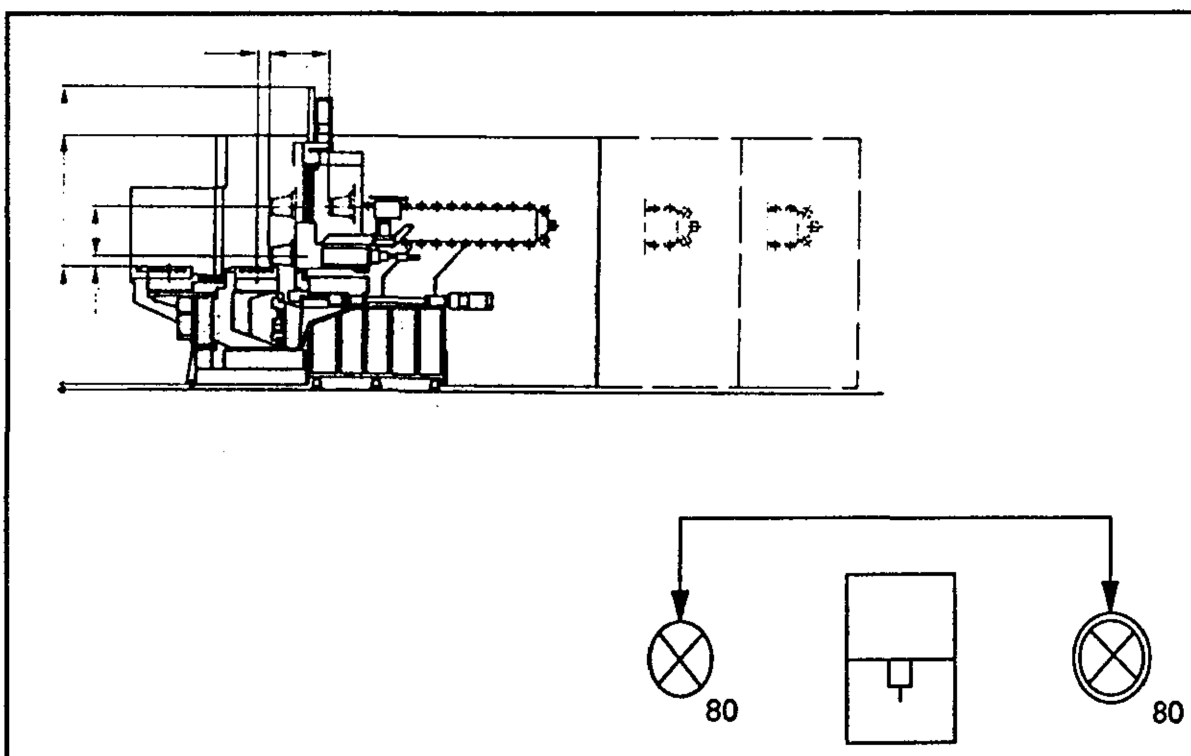


Figure 3.2	DECKEL DC Series Machining Centre with dual magazine	LUT - FMS Research Group

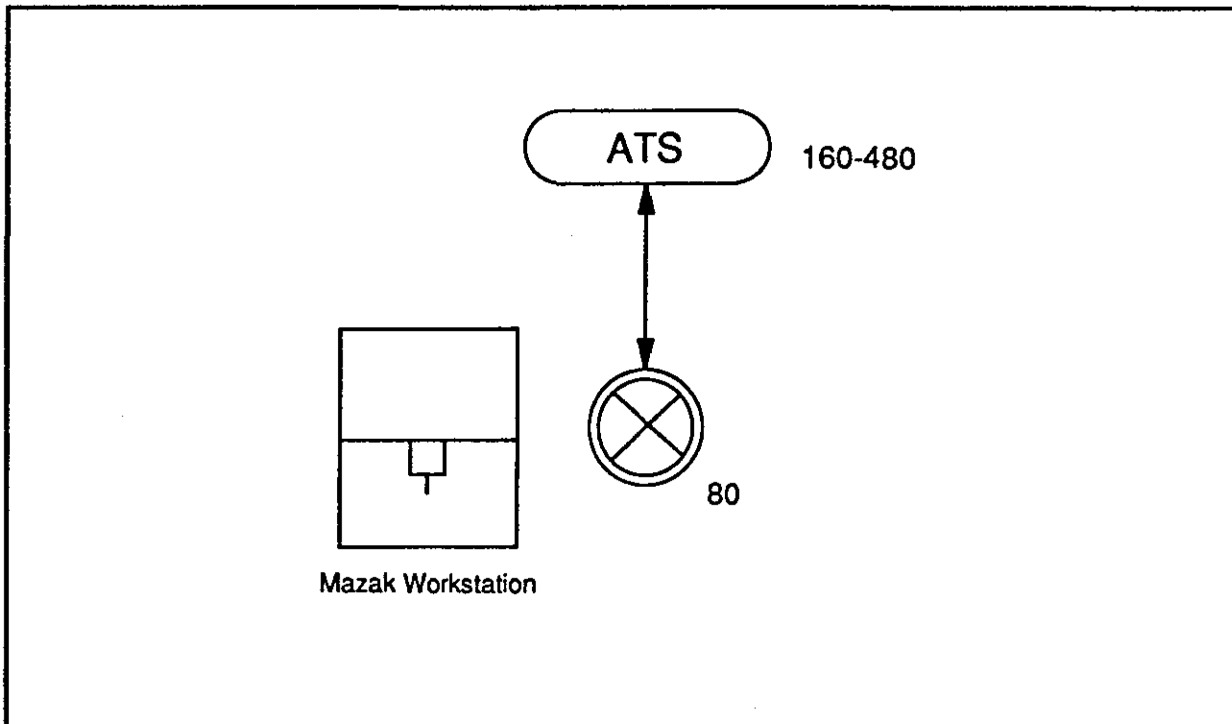


Figure 3.3	MAZAK "Tool Hive" Auxillary Tool Store System	LUT - FMS Research Group

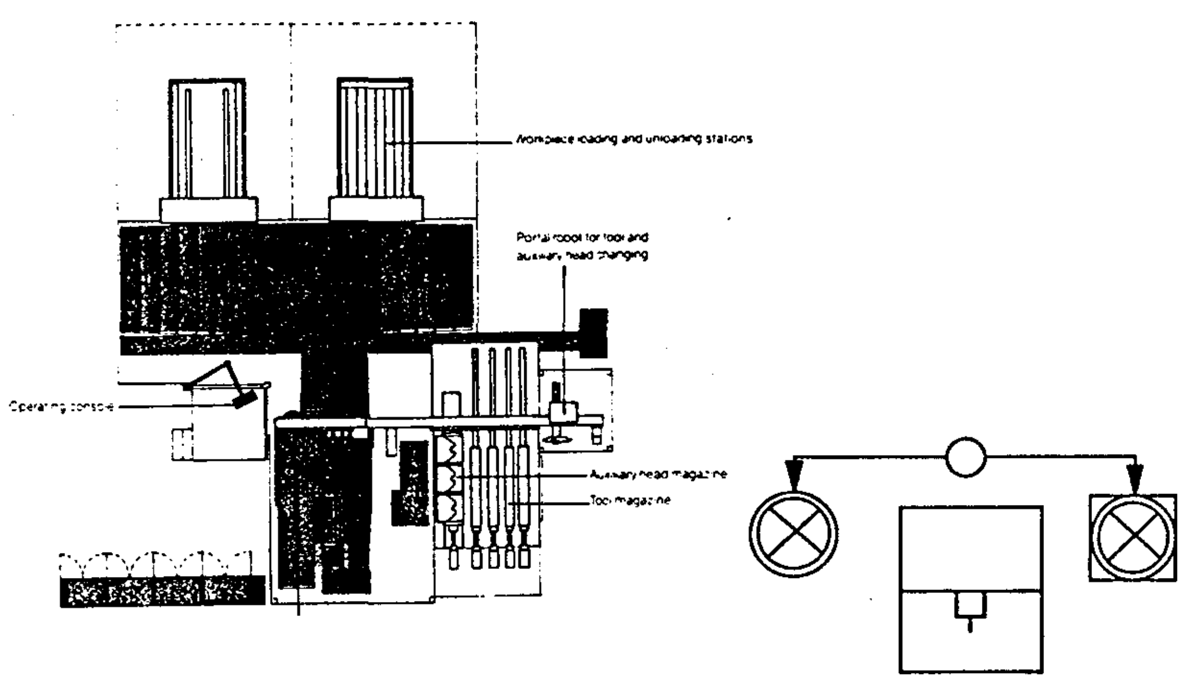


Figure 3.4	Kolb Cubimat HC 1500 with Active Multi-Head Magazine (Ref.to 135)	LUT - FMS Research Group

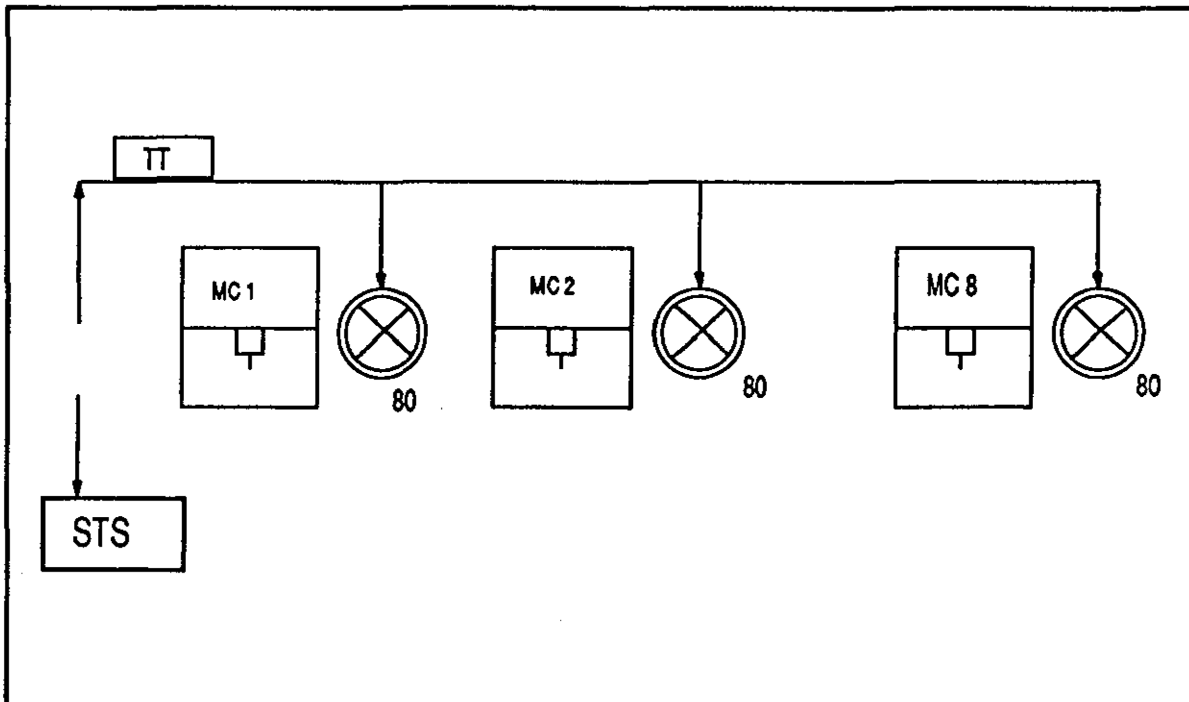


Figure 3.5	Yamazaki Worcester Plant Small Prismatic Part Production Cell	LUT - FMS Research Group

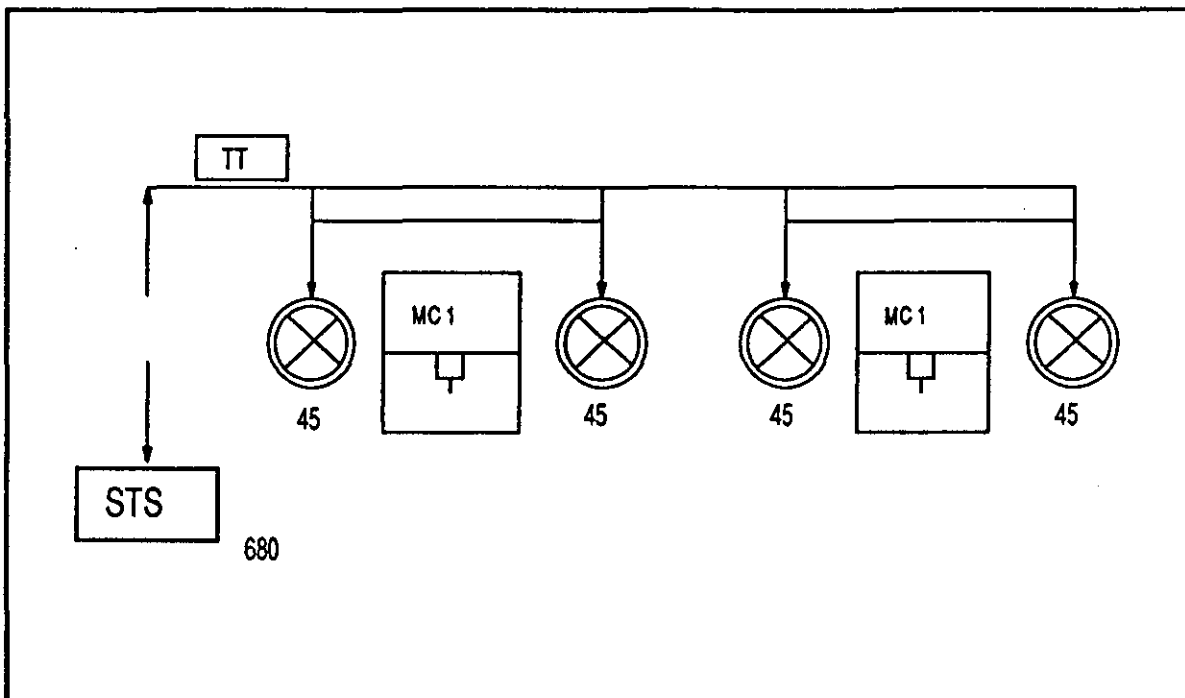


Figure 3.6	Cincinnatti T10 Machining Cell	LUT - FMS Research Group

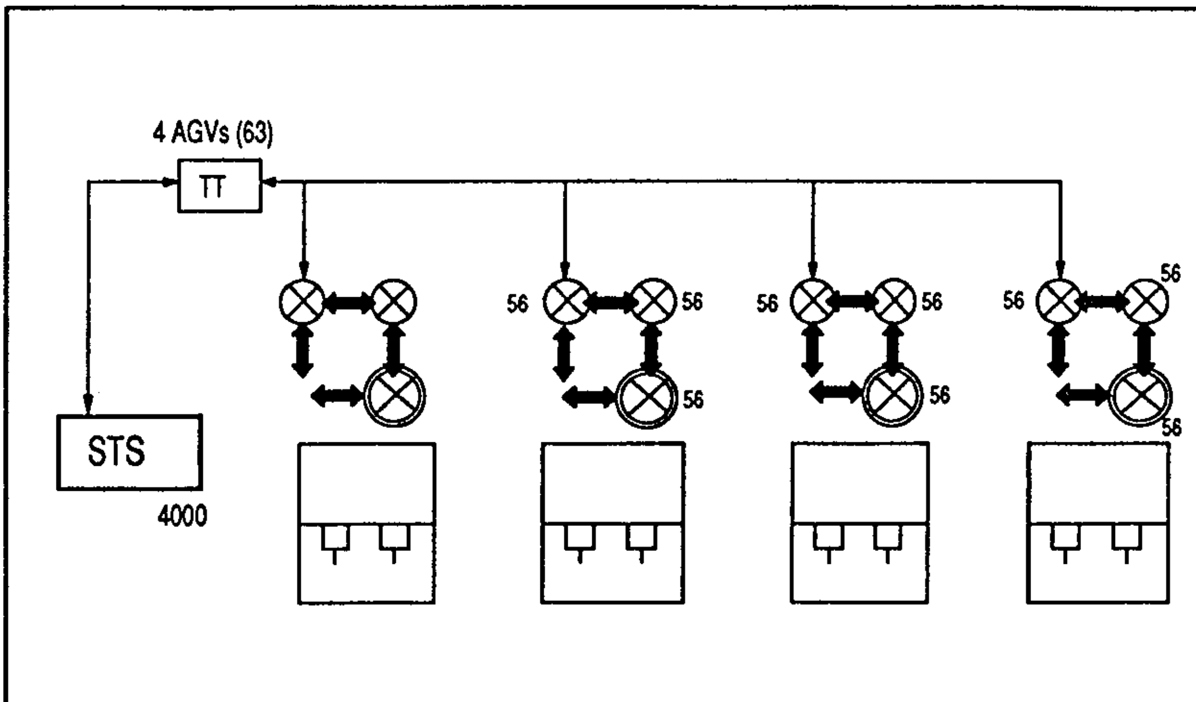


Figure 3.7	BAe Small Parts FMS at Preston	LUT - FMS Research Group

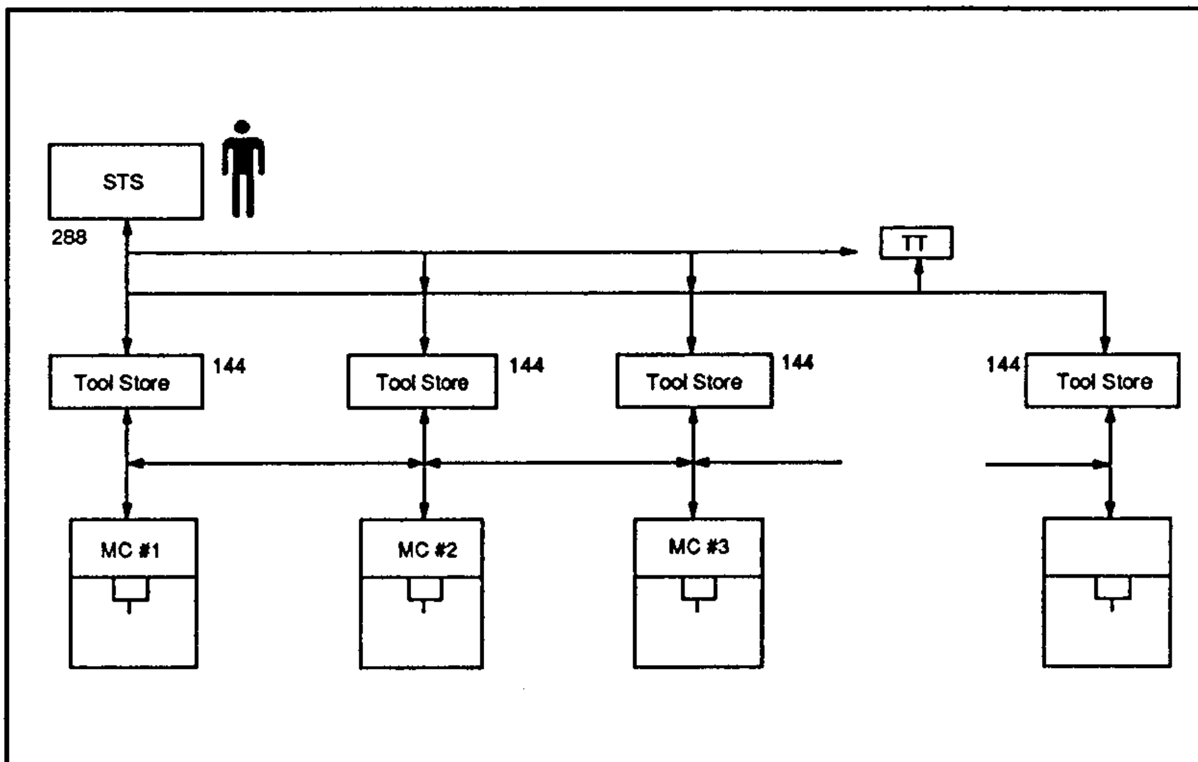


Figure 3.8	TOS Olomouc Tool Management System	LUT - FMS Research Group

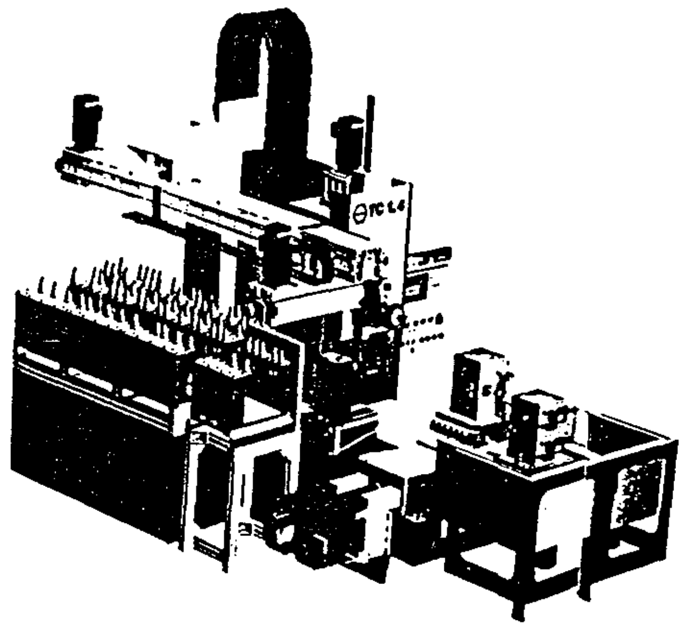


Figure 3.9	WERNER TC Series Workstation with Cassette System (Ref.256)	LUT - FMS Research Group

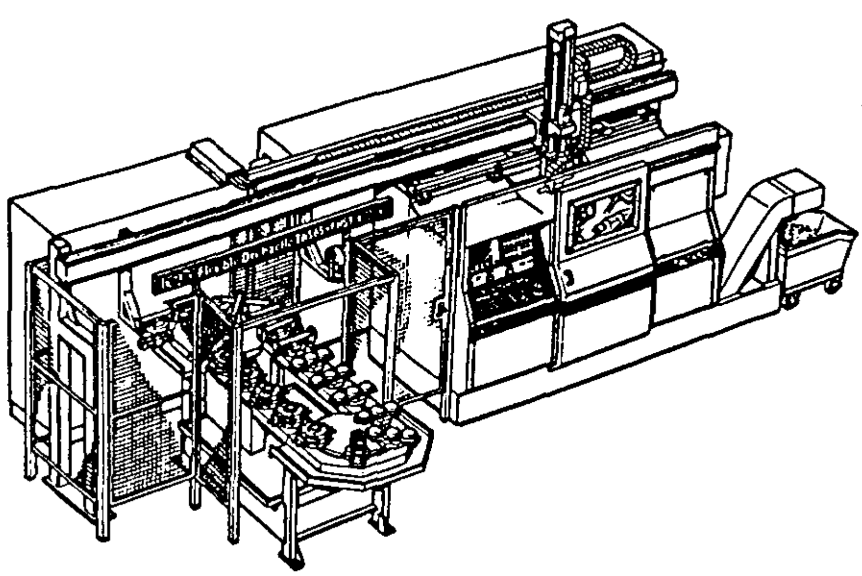


Figure 3.10	TRAUB TNS65 Turning System (Ref.250)	LUT - FMS Research Group

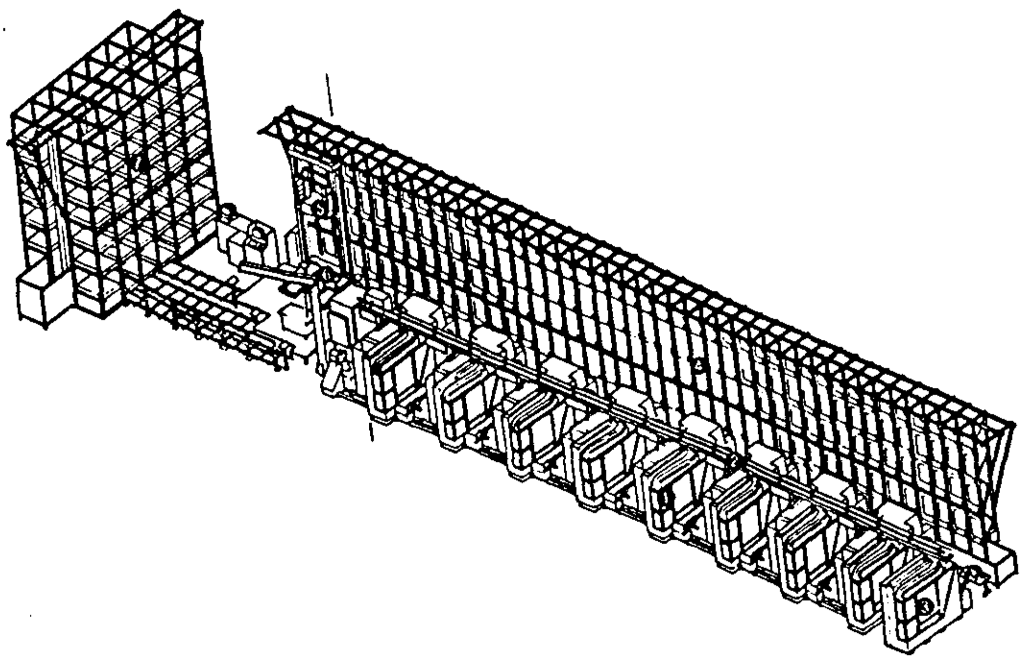


Figure 3.11	Yamazaki Mazatech H-500/50, Mazatrol FMS (Ref. 265)	LUT - FMS Research Group

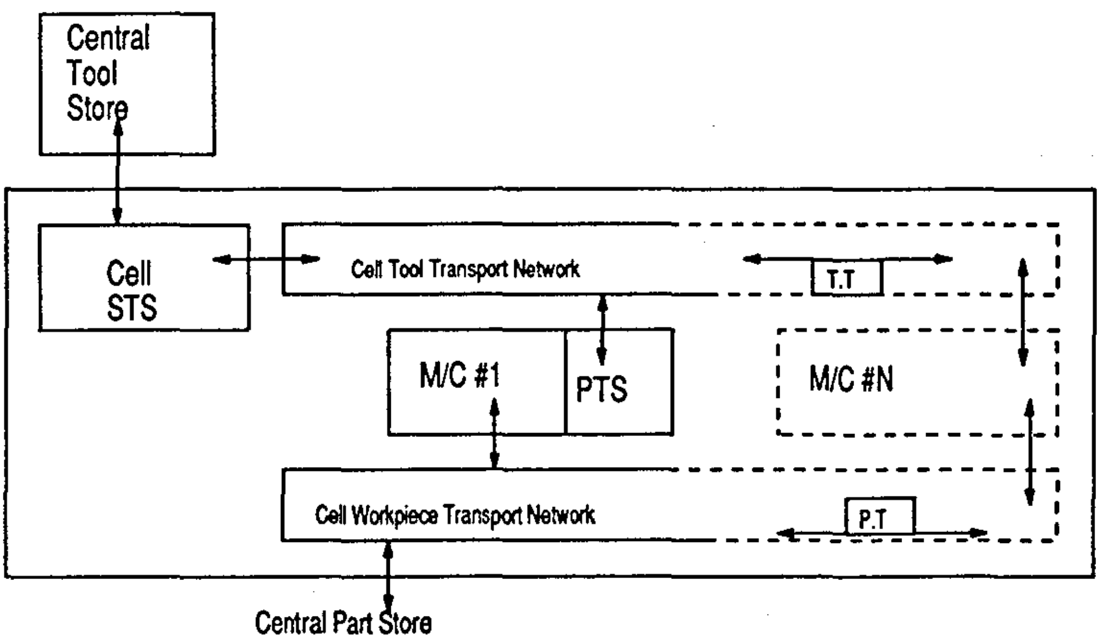


Figure 3.12	Cell Level Tool and Part Flow	LUT - FMS Research Group

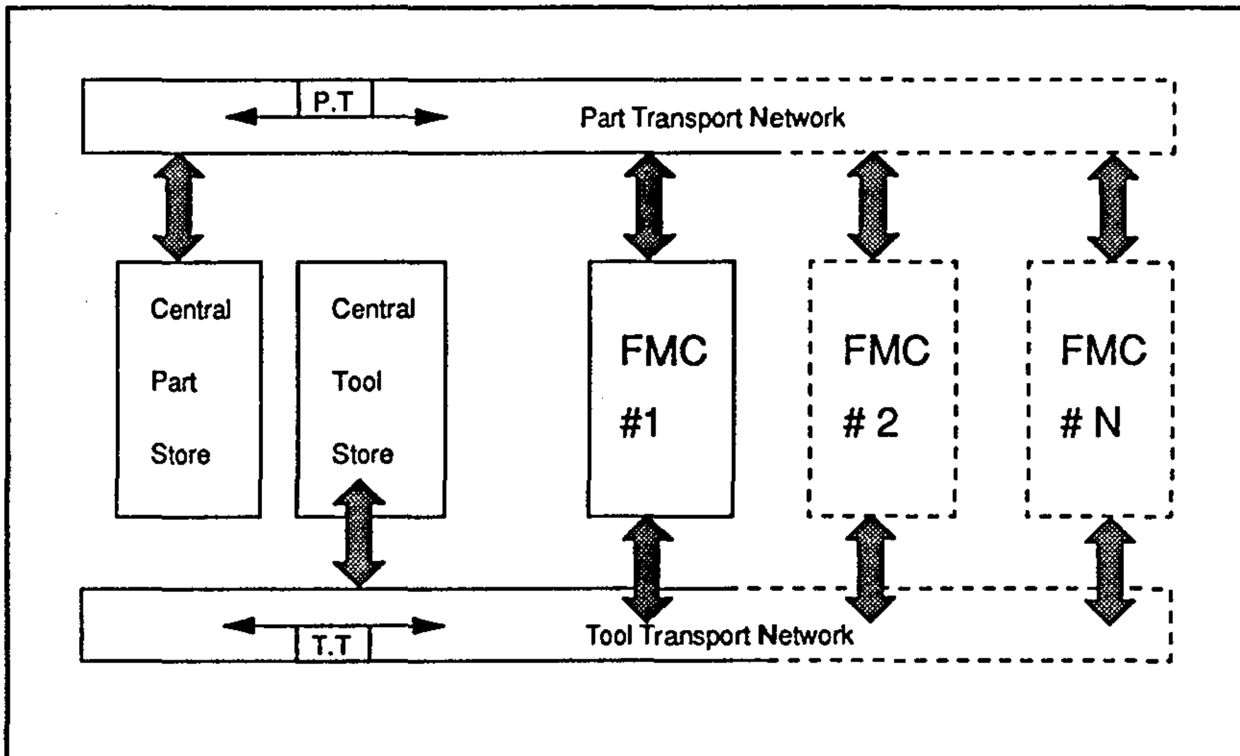


Figure 3.13 | Factory Level Tool and Part Flow | LUT - FMS Research Group

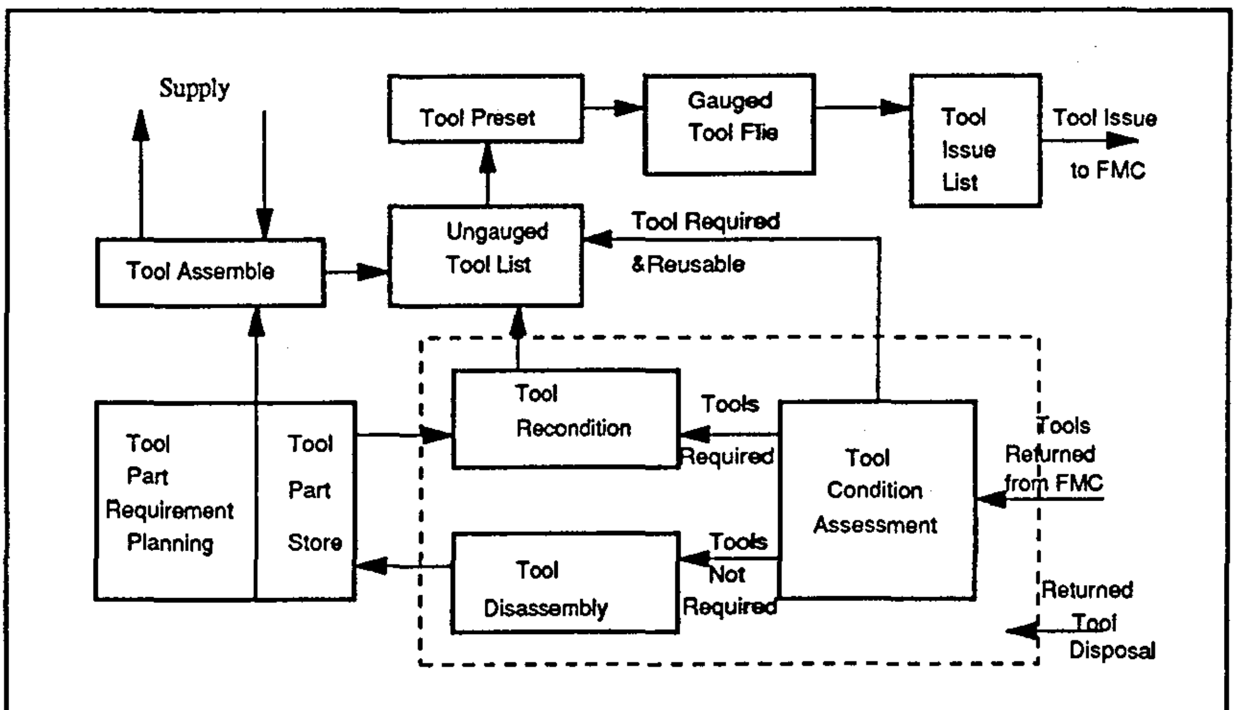


Figure 3.14 | Central Tool Store (CTS) Organisation | LUT - FMS Research Group

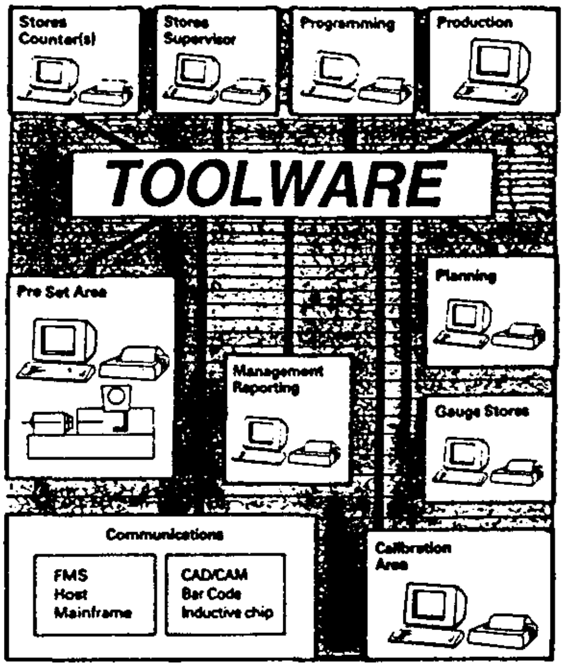


Figure 3.15	ISIS Tool Management System (Ref.118)	LUT - FMS Research Group

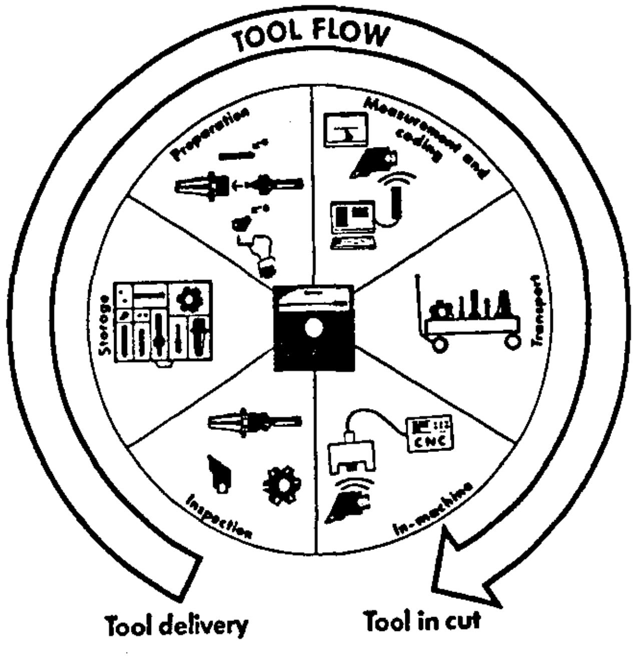
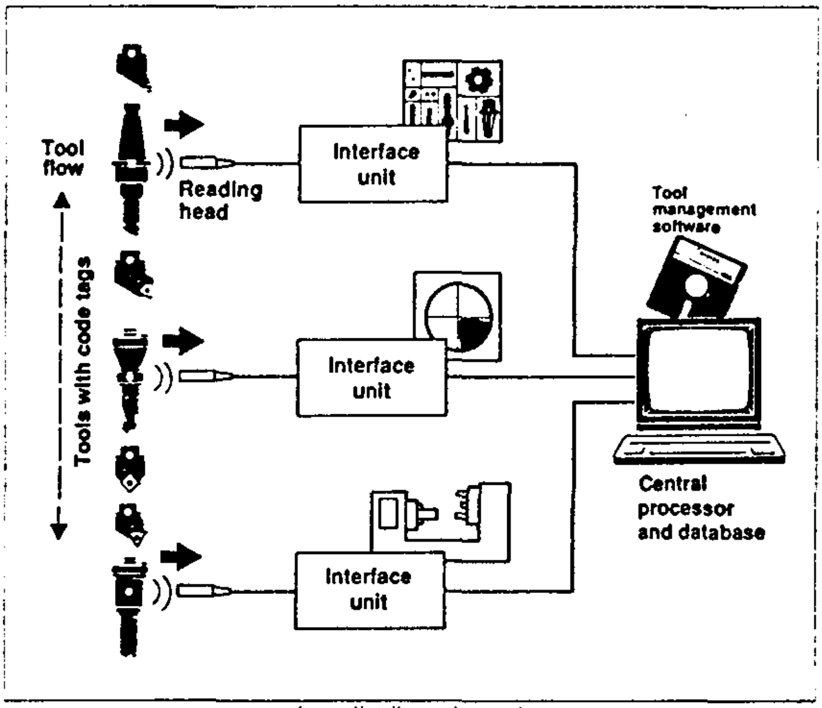


Figure 3.16	Sandvik Coromat CoraTas Tool Management System (Ref.207)	LUT - FMS Research Group



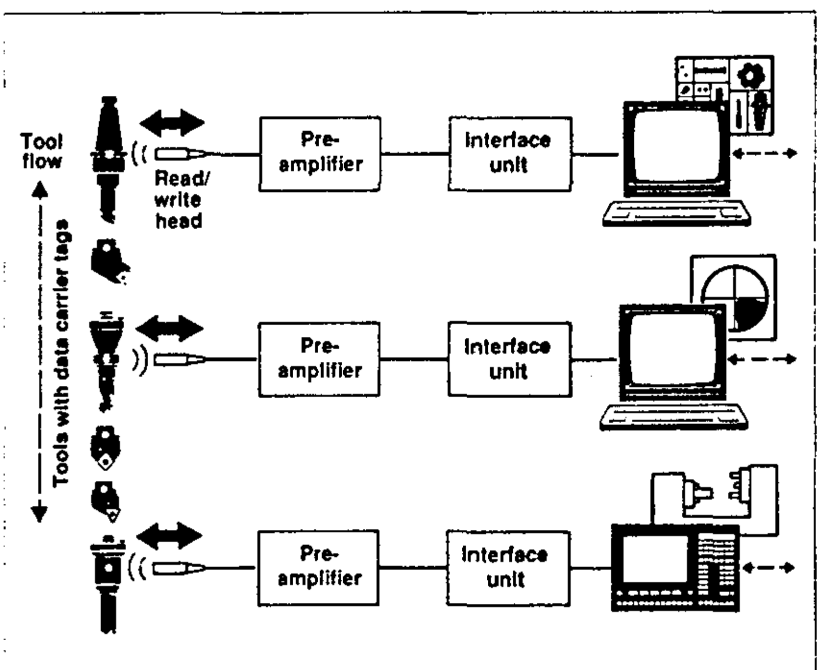


Fig. 3.17	Sandvik Coromat Tool Identification System (Ref. 208)	LUT - FMS Research Group

Chapter 4
TMS Parameters

4.1 Introduction

The purpose of this chapter is to introduce the reader to the tool management system parameters which are used throughout the entire research in both design and experiment stages. They are explained in the TMS research context undertaken in this thesis.

4.2 Production Requirement Parameters

The work list and the associated tool set that is processed in the manufacturing cell has been determined by an MRP system and the work enter the shop floor in batch form. The full part-tool list has been divided into three families where each family contains a different part-tool matrix in terms of size. Family one contains 15 part types and 51 tool types; family two contains 40 part types and 71 tool types and family three contains 70 part types and 76 tool types. Each part type has a different production requirement (process batch size) which is based on daily requirement. (See Appendix I).

The size of the transfer batch is based on the quantity of pallet and the capacity of each pallet. Two size of transfer batches are considered which are common in practice. The small batch contains up to eight components and the large batch contains up to fifty components. (See Chapter 6). Each transfer batch is considered as a job and sent to one machine with the pallet(s).

4.3 Cell Control

4.3.1 Part Release Rules

Part are released to the cell according to operational rules. For the sequencing and scheduling of jobs, four rules are considered.

Earliest Due Date (EDD): which sequences and schedules the jobs according to the required finish time of the jobs. The job which has the earliest due date is sent first.

Shortest Processing Time (SPT): which sequences the jobs in increasing order of processing time. The job with the shortest processing time is scheduled first, then the job with the second shortest processing time, and so forth.

Longest Processing Time (LPT): which is the reverse of SPT and sequences and schedules the job first which has the longest processing time.

Grouped Parts (GRP): which is based on group technology principles and first groups and sequences the parts according to the commonality of tools used and schedules the jobs first which have the most tool commonality.(See Chapter 6)

It is assumed that all the jobs are ready at the same time and produced sequentially. The system is set up to produce a batch and when a batch is completed machines are retooled according to the adopted tool issue strategy and the next batch is released.

4.3.2. Control and Loading

It is assumed that the number of batches (jobs) to be produced in the specified manufacturing period is known. Batches are determined in a deterministic way and the maximum size of a batch is known. There is no random event acceptable such as machine breakdowns, changes in plan, job cancellation, or unplanned job release. Part routings are comprised of operations. Each operation requires a specific tool and has a set of feasible machines to which it may be assigned. It is not sought to optimize specific objectives mathematically such as work-in-process, intermachine moves or workload. The only objective is to attempt to balance the workload using the scheduling rules by assigning jobs sequentially first to the available machine and to load tool magazines equally with the required tools.

In the cluster analysis (See Chapter 15), the aim is to minimize the tool requirement by grouping the same operations which use the same tool type and assigning them to a machine. At the same time this reduces the part movement between machines.

4.4. Tool Flow Parameters

Tools are kept in hierarchical tool stores. The main store is a factory level tool store, known as central tool store (CTS), where tools are assembled, disassembled, refurbished or thrown scrap. Tools are transferred from the CTS to the cell level secondary tool store (STS) and from the STS to machine level primary tool store (PTS) according to tool requirement planning in which a specific tool issue strategy is in operation. Tools may be kept until the end of the manufacturing period if the adopted strategy permits. Tools are loaded either at the beginning of the production period or simultaneously with each new batch which is assigned. Worn tools or unwanted tools are immediately removed from the PTS and usable tools are kept in STS if they will be needed again in the planned manufacturing period. Otherwise tools are all returned to the CTS.

4.5. Tool Issue Strategies

The workpiece oriented strategies issue tools according to the given job lists to the related machines. The approach ensures maximum tool availability and flexibility in the system. A rationalism can be applied to share available tool life across the job list in order to keep tool requirements to a minimum. In many cases this approach may be a good solution for the tool management problem if it is supported by appropriate technology, for example in the transportation mechanism or tool magazine and a well established scheduling system.

Tool oriented strategies, in contrast, issue the cutting tools according to one of available group technology (GT) techniques. The required jobs are then released to a machine holding the appropriate tool set. The approach is applicable especially if there is no due date pressure on the jobs and dynamic scheduling is in practice. This approach aims at sharing the available tool life as much as possible, resulting in effective tool life utilisation and keeping the tool changes to a minimum.

Six tool issue strategies have been put into practice for this thesis. Three of them are workpiece oriented strategies and are known as the kitting strategy, the differential kitting strategy and the single tools strategy. Two tool issue strategies are tool oriented strategies, known as tool cluster analysis full kitting and differential kitting which is discovered during the experimental work. One more strategy has been discovered during experimental work and called hybrid strategy and fully explained in the devoted chapter (Ref. to Chapter 17) The following sections explain the logic of first four strategies as well as their influence on tool requirements planning. The two new strategies explained in the related chapters.

4.5.1 Kitting Strategy

Basically, a kit of tools is allocated with every job to be processed at a machine. The kit is usually returned to the secondary tool stores when the particular job to which it is assigned has been finished.

The strategy is highly flexible and ensures tool availability. However, a large number of basic and sister tools are unavoidably required. Since there is no life sharing across the production period there is no need to trace the available tool life. Therefore, it is easy to operate and control.

The strategy is applicable to hierarchical systems and especially to facilities where machines have limited total magazine capacity as well as small dynamic magazine capacity.

4.5.2 Differential Kitting Strategy

The differential kitting strategy is an improved form of the kitting strategy and its basic principle is that it allows tool life sharing between successive batches.

The rule for issuing tools according to the differential kitting strategy is :

If any tools used by the existing job are common with tools required by the new job and if the common tools have enough life to carry on the operations required for the new job, then keep these common tools on the machine. Then remove the remainder of the existing tool kit and assign the new tools which are required by the new job to the machine. Repeat for successive jobs.

Since the strategy allows for tool life sharing across kits, tool life may be used more effectively and tool inventory may be reduced. However, if jobs which have no tool commonality with previous jobs are sent to the same machine, then the strategy may work very inefficiently. Therefore, the differential kitting strategy is applicable to a special case where the jobs that use some common tools should be sent to the same machine, in order to gain maximum benefit. When coupled with a convenient part scheduling rule, the strategy may work very efficiently and it is possible to save a large number of tools, especially in long term production.

The strategy may also reduce machine down time due to tool loading and unloading.

The strategy needs to trace the available tool life on the machines, therefore it needs a sophisticated control mechanism.

4.5.3. Single Tools Strategy

The single tools strategy is more progressive in the sharing of available tool life across batches in comparison with the differential kitting strategy. The strategy is very much hardware dependent and needs a relatively large magazine capacity and a dedicated tool transport system. The logic is based on group technology principles.

At the beginning of the manufacturing period, a rationalised set of all the tools required are loaded into the PTS of each machine, according to the job list to be processed. New tools are required when they are not already available on a machine or when the available tools have become worn. Tools are unloaded when a magazine is full and they are no longer required or worn.

The strategy shares the available tool life intensively among several jobs and is therefore used very effectively. However, a large magazine capacity is required to accommodate all the necessary tools for a given job list and a fast transport system is required to supply the tools when needed. The strategy again depends on part scheduling rules very much, in that if a job list contains diverse components which need many different tools then tool life sharing may be ineffective and tool requirements may increase dramatically. The advantage of using this strategy could then be lost despite expensive hardware investment. In order to keep track of the available tool life, the strategy needs a sophisticated control system.

4.5.4 Tool Cluster Strategy

The tool cluster strategy is based on group technology principles and was originally developed by the Japanese Machine Tool Builder, Makino Max [209].

There is generally a certain degree of commonality among the tools used to process a number of parts in a given production period. Cluster analysis sequences jobs by grouping parts which can be manufactured using the same set of tools. The clustered tool sets are transferred to machines and the associated part families are then assigned. Thus, for the parts to be processed, a great percentage of the tools are common and so available tool life can be utilised very effectively. Therefore, it is possible to achieve a substantial saving in tool inventory and significant reductions in tool flow, tool exchange and machine down time.

The original strategy developed at LUT has been further improved by the repetition of the clustering of parts and tools from the initial matrix. Those jobs already clustered and assigned to a machine are removed from the job list and the remaining jobs regrouped to produce new tool clusters. This potentially reduces the tool requirements further and is also applicable to multi-cell a multi-machine environment. (Ref. Chapter 15)

The cluster strategy is applicable to a job list if there is no time pressure from a need to meet due dates or if external scheduling is not in use. The strategy requires a relatively large magazine capacity and large transporter capacity to work effectively.

4.6 Hardware Parameters

4.6.1 Number of Machines

The hypothetical flexible manufacturing cell contains up to eight machines. The minimum machine number considered in a cell for the experiments is three. The machines are considered as highly automated workstations and capable of doing multiple-process. Machine groups may be treated as multi-cell by separating into two four-machine cells.

4.6.2 Tool Management Hardware

Each machine has a primary tool store (PTS) with either 60 or 120 tools capacity. Each cell has a cell base secondary tool store (STS) which feeds the PTSs. Also system is assumed that has a factory level central tool store (CTS) where all the tooling activities take place such as tool assembly, disassembly, refurbishment so on.

A dedicated tool transport mechanism is considered which transfers the tools from the higher level tool stores to lower level tool stores and returns them. It is assumed that transporter can carry one tool to up to full kit size tools at a time.

4.7 Performance Criteria

The following criteria have been used to draw conclusions from the output generated from each of the experiments. They are applied to all approaches used in the experiments, namely, workpiece-oriented, tool-oriented and hybrid approaches.

i. Total Tool Requirements

Total tool requirements is defined as tools ordered for a specific job list for a certain production period and may be expressed in the form:

$$TTR = \sum_{i=1}^{n} TR$$

where $i = 1...n$ number of jobs and TR is tool requirements (kit size) for a job.

The tool requirements for both individual jobs and the overall production period are considered as the primary indicator of performance of the TMS. The aim is to minimize tool requirements for the production period, avoiding any unnecessary tool assignment.

ii. Tool Inventory

Tool inventory is defined as the total tools available in the system which covers resident tools in stores as well as tools in use and spent tools. Tool inventory may be expressed as

$$TI_s = \sum_{i=1}^{n} TotalToolRequirement + \sum_{i=1}^{n} SpentTools$$

where *i=1,..,n tool types*. Tool inventory is used another performance indicator of a TMS, and the aim is to minimise TI_s

The tool inventory predicted, TI_s, by the model using a particular strategy and first a form of a dead reckoning which may not be judged always practically acceptable. In order to accommodate this necessary consideration, a second major tool inventory described as TI_m is introduced where:

$$TI_m = \sum_{i=1}^{n} TotalToolRequirement + \sum_{i=1}^{n} SpentTools \sum_{i=1}^{n} (MinimumToolRequirement - SpentTools)$$

The minimum tool requirement, T_m is the number of tools which would be used if the work required in a particular manufacturing system is machined in the most simple and unrealistic manner, this implies that no tools are used in a circulating system to support efficient cellular manufacturing system but simply to remove the metal.

iii. Tool Flow Rate between Tool Stores (Tool Traffic)

Tool flow rate is defined as tool movement between tool stores for a given job list and production period and is expressed by:

$$TT = \sum_{i=1}^{n} (ToolMovement)$$

where i=1..n is number of jobs.

Tool traffic is directed by the tool issue strategy adopted in the manufacturing facility. A badly chosen tool issue strategy may cause very heavy tool flow between stores which is considered undesirable in terms of transportation utilisation, throughput time and tool life utilisation. The aim is to keep balance between the tool flow and the production rate.

iv. Machine Utilisation

Machine utilisation is defined as the non-idle time for which a machine is busy with machining operations over a certain production time and is expressed by:

$$M = \sum_{i=1}^{n=8} (OperationTime/ProductionPeriod)\%$$

For a given machine, the tool magazine capacity is limited, and tools are required to be loaded/unloaded periodically to/from the magazine. Long loading/unloading times or too frequent tool changing may result in low machine utilisation which is considered to be undesirable for a successful TMS. The aim is to balance the machine utilisation against production period.

v. Throughput Time

One of the objectives in a manufacturing system is to minimize the overall manufacturing time. Since all the activities which take place in tool management are time related, they significantly affect the throughput time. The objective is to minimize the time caused by TMS activities. The formula considered for throughput time is:

$$ThroughputTime = \sum_{i=1}^{n} MachiningTime + \sum_{i=1}^{n} PartSetupTime + \sum_{i=1}^{n} ToolSetupTime$$

where $i = 1, .., n$ *number of jobs.*

v. Transportation Utilisation

Transportation utilisation is defined as the non-idle time for which the tool transporter is involved either load/unload or handling operations and is expressed by

$$TU = \sum_{j=1}^{m} (OperationTime/ProductionPeriod)\%$$

where j=1,..,m is the number of journeys.

Depending on the tool flow, the transporter may be used very frequently or seldom and the aim is to balance utilization against production period as for in tool flow and machine utilisation. In order to simplify the calculations, the transportation operation time is not linked to transporter speed, instead, an average journey time between STS and PTSs plus an average transporter load and unload time is assumed.

vi. Effective Usage of Available Tool Life

The effective usage of tool life is one of the major problems which a successful TMS attempts to overcome. Life utilisation depends on the tool issue strategy adopted and the aim to is to maximise the life utilisation, rather than changing tools after only a small part of the available tool life has been used. Thus, number of discarded or partly used tools, tool changing and tool flow between tool stores may be minimised.

Chapter 5
TMS - Design Challenge

5.1 Introduction

The purpose of this chapter is to identify the challenges in TMS design. The family of issues involved in the design of TMS is also highlighted. The design concepts behind the modelling facility are introduced.

5.2 Design Challenge

The characteristics and functions of a TMS at the planning and control level shown are in Figure 5.1 as depicted by Eversheim et al. [20]. Functions are basically categorized in two main areas which are organizational and hardware areas. This research work focuses on the tool flow, timing, capacity planning, monitoring and tool procurement issues.

A hierarchical representation of tool flow in flexible manufacturing environment is depicted in Figure 5.2. The hierarchy considered is three-level: factory level - central tool store, cell level - secondary tool store and workstation level - primary tool store. Each level as well as transportation between stores has a set of rules and strategies for operation.

A number of TMS issues are considered as the design challenges in this research and the brief list of the challenges are given below and are detailed in following section, these are:

* Design method

* Concept of the modelling facility

5.3 Method of Design

The research represented in this thesis is based on previous design work done in the laboratory to provide tool management solutions for short term manufacturing tasks. This work was implemented using algorithmic modelling which was severely limited by entity restrictions resulting extremely slow software run time. Also, although algorithmic models are capable of modelling tool flow detail, they focus totally on the design of installation hardware and hence lack of balance in that there is no connection with organizational issues.

The complementary theses are available for the algorithmic modelling of tool flow in prismatic part manufacturing systems [66] and tool flow in cylindrical parts manufacturing systems [272] which covers the modelling of live tools and more complex automation at machine level as well as labour.

A TMS is a complex system which involves many complex relationships. Thus, at either the design stage or the operation stage, design and the method of design are important factors. There are several different methods that may be used to design a TMS. A broad classification and wide explanation of these methods has been given in Chapter 2.

None of the mainstream modelling methods listed is capable of designing a TMS properly alone. Therefore, a method which is a composite of algorithmic and knowledge based approaches has been used in the research to design TMS. This hybrid approach use the power of both approaches and is capable of modelling detail with accuracy and can make decisions. This new approach can also manipulate large bodies of data. It is also a flexible system which lets the user input his/her own particular data such as tolerance limits as well as hardware configurations.

5.4 Concept of the Modelling Facility

The modelling facility has been built up to support the wide range of research issues. The modelling system is dedicated to the hybrid representation of a TMS. General inputs that are required and the output generated by the design facility are depicted in Figure 5.3. It is seen that, design facility supports both design and operational issues to support both hardware and organizational issues.

One of the major design factors is the job list for each machine to which appropriate tools are assigned. Although it may be counted as a separate issue, the TMS design has to support job scheduling either internally or externally and it should suit the requirements of the tool management system.

A more detailed picture of the major inputs and outputs of each of the individual design facility modules is given in Figure 5.4. This figure also shows the interdependency of the modules. The software which has been created to support the exploration of the research issues embodied in the four modules is presented in detail in the next four chapters. Chapter 10 follows to summarize the design facility capability.

The design models functions, approaches and their environments can be briefly listed as follows:

Model	Functions	Approach	Environment
Scheduling	* Job Scheduling to Machine * Job Scheduling to Cell	Knowledge-Based	KES
TRP	* Tool Inventory * Tool Requirement * Kit Size * Spent Tools * Machine Utilization * Transport Utilization * Makespan *Tool Life Utilization	Algorithmic	Lotus 123
Strategy Selection	* Best Strategy for Machine * Best Strategy for Cell * Best Strategy for Factory * Strategy Report	Knowledge-Based	KES
Output Analysis	* Tool Store * Tools * Machines * TRP * Transportation * Lead & Throughput Time * Fault Diagnosing - Machine - Tools - Cell - Tool Stores	Knowledge-Based	KES

Great emphasis has been given to the exploration of the interactions between the TMS design factors. A large number experiments for the three approaches, namely, workpiece-oriented, tool oriented and hybrid, have been created to explore the relations and trends and this part of research is presented through chapters 11 to 17.

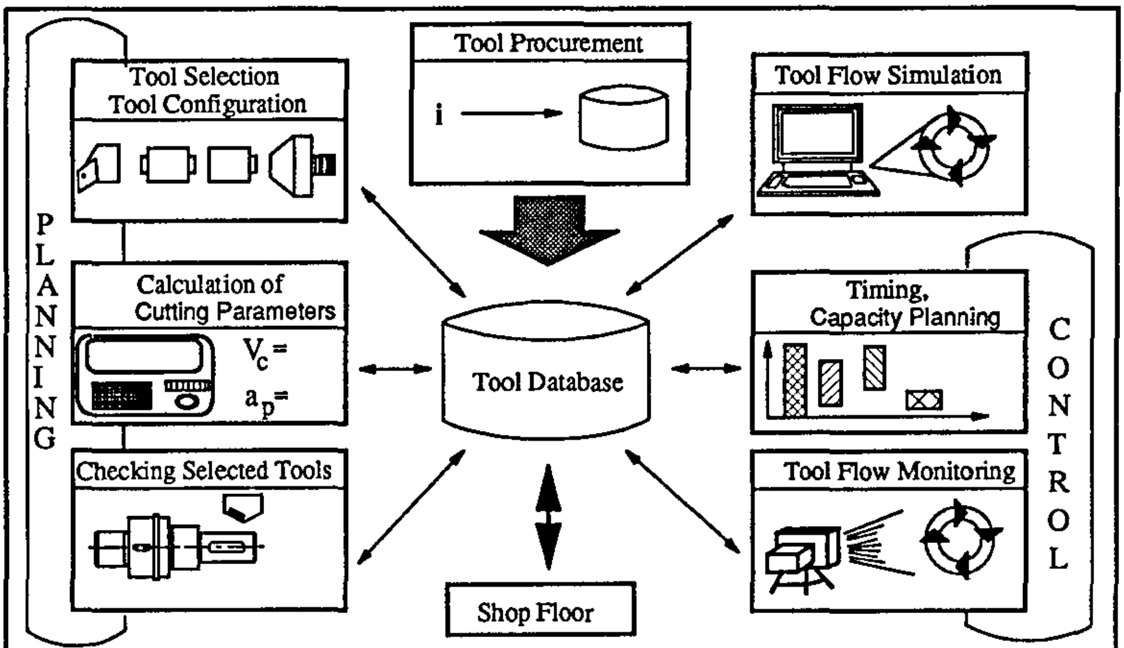


Figure 5.1 | Tool Management Functions - Planning and Control Level (Ref. 73) | LUT - FMS Research Group

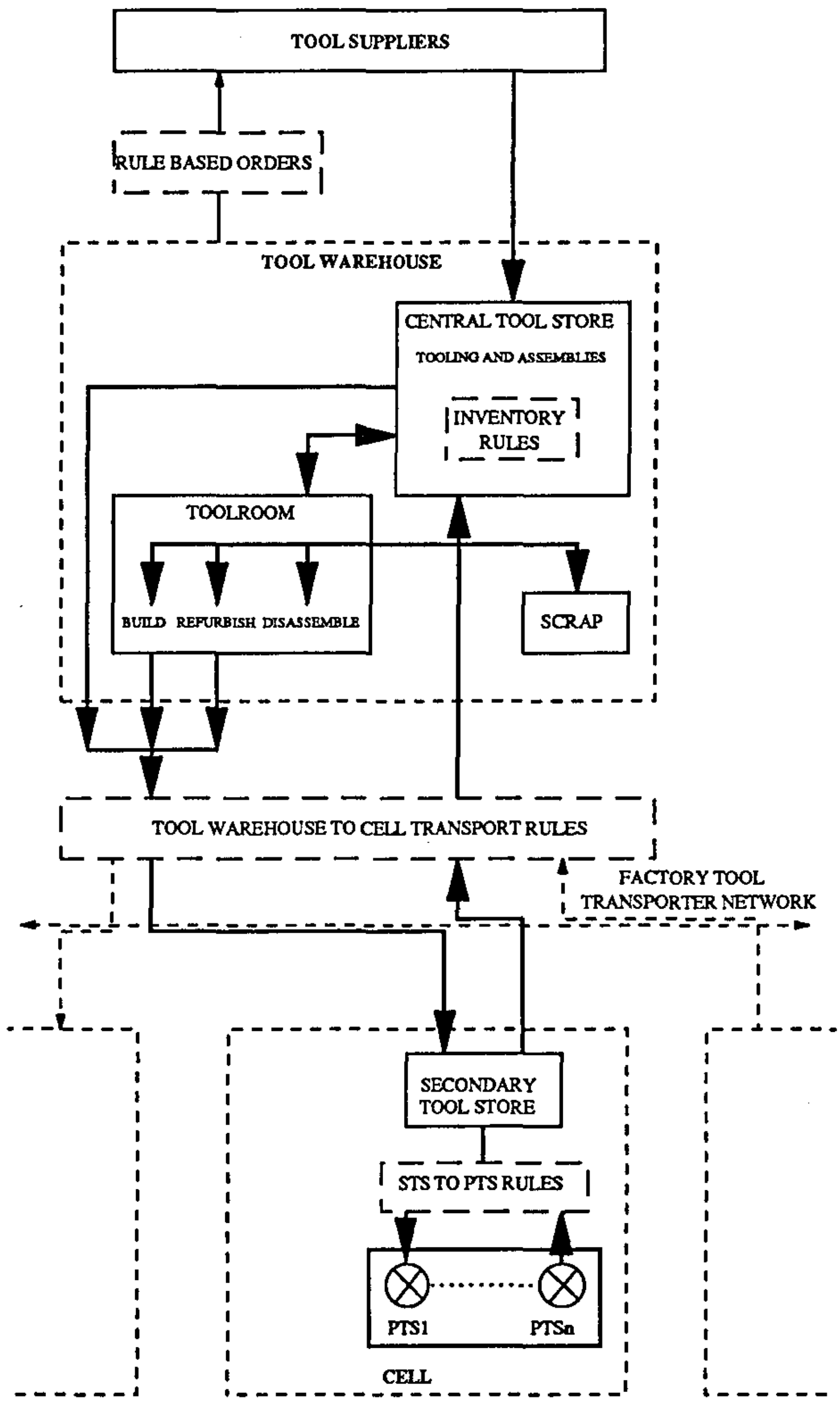


Figure 5.2	Flow of Tools in Batch Manufacturing	LUT-FMS Research Group

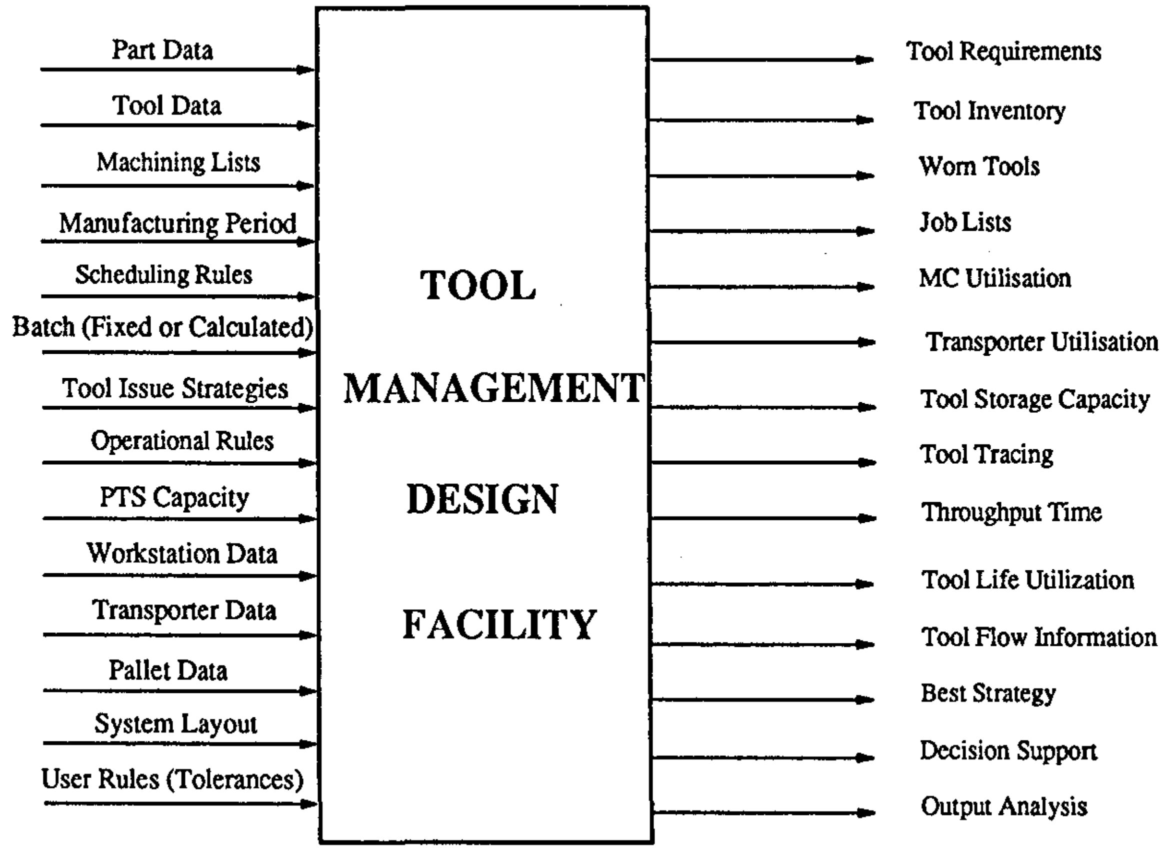


Figure 5.3	General Input and Output of the Design Facility	LUT-FMS Research Group

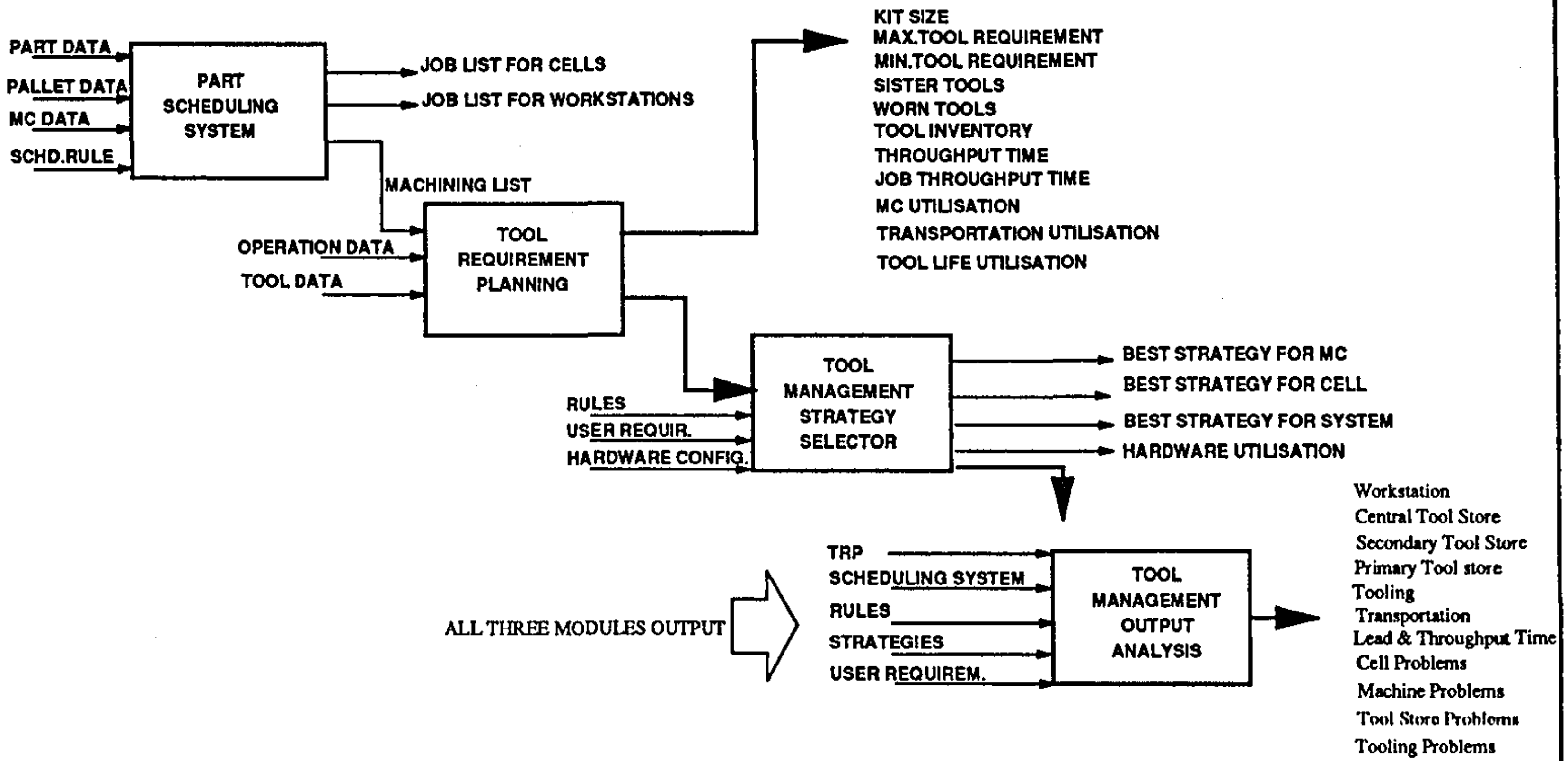


Figure 5.4	Individual Modules' Major Inputs and Outputs	LUT-FMS Research Group

Chapter 6
Part Batching and Scheduling

6.1 Introduction

Part batching and scheduling functions have been added to the TMS design facility with an aim to produce the machining list required by tool requirements planning (Chapter 8) and examine their effects on tool flow in FMS. No attempt is made to develop optimal rules, but the batching and scheduling module has been incorporated to maximise the efficiency of the design facility. This chapter defines the expert part batching and scheduling module and its function in the entire modelling environment.

6.2 Nomenclature

The nomenclature and terminology used for the batching and scheduling problem is set out as below and the mathematical models built for batching and scheduling are given in Appendix III.

$I:\{i \mid i = 1,2,\ldots,N\}$ *the index set of jobs*
$M:\{m \mid m = 1,2,\ldots,U\}$ *the index set of machines*
$J:\{j \mid j = 1,2,\ldots,V\}$ *the index set of operations of part i*
$T:\{t \mid t = 1,2,\ldots,L\}$ *the index set of tools*
$S:\{s \mid s = 1,2,\ldots,F\}$ *the index set of components that form the batch(job)*
$V:\{v \mid v = 1,2,\ldots,D\}$ *process batch (order quantity) for a given period*
$P:\{p \mid p = 1,2,\ldots,E\}$ *the index set of pallets*
$C:\{c \mid c = 1,2,\ldots,H\}$ *the index set of parts*
d = *due date*
T_m = *available time for machine m,* $m \in U$
$X_{ijpm} = 1$ *if operation j of pallet p of job i assigned machine m*
$= 0$ *otherwise*
$Z_{ijp} = 1$ *if operation j of pallet p of job i is assigned*
$= 0$ *otherwise*
$W_{ijm} = 1$ *the processing time of operation j of all components of pallet p, job i*

6.3 Part Batching in FMS

Part batching is important factor in an FMS.[53][117][44][167][64] All the jobs which will be accomplished use the same finite resources such as machines, materials, tools, time, labour, etc. The competition for the same resources makes the batching a vital function for manufacturing and needs particular attention.[251]

There are two main system design constraints to decide the batch size. These are magazine capacity and transporter capacity. [158][65]

Especially large batches need a great number of tools on the machine. Small magazine capacity presents a serious problem to deciding the batch size. Small batches frequently result in very large number tool changes and inefficient tool life utilisation as well as longer throughput time. Larger batches face the magazine capacity as well as transporter capacity constraints.

In case of practising a kitting strategy in particular the transporter capacity creates a major problem. This constraint may be overcome by running transporter frequently but then the lead time and machine idle time increase [185]. Ideally it is thought that the transporter should transfer all the necessary tools needed by the job and should bring the returned tools back at one visit. However, frequent transporter visit have been accepted and are not counted as a constraint in deciding the batch size.

The hardware considered in FMS is given detail in Chapter 7.

A number of rules that are applied consistently throughout the batching process and the data required as input for the batching as shown in Figure 6.1, is listed as:

- A sequence of job assigned to each machine for every accepted manufacturing period,

- A list of alternative machines which have the capability of processing the jobs,

- The status of all machines (available or idle),

- Processing time,

- Available tool life,

- Number of tool requirement for each batch,

- Magazine capacity, 60 or 120-tools,

- Tool transporter capacity.

The batch size decision is based on a simple if-then rule set which automatically determines the batch size that the machine can afford and still contain all necessary tools.

The decision mechanism is built up by the following rules:

The first rule determines the number of transfer batches or jobs required from each process batch of a particular part type. The process batches are the total manufacturing requirement of each part type for the given manufacturing period. The rule is:

IF
process batch size less than or equal to available pallet capacity
THEN
keep process batch size as it is
ELSE
split the process batch into transfer batches until available
pallets satisfy the condition

The second rule, checks the already automatically calculated tool requirements and the magazine capacity or empty pockets. The rule is:

IF
tool requirement less than or equal to available magazine pocket
THEN
release the job to the available machine
ELSE
reduce the batch size until its tool requirement matches the available magazine pockets
THEN
release the job to the available machine

The routine decided by the above rules does not seek to optimize instead it tries to seek the batch size which satisfies the necessary constraints. This does not necessarily mean that the required tools are the optimum tool quantity but rather that the magazine capacity is large enough to hold all the necessary tools.

6.4 Part Scheduling

6.4.1 Part Release and Manufacturing Environment

Only static part launching is considered where all the parts to be processed must be available when they are required. Pallets are assumed to be ready and loaded with components before transportation to the machine. No parts are permitted to leave and re-enter during manufacture. The detail of the operational rules is presented in Chapter 7.

This type of part release mechanism is most evident in highly automated unmanned systems for short term production and it is intended to meet this type of system's requirements [139]

Since the scheduling mechanism is a separate module which feeds to tool requirements planning, any external part release mechanism may be accepted to generate the machining lists. [175][158]

6.4.2. Part Scheduling Algorithm

The part scheduling algorithm is presented to show the background of the rule-based scheduling module built. The production scheduler first sequences the jobs according to the preferred scheduling rule. Then there is search for the first available machine from all machines capable of doing all the necessary processing. Then the first available job is released to the machine. This procedure is repeated until all the jobs have been scheduled. The logic of the algorithm is depicted in Figure 6.2 and described below.

Step 0 : Initialise all the variables, i.e.

- Set current time t = 0

- Set $J_i = 0$

- If operation belongs to first job the job's predecessor job is job none

Step 1 : Priority Sequencing

1.1. When Earliest Due Date (EDD) is selected, sequence the jobs according to their due date, i.e:

if $d_i \leq d_i$' then pallets of job i come earlier than pallets of job *i*'

1.2. When Shortest Processing Time (SPT) is selected, sequence pallets according to operation time i.e:

if $P_i \leq P_i$' pallet p of job i which operation time less than job i', comes earlier than pallet p' of job i'

1.3 When Longest Processing Time (LPT) is selected, sequence pallets according to operation time which is reverse of SPT, i.e:

if $P_i \leq P_i$' pallet p of job i which processing time longer than job i', comes earlier than pallet p' of job i'

1.4 When Grouped parts in terms of tools used (GRP) is selected, sequence pallets according to the tool list content, i.e:

if $P_{it} \equiv P_i{'}t$

Pallet p of job i's tool content is identical to pallet p of job i's tool content. Then the pallet which requires less tools goes first, if all tools types are exactly the same, jobs are selected randomly amongst the identical tools used. This rule has been created by using the principles of internal scheduling which is in section 6.3.4.

Step 2 : Find the first available machine m which satisfies the following conditions:

$T_m = \min\{T_m\}$

$$T_m = \sum_{i \in N} \sum_{j \in V} \sum_{m \in U} P_{ijm}$$

Step 3 : Locate pallet

Try pallets from the list formed in Step 1. Send the first pallet to the first available machine which must satisfy the following conditions:

$$T_m > e_i$$

$$X_{ijpm} = 1$$

$$Z_{ijp} = 1$$

If Step 3 is successful Goto Step 5, else Goto Step 4

Step 4 : If no more operations require machine m, then remove machine m from M, Goto Step 2 until M is empty (all pallets have been assigned) else
delete machine m temporarily until next sequence has been made, Goto Step 2

Step 5 :

Update job priority

Update pallet processing time

Update machine available time

Update process factor

Delete operations of the pallet from the waiting list Goto Step 6

Step 6 :

If all pallets finish operations then stop else

Goto Step 2

6.4.3. Rule-based Scheduling System

In the algorithm presented above once the sequencing rule is selected, all the jobs are scheduled to the available machines according to the machines' technological capability. The manufacturing conditions considered in the rule-based scheduling system are listed below :

1 - A job is a visit to a machine (an operation)

2 - A job has suboperations which require a toolset

3 - A job returns to the job list on completion of an operation

4 - Operation precedence must be preserved

5 - A job is a transfer batch quantity

6 - A number of jobs of the same type may exist in the list due to the process batch quantity

7 - The job is picked in relation to sequencing rule adapted

8 - The number of times a job is released depends on 7, required quantity and pallet quantity

9 - Jobs are specified in pallet quantities

10 - A job priority of 0 is greater than job priority of 1

The job release mechanism is depicted in a schematic form in Figure 6.3a and 3b. Since expert system logic may process backward as well as forward, the figure depicts the backward chaining logic to release a job.

First, a job is found which has the preferred entering conditions, i.e hardware conditions, the job is then given an operation consideration factor (O.C.F) of 1. Since each batch is considered as a job, then the pallets are checked. If pallet capacity is enough to allow the transfer of the job to the system, then job is transferred. If the pallet capacity is not enough, then the second highest priority job is assigned and a new O.C.F of 1 is given.

After that, the earliest start time of the first available pallet is checked and is assigned as a job start time. At the same time, the machine available time is checked and compared with the pallet start time. If the machine available time is not matched with job start time, another job is released. Job and pallet available times are modified and should be less then machine available time, If not, another job is selected.

The new pallet's earliest start time is checked and the clock is updated until the pallets have returned one assignment. If the first pallet available time is much longer then the clock start time, then a delay time is calculated. If the delay time is too long, this job is abandoned and another job is sought which has an O.C.F. of 0. This situation is repeated until there are no jobs which have an O.C.F. equal to 0.

The related rules in the knowledge base are given below:

```
\*** determine which jobs are feasible ***

forall J:jobs do
    if
      (inclass(J>job_op predecessor, jobs)=true and
   J>job_op predecessor>process_factor = 1 and
      J>job_op predecessor # "none" and
      J>op_number gt 1 and
      J>op_number = 1 and
      J>process_factor = 0)
    then
      reassert J>feasible = true.
      message
      combine("job:",J,"is feasible").
      else
      reassert J>feasible = false.
      message
```

```
combine("job:",J,"is not feasible").
endif.
endforall.
```

and the job selection is decided by the following rules:

*** *jobrule1 selecting a feasible highest priority job rule:*

```
J:jobs

if
 J>lowest priority number = true and
 J>feasible = true
then
 reassert chosen job = J.
endif.
```

*** *jobrule2 finding the lowest priority job rule:*

```
JX:jobs, JY:jobs

if
 JX#JY and
 JX>job priority le JY>job priority
then
 reassert JY>lowest priority number = false.
endif.
```

*** *erase the 'lowest priority number' attribute value of each job to force their determination each time*

determined(chosen stn>current stn release_value) = false
then
chosen stn>current stn release_value = 0.
endif.

The above rules search for jobs which have the " lowest priority number " expert system attribute set to " true " and the " feasible " attribute set to " true ". The "feasible " attribute is determined considering job's predecessor and process factor. The " lowest priority number " is always initialised by being erased. This enables the " lowest priority number " to be determined each time.

The decision for the station chosen is determined by the rule:

S:stations

if
S>lowest candidate mc priority_est = true
then
reassert chosen stn = S.
endif.

The rule which decides which job or station starts first is as follows:

if
chosen job>job start time ge chosen stn>stn available time
then
reassert chosen job>job start time = chosen stn>stn available time.
else
reassert chosen job>job start time = chosen job>job start time.
endif.

The rule based system developed in this thesis is based on user preferred sequencing rules. Before jobs are released, the expert system asks the user which one of the four sequencing rules is preferred. Then jobs are released to the machines or machine groups which form the manufacturing cell following the logic described in the previous paragraph.

The rule base outlined above plays a critical role in the expert scheduling system. It is implemented using the KES (Knowledge Engineering System) production system (PS) shell. The detail of the prototype software is given in Appendix II; The detail of output of scheduling model is given in Appendix III, and the detail of the knowledge-based modelling approach is given in Appendix V.

6.5. Internal Production Scheduling

When tooling cost is considerably high and the meeting of jobs due dates is not necessary during manufacturing period, the internal production scheduling model can be implemented. It was initially built as part of the Tool Flow model developed by De Souza [66] based on clustering algorithm and is run to sequence parts and tools. This scheduling approach aims to minimize the tool requirements and sent parts which use identical tools to the same machine so that tool life sharing is maximized.

The input to the internal scheduler is from Dynamic Cluster Analysis which determines the preferred tool clusters and associated part families. Each tool cluster set may be treated as a tool kit dedicated to a part family. (Reference to Chapter 15).

The technique is based on tool similarity which is defined as :

Similarity = Common tools that are present in the machine tool magazine / Total number of tools required by the batch

The batch which has the highest similarity will be selected first and the rest are sequenced using the same logic.

This scheduling rule has been used for both the tool oriented tool issue strategy and workpiece-oriented tool issue strategies.

If the grouped jobs and the associated tool kit are sent to the same machine, the maximum benefit can be obtained. Otherwise, if it becomes necessary to split the batches to several machines, then tool sharing among several batches is put in jeopardy. Hence it becomes very difficult to achieve the intended benefit.

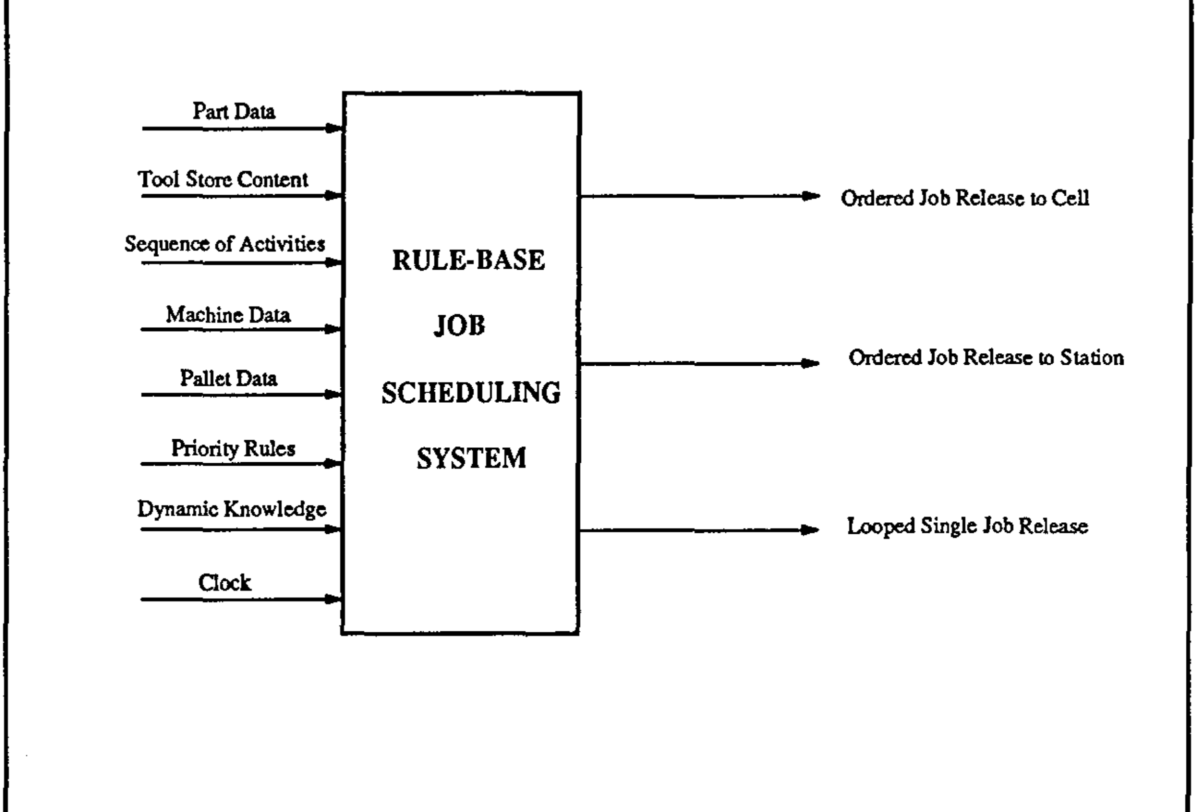


Figure 6.1	Inputs and Outpus of Knowledge-Base Scheduling System	LUT-FMS Research Group

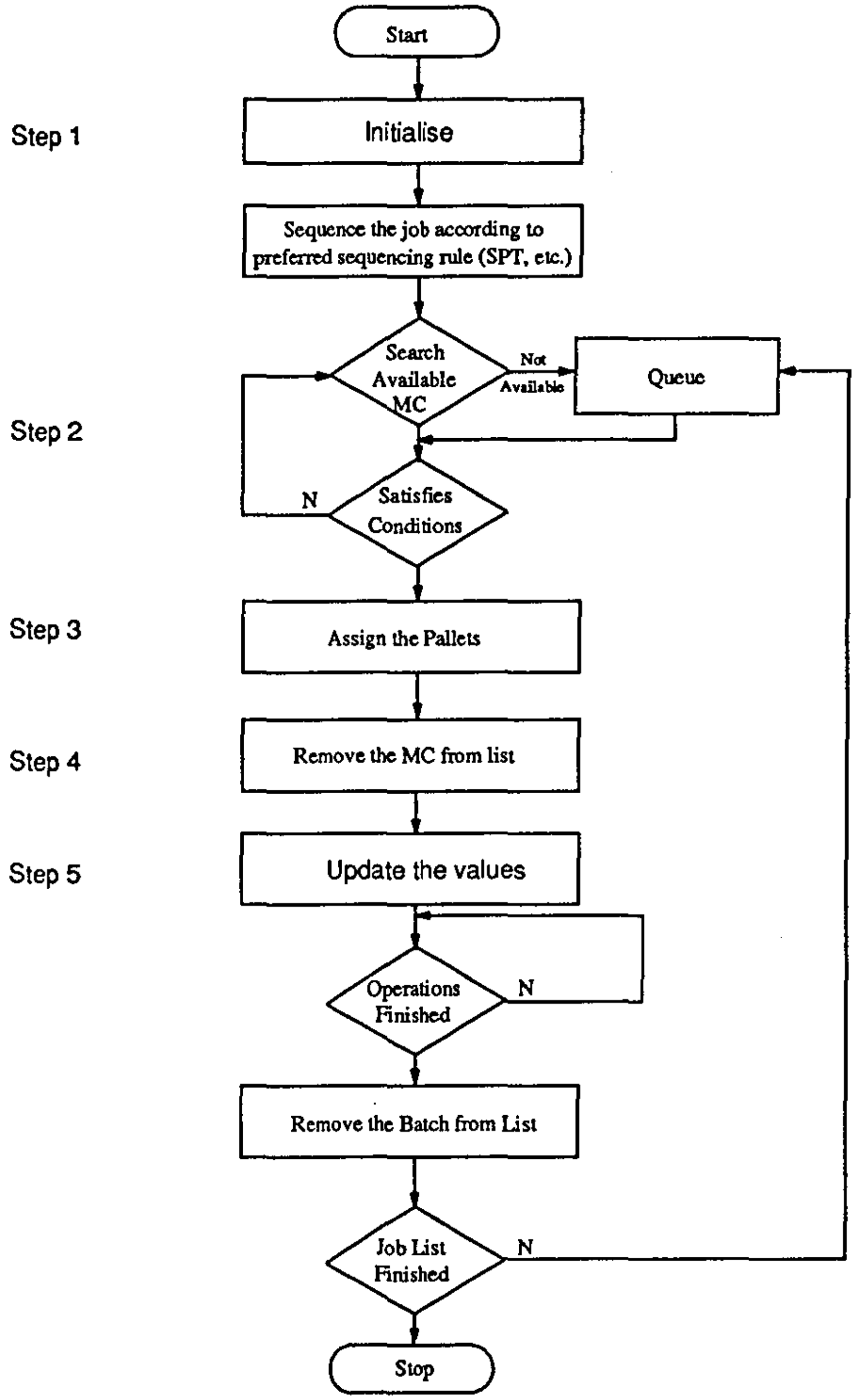


Figure 6.2	Scheduling Logic	LUT-FMS Research Group

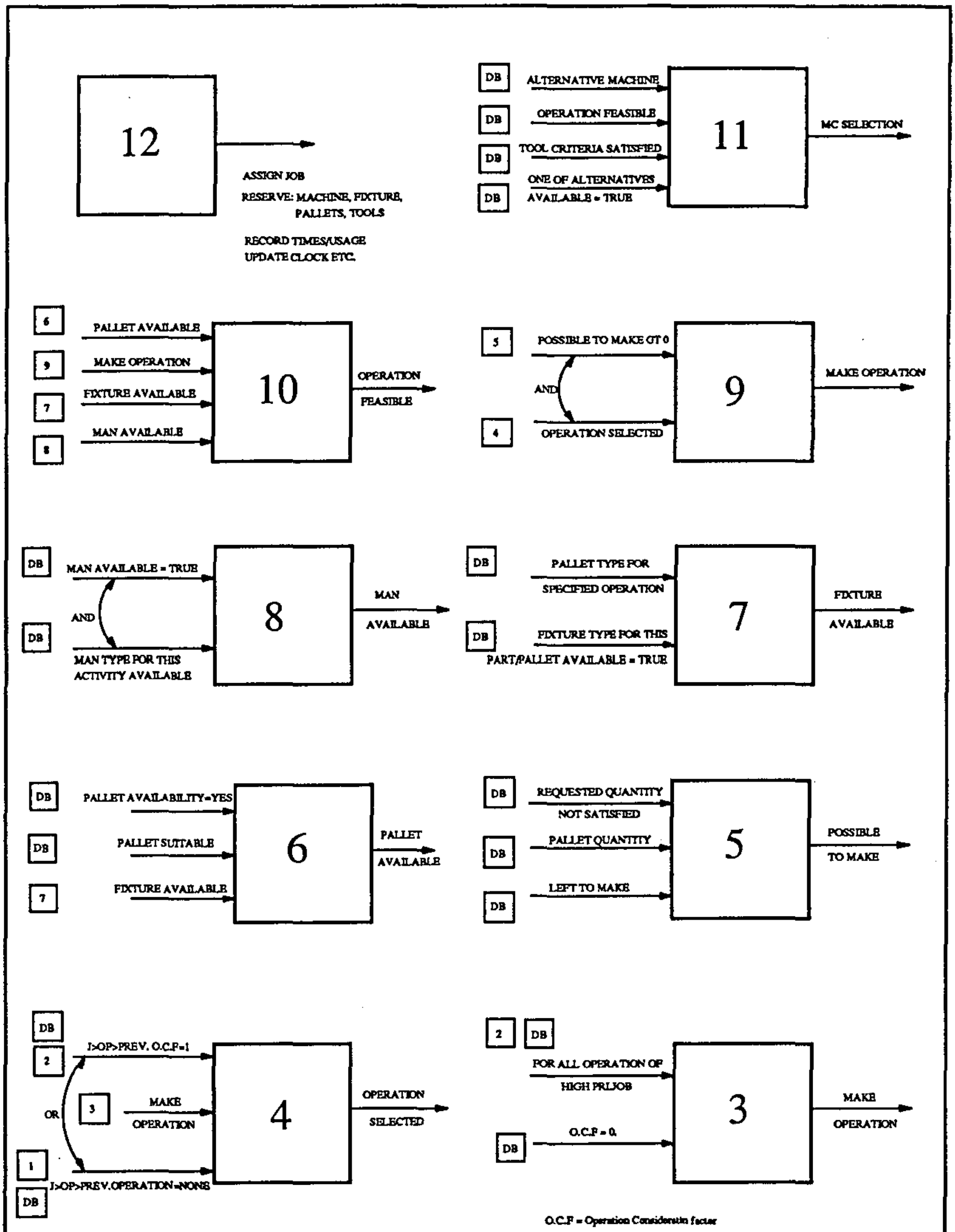


Figure 6.3a	Rule Base Job Release Mechanism -1	LUT-FMS Research Group

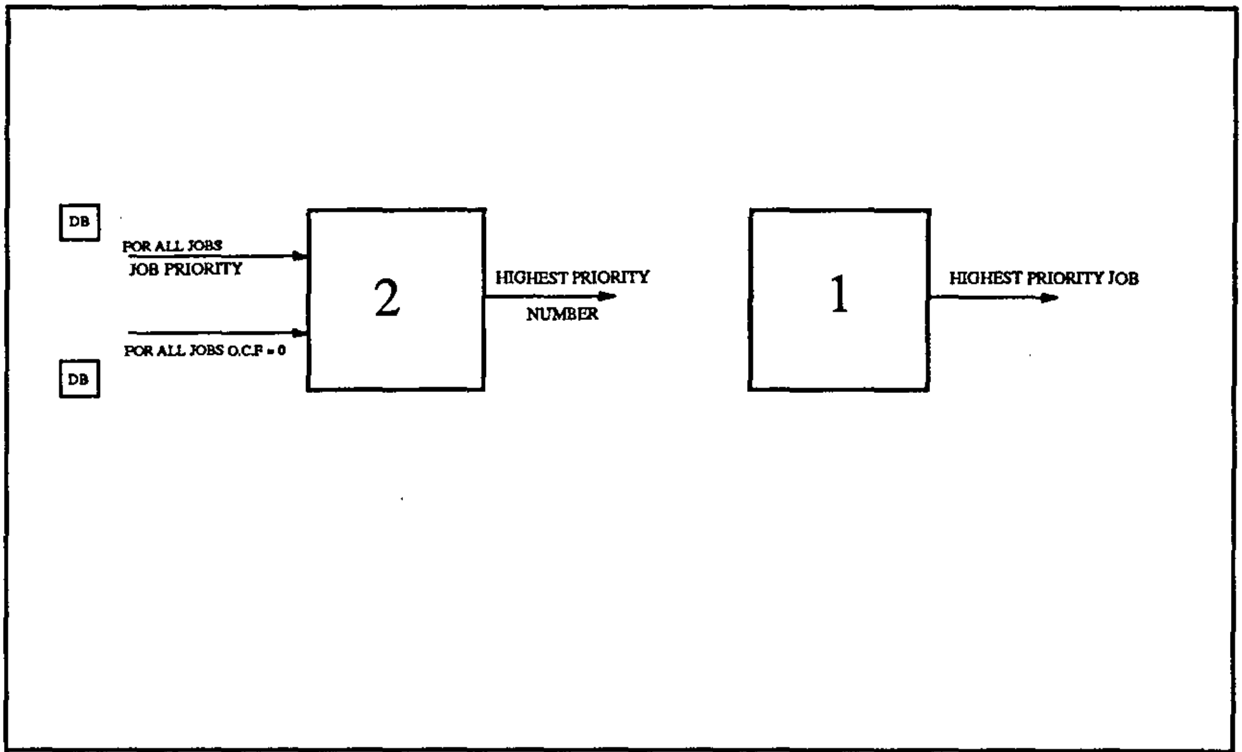


Figure 6.3b	Rule Base Job Release Mechanism -2	LUT-FMS Research Group

Chapter 7
Tool Requirements Planning

7.1. Introduction

This chapter presents tool requirements planning (TRP) in a multi-machine environment. The purpose of the work is to illustrate the implementation of the tool management system design facility with the aid of an algorithmic approach. The TRP module is one of the four integrated design modules and produces the major part of the design facility output by applying tool issue strategies as well as operating rules and the combined design parameters.(Ref. to Chapter 13)

7.2 Role of TRP

This is the one of the four modules designed for the TMS design facility. Figure 7.1 indicates the output provided by the model and also the data set required to initiate the module. The following discussion will pick up the issues on the appropriate arguments which the module has the ability to address. The rules and strategies as well as the constraints are also discussed.

7.3 Background

The TRP module is based on previous algorithmic work done in the laboratory which specifically studied tool flow for prismatic part machining [66] and cylindrical part machining [272]. Both used an algorithmic modelling approach which was implemented in the Pascal programming language.

The model developed by De Souza [66] Figure 7.2, has the ability to record large amounts of user specific data on the operation of tool flow systems. The model basically offers solutions to support how to store, handle, transport and load tools. The model can also predict the influence of tool life. Therefore, it can forecast tool inventory level and tool changes. The model can be used in a number of ways, ranging from as a standalone forecasting tool to part of the integrated design facility to provide output. The modelling of over 2000 activities [66] imposes a severe restraint on the system and the computing run time may extend over a couple of days. The model also includes the tool-oriented approach, which was cluster analysis to rapidly configure tool cluster sets without going through the rigours of full scale modelling. The module permits tool cluster sets to be configured for changing batch sizes and different tool life specifications. The model determines the fixed or resident the tools to be held in tool magazine.

Zhang [272], built another algorithmic model to evaluate the merits of different system design, operation and tooling strategies for cylindrical part machining. The model has the ability to record considerable amounts of user specific data on the operation of turning systems, tool flow systems and tool specifications. Once subjected to a comprehensive analysis, these outputs can be applied to improve the overall tool flow system performance. The model can be subjected to multi-run experiments. Thus, a particular tool flow can be modelled for several periods, and a comprehensive tool inventory and requirement can be determined. The model essentially tests out the acceptability of lathe solutions and offers a facility for assessing turning system performance. The results obtained from the model typically include tool transfer schedules, throughput times, tooling requirement, tool life analysis, transient capacities, tool exchanges forecasts, manning patterns and utilization.

For this research, a new reduced generic model has been built using the same algorithmic approach. Figure 7.3. indicates the algorithmic approach followed to build the new reduced model. Recording necessary data through the operation of the model severely limited the speed of model response. Therefore, a built-in data has been separated from the main design facility and put in a separate supporting manufacturing database. (See Appendix II for the detail of the database)

Since this model is not focussed on a specific machining technology, the detail of a specific machining technology as well as tool store and tool exchange activities have been omitted. Thus, the large amount of activity calculations which severely limited modelling speed previously, have not been included. Instead, a compact generic tool requirement planning model has been built which has the ability to model TMS in sufficient detail, (See section 7.3), to act as a design aid. Figure 7.4 depicts the new reduced model's major input and output blocks, generic working environment, and the strategies and rules stage. Despite the fact that many modelling details have been left out, the output produced has substantially the same detail as previously (See Supplementary Output Book and Appendix IV. Also, the computer run time is enormously reduced from over two days to a maximum of eight hours. The TRP module can work with the built-in database which it gives the capability to work in a standalone mode for quick modelling. (See Appendix II for the prototype TRP modelling detail).

The second major part of TRP modelling which again uses an algorithmic approach, focuses on tool-oriented tool requirement planning and is based on the previous static model built by De Souza and Bell [67]. Computer Assisted Dynamic Cluster Analysis (CADCA) offers a dynamic approach and considers the multi-cell multi-machine environment through repeated clustering and re-organization of the initial part-tool matrix. This gives the opportunity to find better cluster sets which further improves the quality of modelling. The extensive rule set applied as well as the structure of the model has been given a separate chapter, (See chapter 15). The detail of dynamic clustering software use is given in Appendix II. The modelling experiments and outputs are given in Appendix IV.

A new software environment, Lotus 123, has been chosen to implement the TRP model. It is easy to use allowing easy implementation ideas with a reasonable speed. Also, it allows the whole output to be seen on one screen which is very helpful to trace back to the beginning of the modelling as well as to see the modelling stages [113].

7.4. Structure of TRP

Tool requirements planning (TRP) is the core of the integrated TMS design facility applying three main approaches for provision of cutting tools namely, the workpiece-oriented; tool-oriented and the hybrid approach.

The module has four main inputs through a relational database, ORACLE. These are part data, tool data, machining lists and rules and strategies. The jobs have been sequenced and scheduled according to one of four scheduling rules and each machine has its own list produced by the rule-base scheduling system, (See Chapter 6).

The job, batch size, suboperation times, tool type used, available tool life and the machine used are known from the database. The data structure used in the TRP module and the hypothetical flexible manufacturing cell layout is depicted in Figure 7.5. The module calculates the kit size for each job released according to the strategy applied, the tool requirement for each type of tool; gross, minimum and maximum tool requirements; tool inventory, tool life usage;

throughput time; machine and transporter utilization. The extensive number of TRP experiments with different parameter combinations and modelling outputs are given in a supplementary output book and the parameter set is explained in Chapter 4.

Although TRP is a static planner, it is possible to trace tool life during the operations. For this purpose, a separate tool tracing file is allocated to each machine which is updated during operations throughout the manufacturing period. Therefore it is possible to trace the history of each individual tool type. It is also possible to trace how long each tool is kept on which machine, when it is changed, after which job it is changed, if is worn, and if sister tools are required.

TRP makes it also possible to trace the history of each machine, how many tools visited the machine. How long each operation time or idle time takes, and when jobs start and finish, are the main factors calculated for machining time by TRP.

Derailed tool requirements, tool inventory, sister and spent tools are determined by the adopted tool issue strategy. However there are some fundamental tool requirement calculations in TRP which are common to all strategies and are given below:

$$ToolRequirements = \sum_{i=1}^{m} \sum_{j=1}^{n} (operationtime \times batchsize)/AvailableToolLife$$

$i = 1,2,..,m$ *numberofsuboperations*

$j = 1,2,..,n$ *numberoftooltypes*

$m = n$

The issue of tools and the time to change tools are manipulated by the adopted strategy. Therefore, the strategy may create many half used tools which considerably affects the tool requirement and tool inventory. The role of the tool issue strategies in determining tool requirement and tool inventory is explained in the next section.

7.5. Strategies and Rules in TRP

Since cutting tools are strategically important, the issue of tools is the vital factor to the timely supply of the required tools in the right quantity. Tools are issued to the shop floor using rules and strategies with consideration of the constraints imposed by the available technology.

Although the philosophy behind each strategy is important, it is the associated technologies such as magazine capacity, transporter capacity and the tool exchange mechanism which make the strategies applicable or severely limited.

In this research tool issue strategies are classified into three categories. These are:

1. Workpiece-oriented strategies,
2. Tool-oriented strategies, and
3. Hybrid strategy.

The experiments conducted are based on these three approaches. Each of these approaches has its own advantages and disadvantages and guarantees the right-tool at the right-time. However, the quantity of tools issued entirely depends on the unique characteristic of the tool issue strategy adopted.

The workpiece-oriented approach comprises three strategies. These are full kitting strategy, differential kitting strategy and single tools kitting strategy. The detail of the each strategy has been given in Chapter 4.

The full kitting strategy, Figure 7.6, is the most flexible strategy and is easy to control and practice. It assigns a tool kit simultaneously with each part assignment, removes all the tools when the job is finished and then assigns a new tool kit for the new job. Since it does not permit tool life sharing between jobs it works with an excessive quantity of tool inventory.

The differential kitting strategy, Figure 7.7 is more elegant and permits tool life sharing between successive jobs. Therefore it needs a sophisticated control mechanism to keep track of the assigned tool life. The strategy seeks two important conditions. These are commonality between tools and sufficient tool life on the previously assigned common tool. When these two conditions are satisfied, the strategy saves the tool. The rule formulated in TRP is:

if
tool is common with next required tool
and
tool has enough life to operate next process
then

keep tool on machine
else
remove tool from machine magazine.

Since the strategy permits tool life sharing, it significantly affects the tool requirement and tool inventory. When this strategy is coupled with an elegant part scheduling rule, it works very efficiently. (See Chapter 14)

The single tools kitting strategy, Figure 7.8 is the last workpiece-oriented strategy applied in TRP and a more powerful strategy in terms of tool life sharing and efficient working. It shares tool life across the manufacturing period and keeps all the tools in magazine and only changes tools when they become worn and the magazine has reached its capacity. The rules formulated in TRP are:

if
tool is common with next required tool
and
tool life is enough to operate next process
then
keep tool on machine.

if
tool is common with next required tool
and
tool is worn
then
exchange the tool with sister tool.

if
a new tool is needed
and
magazine capacity is full
then
exchange the tool only with tool not needed.

This strategy requires a sophisticated and fast transporter mechanism, a relatively large magazine capacity and a sophisticated control mechanism. The strategy significantly reduces tool requirement and tool inventory because it allows tool life sharing across the manufacturing period. (See Chapter 14)

The tool-oriented approach comprises two tool issue strategies, which are the dynamic full kitting strategy and the dynamic differential kitting strategy. Detail of these strategies is explained in Chapter 4. The dynamic clustering full kitting strategy is based on the previous static clustering approach [67] which uses the same clustering algorithm [129]. Dynamic clustering differential kitting has been invented through experimental work as is explained Chapter 15. The dynamic full kitting approach which is depicted in Figure 7.9 has the advantages of both clustering and repeating the clustering to get more cluster sets and saves the tool requirement and tool inventory considerably. A list of the experiments conducted using the dynamic clustering differential kitting approach and the outputs of the strategies are given in Appendix IV.

The hybrid approach which is a composite of the workpiece-oriented and tool-oriented approaches, is also applied in TRP. It too has been, invented through experimental work and is explained in detail in the devoted Chapter 17 The list of experiments as well as the outputs are given in Appendix VIII.

7.6 Modelling Assumptions

Since the research presented in this thesis has been initiated by a project work, the lists of the assumptions and the conditions attached to the building of the models are based on the tool management research project and are subdivided into four groups. [157]

7.6.1 Workpieces

a) All workpieces to be processed must be available at the start of the modelling (scheduling) period

b) No other workpieces shall arrive during the modelling period

c) Pre-emption is not permitted. Once started, an operation must be completed.

d) The processing times of successive operations of a particular job are not allowed to overlap. A job can be in process, at most, one operation at a time.

e) The processing times for each operation and the technological order of the operations for each job are known at the start and are fixed. This strictly-ordered sequence considers that for each operation there is at most one operation which directly precedes it and one operation that directly succeeds it.

f) No jobs included in the modelling period are allowed to be cancelled.

g) Each operation may consist of a number of sub-operations.

h) Each sub-operation is considered as a tool activity

i) Workpieces are transferred from one machining stage to the next machining stage for this workpiece immediately after completion of the activity.

j) Workpieces may be assigned to machine groups or to specified machines.

k) The process batch is the manufacturing order for specific manufacturing period for each part type.

l) Process batch splitting is permitted, providing that each sub group is separately identifiable as a transfer batch.

m) A transfer batch (job) is considered as the number of workpieces that can be accommodated on a pallet(s).

n) Each transfer batch (job) has to be completed on the machine to which it is assigned.

7.6.2 Tools

a) Each operation of each job is made up of a specific list of tooling operations called a tool list. A collection of these tool lists assigned to a particular machine constitutes a machining list.

b) The machining list once started must be carried out to completion.

c) A tool list may be in process, at most one operation at a time.

d) The processing time for each activity on the tool list is known and fixed.

e) The technological order for each tool activity on the tool list is known and fixed.

f) For a given tooling activity there is at most one tooling activity which directly follows it and one tooling activity which directly precedes it.

g) Consecutive tooling activities, tooling activities on the same tool list or on the same machining list or even on another machining list, may be performed by the same tool providing there is sufficient tool life and depends on the tooling strategy selected.

h) Oversize tools are allowed, and automatically require one free tool pocket on either side of its position in the tool storage facility.

i) The number of tools present in the system is dependent on the schedule and the hardware constraints.

j) Tool life must always exceed or equal each sub-operation time except in the case when conventional machines are included and no means of monitoring tool life is available.

k) Tool breakage is not considered statistically, but a tool life limit or confidence limit is set, at or above which the tool is considered unsuitable for use.

7.6.3 Machines

a) The flexible manufacturing facility is considered to be idle at the commencement of the modelling period and machines are completely available for work, although the tool store contents from the previous modelling may be in existence at each major store, if a continuous run is desired.

b) Each machine is continuously available for assignment during the modelling period, and breakdown and maintenance time are not allowed.

c) No machine may process more than one operation at any time; conversely no operation may be worked on at more than one machine at any one time.

d) There are no restrictions on the number of primary tool stores available on a machine.

e) Multi-spindle machines may be modelled providing all spindles use the same tool type simultaneously

f) There is no restriction on the type of primary tool storage facility present, providing that an upper limit on tool capacity can be specified.

7.6.4 Manufacturing System

a) In-process inventory is not allowed.

b) Pallets and fixtures are always available.

c) Pallets and fixtures are never separate.

d) It is possible to mount more than one component on a pallet, providing they are of the same type and can be considered as a batch.

e) Pallets may be indexed through 360° on the workstation.

f) Transportation time must be fixed regardless of the travelling distances.

g) One or more transporters may be employed in the system.

h) Several transporter types can be modelled.

i) The transporter may carry up to a predetermined number of tools.

j) Either a tool kit or single tools may be carried.

k) No blockage or breakdowns are allowed.

l) The transporter operates at a predetermined speed.

m) Transporter route is unidirectional.

n) The transporters are accessible by all the machines in the system (cell).

7.7 TRP Specifications and Performance

TRP generates two major outputs, tooling and performance of hardware. Tooling outputs consist of tool requirement, tool inventory, sister tool requirement, spent tools, maximum tool requirement, minimum tool requirement, STS, and PTS contents. The performance outputs consist of machine utilizations, transport utilizations and tool life utilizations.

The module employs six tool issue strategies and all outputs listed above are available for each one of the strategies. This establishes the input data for the strategy selection module which compares the strategies with each other. (Ref. to Chapter 8). The module could be used as standalone software to forecast tool requirement and tool inventory with the supporting performance indicators for medium to long term manufacturing periods with the great degree of accuracy. Alternatively the module may be a part of the integrated design facility which altogether offers a complete solution to TMS design problems.

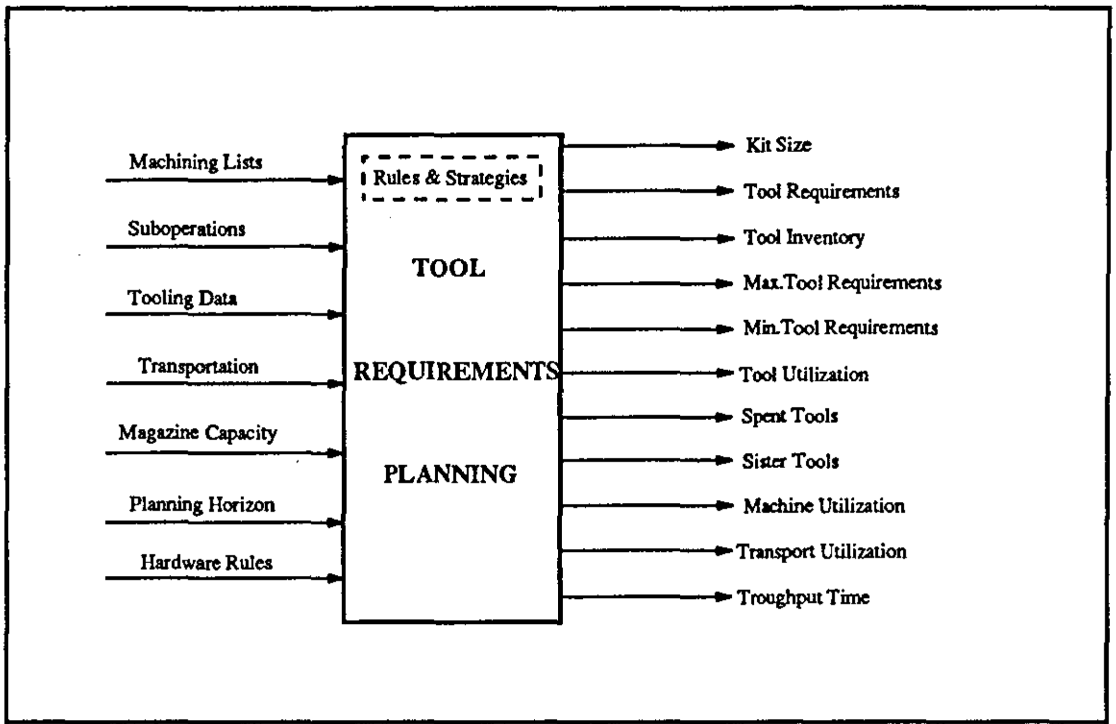


Figure 7.1	Inputs & Outputs of Tool Requirements Planning	LUT-FMS Research Group

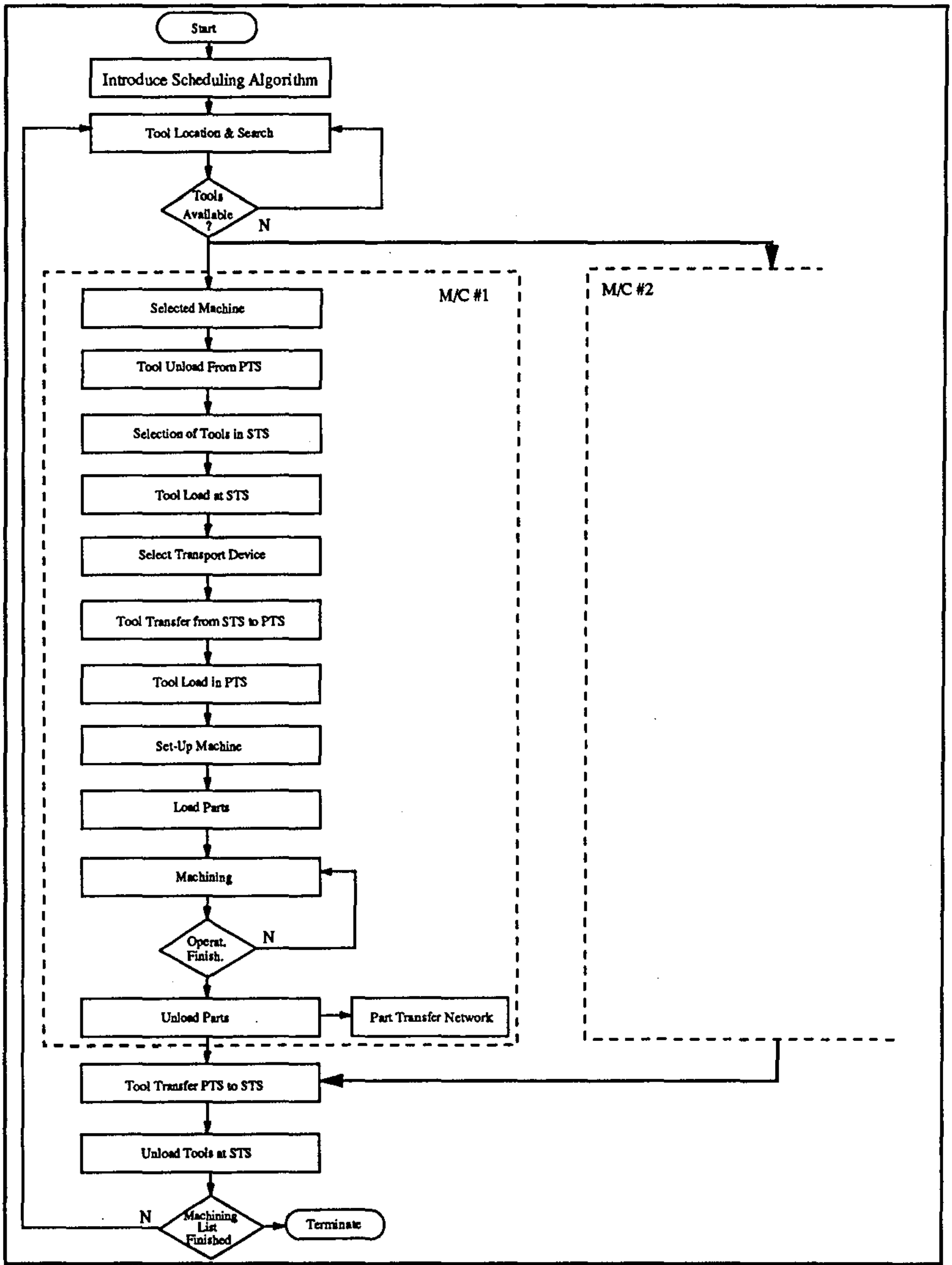


Figure 7.2	Prismatic Part Machining Cell Algorithmic Approach	LUT-FMS Reserach Group

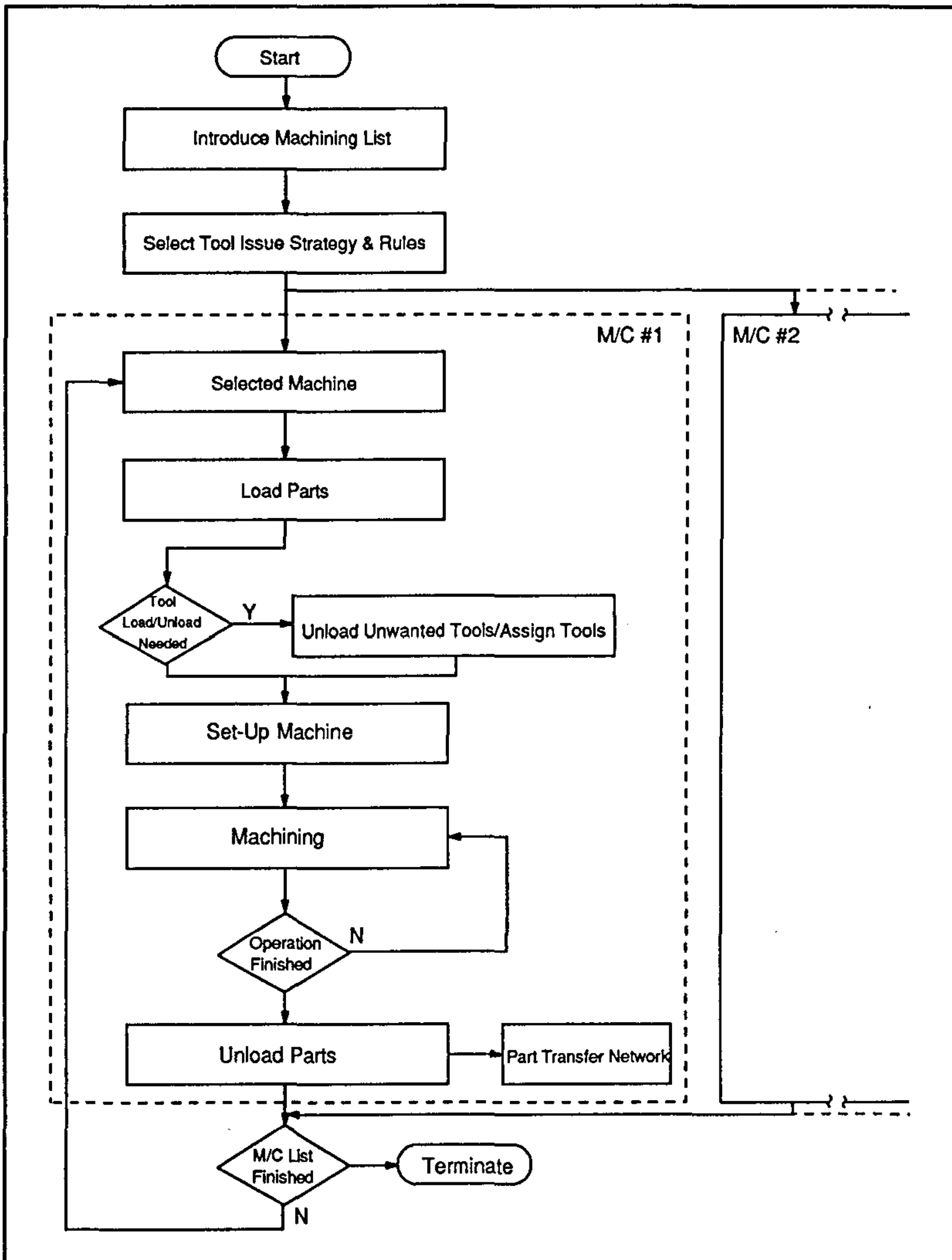


Figure 7.3	TRP Multi Machine Algorithmic Approach	LUT-FMS Research Group

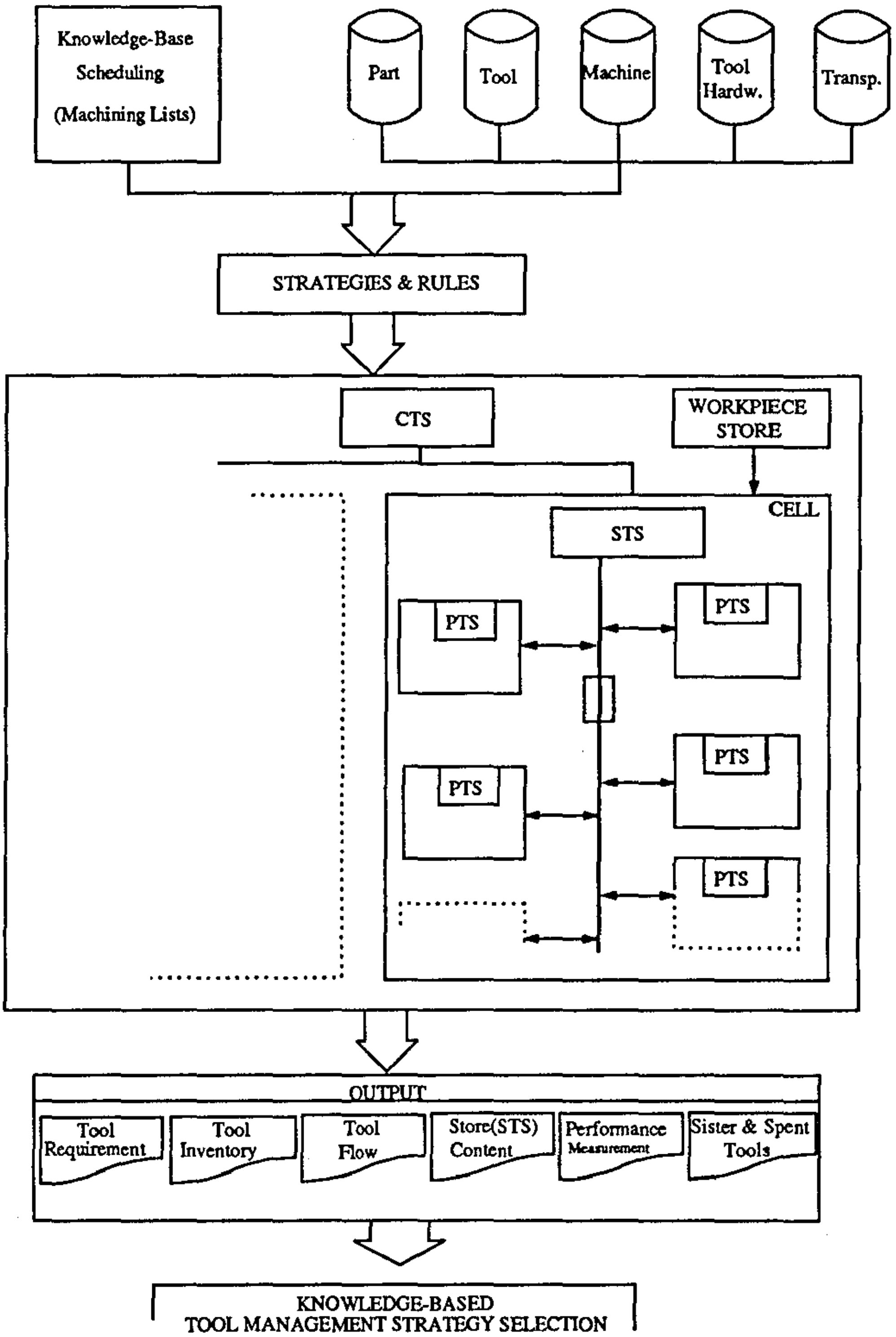
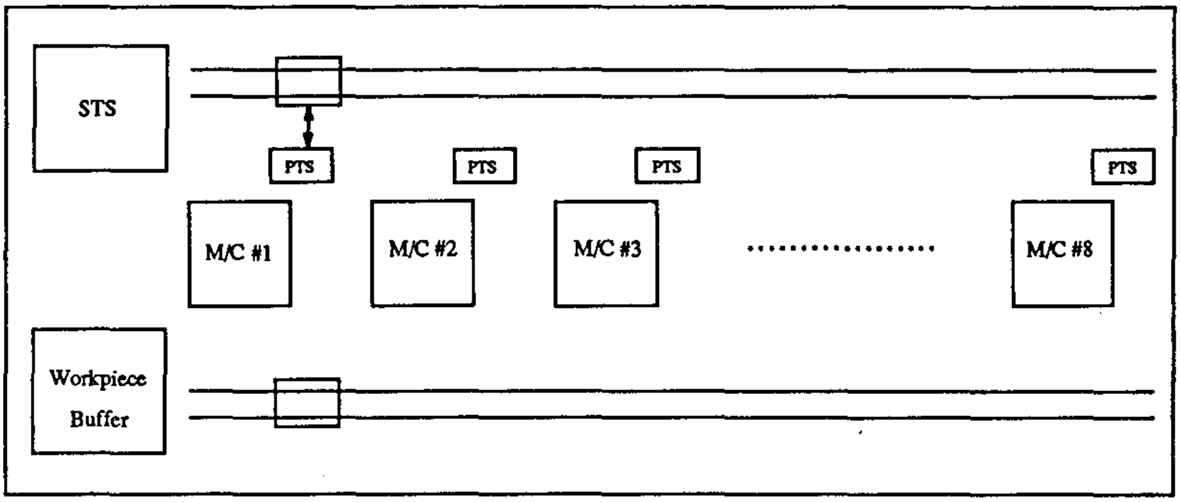


Figure 7.4	Tool Requirement Planning Inputs-Outputs & Modelling Environment	LUT-FMS Research Group



Operational Data

Job No.	Part No.	Proc.Batch Size	# Pallet	Pallet cap.	Transf.Batch Size	Part Setup Time	Tool Setup Time
1	39962421	9	3	3	9	7.5	5.5
2	6231504	16	4	4	16	13	5.5
3	6406623	8	2	4	8	6	5.5
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Suboperation Time Data

Part Type -->	39962421	6231504	6406623	....
Tool Type				
T1001	0	0	0	
T1025	0	0	0	
T1033	0	0	0	
T1042	0	0	0	
T1050	0	0	0	
:				

Tool Data

Tool Type	Tool Life	Permiss.Tool Life	In Store	....
T1001	360	90%	20	
T1025	60	90%	20	
T1033	60	90%	20	
T1042	120	90%	20	
T1050	90	90%	20	

Figure 7.5	The Layout of Cell and the Data Set Used	LUT-FMS Reserach Group

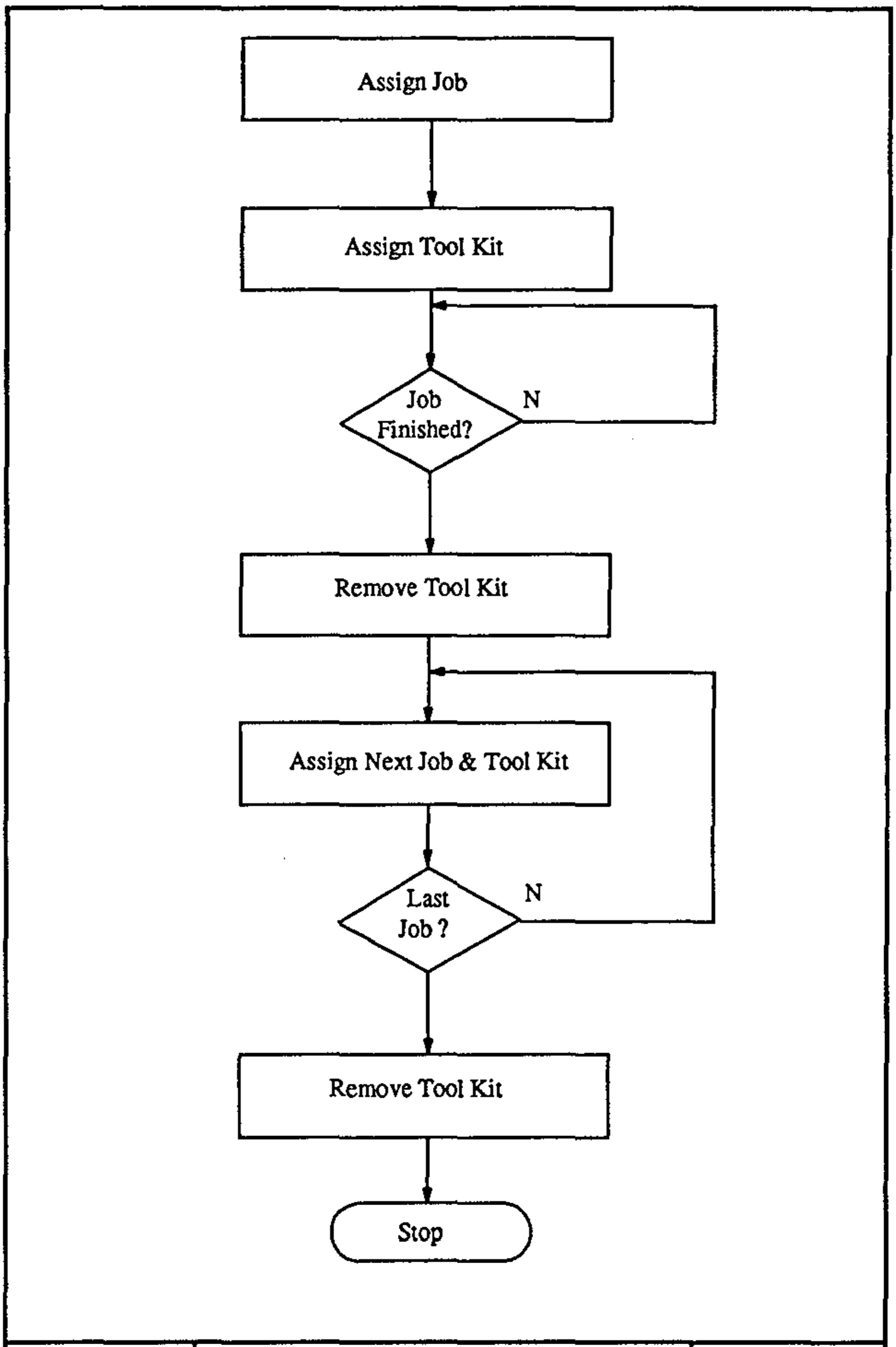


Figure 7.6	Full Kitting Strategy	LUT-FMS Research Group

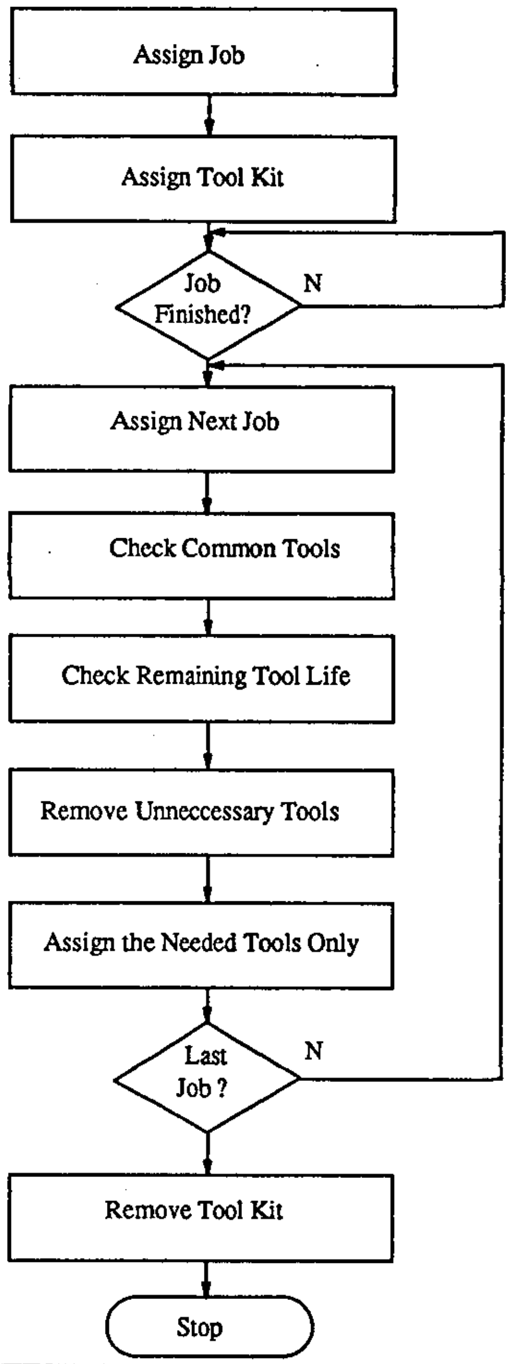


Figure 7.7	Differential Kitting Strategy	LUT-FMS Research Group

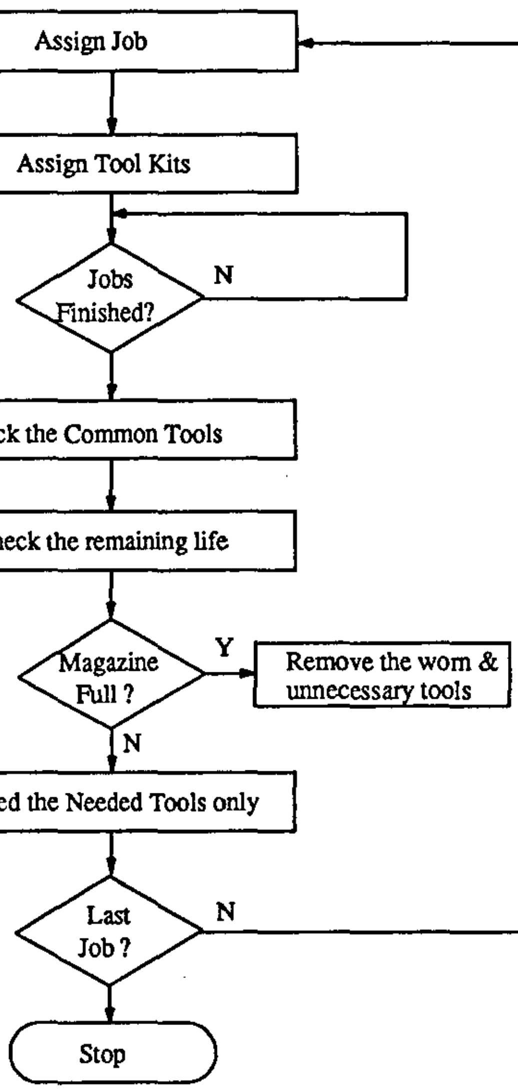


Figure 7.8	Single Tools Kitting Strategy	LUT-FMS Research Group

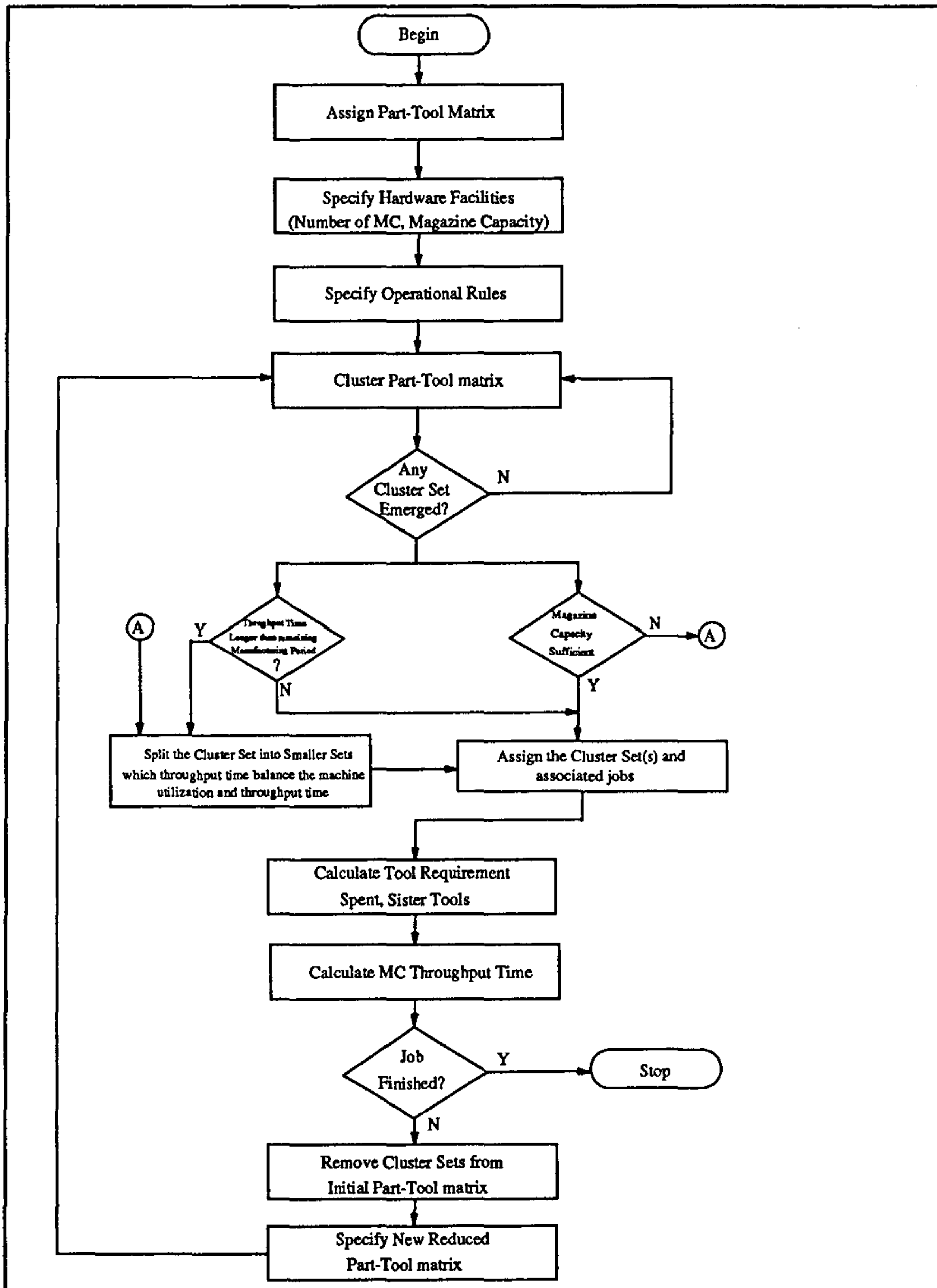


Figure 7.9	Dynamic Cluster Analysis (Full Kitting)	LUT-FMS Research Group

Chapter 8
Tool Management Strategy Selection

8.1 Introduction

Recent developments in both manufacturing and computer technologies and increasing competitiveness have led manufacturing organizations to seek more intelligent and specialised solutions for complex manufacturing problems. Artificial Intelligence (AI) techniques, in particular, knowledge based systems, are widely used to solve these problems and have the ability to play a crucial role in automated manufacturing systems [176] [189] [218] [130]. (See Appendix V for the theoretical background of Knowledge-base modelling)

This chapter describes the structure and function of the knowledge based tool management strategy selection module. The module is fed by the tool requirements planning module and manufacturing database.

8.2 Strategy Selection

Since tool availability at the desired place is vitally important in Tool Management, the issue of tools to the shop floor becomes a crucial point. There are many different strategies applied to the issue of tools (Ref.to Chapter 2) and every one has its own advantages and disadvantages as well as a set of prerequisite conditions to be applied. Therefore, many hardware and planning issues are involved in running a strategy and for a successful application, some conditions must be satisfied. *

Since many different parameters are involved and each strategy offers an advantage, it is a difficult choice to pick one of them, especially in an environment where many uncontrollable parameters influence the design and operation of the system. It is not always possible to find a strategy which perfectly suits the available hardware and operational environment. Therefore, it is important that find a strategy which makes it easier to solve the problem as well as satisfy the manufacturing requirements.

The rule sets presented in Chapter 8 and 9 are ad hoc rules and have been developed during the research. The rules are expressed using KES expert system software syntax.

The strategy selection module has been designed to make easier to select a tool issue strategy which satisfies the conditions required by the manufacturing task as well as suits the operational environment. This is achieved with the help of a rule based system which has great advantages because it has the capability of mimicking the actual system by transformation into simple if-then rule statements.

The following sections explain the structure and working mechanism as well as the basis of the decision criteria.

8.3 Structure of the Tool Management Strategy Selection.

The Knowledge-base tool management strategy selection (KBTMSS) has been basically designed to select the most convenient tool management (TM) as well as tool issue strategies for the related hardware configuration. The module is supported by both the TRP module and the manufacturing database. Figure 8.1 shows the basic input and output of the module.

The expert system is a logic based type which stores the entire knowledge base in the form of a disk file which has no size limitation. The rules in the knowledge base are framed from database clauses, containing the necessary conditional descriptions. The inference engine makes a goal directed search and it has been developed such as to be capable of accepting further inclusion of rules and conditions in the knowledge base.

The strategy selector in the expert system considers the three main tool management approaches and then the six tool issue strategies, each of which is a sub-strategy of one of the three higher level strategies. Figure 8.2. shows the strategy relations. The manufacturing database consists of a number of sub-modules which are job database, station database, pallet database, strategy database and cluster database. The data used in the expert system is based on experimentally determined output which has been produced using the TRP module and transferred to the manufacturing database. The database depending on the TRP module can be updated and modified throughout the manufacturing period.

The expert system is further capable of including the following user selected single or multiple operational goals:

- minimum tool requirement,
- minimum tool flow
- minimum tool inventory,
- minimum production throughput time
- maximum machine utilisation

The module could be updated, modified or replaced as a whole by a more suitable and compatible knowledge base as and when required.

Alternative choices and recommendations are presented to the user during consultation with the system. During consultation, the user is asked for details of the hardware facilities such as magazine capacity, transportation mechanism, scheduling rules applied etc. and the system follows predetermined steps to reach a conclusion for the hardware configuration and the control mechanism applied on the shop floor. The consultation flow indicates that the system assumes that the user has a certain degree of tool management knowledge and experience in order to choose or select a preferred value or answer for the questions asked when prompted with a range of recommended values. If the user wants the expert system to choose a specific TM or tool issue strategy due to his/her own particular reason(s), the expert system can be forced to chose desired strategy by putting the specific default values in the attributes section. This also can prevent the expert system from asking many questions before reaching a conclusion.

8.4 Decision Criteria

Since the expectation from a system is different from organisation to organisation, the criteria for selection vary. KBTMSS can provide decision aid at a number of stage such as determining overall system approach, the best generic or specific tool management strategy, expert advice on specific tool management problems or intelligent assistance during the decision process. The module also gives detail reasoning about the decision. The user is associated to use his/her expertise for KBTMSS during the description of either the TM hardware configuration or the operating of the system. This is needed in order to reduce the unknowns and the complexity of the mechanism, as well as providing a better decision environment.

The decision criteria used are listed as follows:

-minimum tool requirements (captive tools),

-tool inventory,

-maximum machine utilisation,

-minimum throughput time

The criteria have been set according to common sense and the tool management literature survey. (Ref.to Chapter 2)

The user may choose one or more criteria to make the decision. Although most of the criteria are dependent on each other individual criteria may be used.

8.5. Knowledge Base Tool Management Strategy Selection (KBTMSS)

KBTMSS is a menu driven software implementation which could be used either as a free standing set of software tools or a part of the integrated design facility (See Appendix II for the detail of the software). The logic of the strategy selection module is depicted in Figure 8.3.

KBTMSS has been designed to make decisions for users about tool management system design. There are two advantages in the use of KBTMSS. First, an expert system can represent domain specific knowledge related to strategies as well as representing the hardware configuration of the manufacturing system explicitly. Second, expert system can provide a satisfying decision rather than optimal. [2]. This is necessary, since close relationships of the decision criteria mean that in many instances it is too difficult to reach an optimal solution. There are three steps to reach the final decision in the KBTMSS model. First, KBTMSS starts asking a range of questions to require knowledge of the manufacturing environment. Since the hardware configuration is a major constraint to adopting a strategy, it is important to know what kind of environment is going to be worked in. For example, the single tools strategy, by its nature needs a relatively large magazine capacity as well as a specifically designed or dedicated tool transporter system. If these conditions are not satisfied, it is very difficult to apply this strategy. Examples of the rule which describe these conditions are constructed as follows in the attributes section and the rules section:

*** Global Attributes**

hardware_rule10: sgl

{question:"Are the machine magazine capacities large enough to support the single tools strategy application?"}.

{explanation:"Single tools strategy needs normally relatively large magazine capacity"}.

hardware_rule12: sgl

{question:"Does manufacturing system have specifically designed or a dedicated tool transportation system?"}.

{Explanation:"Single tools strategy, by nature, needs a specifically designed or dedicated tool transportation mechanism to accommodate the required tool or to transport back to worn or unnecessary tools"}.

....

*** Rules**

hardware_rule5 selects whether hardware is convenient or not to adopt the single tools strategy:

```
if
  hardware_rule10 = yes and
  hardware_rule11 = yes
then
  reassert issue strategy = single tools strategy.
endif.
```

Once the KBTMSS knows the environment and what kind of strategy is applicable, it is ready to make the second main decision. In the second step, the expert system makes the decision for the tool management strategies, from either the workpiece-oriented, tool-oriented or hybrid strategy. At this stage, KBTMSS again asks a range of questions to know what type of control and planning systems are in use in the manufacturing system. For example, if the manufacturing system uses a scheduling system in which meeting due dates is essential, it is not possible to apply the tool oriented strategies which have their own sequencing and scheduling system. The related rule is:

tool management strategy_3:
if
soft_automation_4 = true and
soft_automation_5 = true
then
reassert system strategy = workpiece oriented strategy.
endif.

The *soft_automation_4* and *soft_automation_5* placed in the rule refer to attributes which the questions or default values attached have triggered when the related rule comes to make the decision in the action section.

At the beginning of the third step, KBTMSS has the idea of what kind of environment is worked in, and what type of control and planning system is practiced. In the third step, KBTMSS is ready to select the most convenient tool issue strategy for the selected manufacturing facility based on (one or more) user selected criteria.

The strategy can be selected for either the overall manufacturing system, or a cell or only for a single specific workstation. These alternatives are needed due to differences between the hardware configuration placed in the manufacturing system. For example, if one of the several machines placed in a cell does not have a large magazine capacity, there is no point to practice the cluster analysis or single tools strategy on that particular machine.

The criteria play a crucial role at this stage. The user is asked to choose the preferred criteria. For example, if there is a pressure to meet the due date, the throughput time may be selected. Or if tool inventory is a major problem then, minimum tool inventory may be selected. Or if tool flow or traffic is a major problem in the system, in this case minimum tool flow may be selected as the criteria.

One of the related rules is presented as follows:

Issue strategy rule_3 selects the best strategy for selected hardware configuration:
SR : strategy, ST : strategy
if
ST # SR and
system strategy = workpiece oriented strategy and
SR> captive tool size lt ST> captive tool size
then
reassert best strategy = SR.
endif.

8.6 Software Capability

The strategy selection software produces two major outputs. Firstly the strategy selection for the desired environment which may be a workstation, a cell or a factory. Secondly a broad strategy report for each one of the strategies applied. It approaches the problem step by step which makes it easier to make decisions or come to a conclusion. These steps are:

1. Recognition of hardware environment,
2. Recognition of operational and planning environment,
3. Recognition of strategies applied,
4. Recognition of user requirements including criteria,
5. Making Decisions.

Since all the decisions made clearly based on data provided as well as the internal rule set which is fed by both database and attributes, strategy selection must be fed by the complete data set required. The contradictions in data set provided or contradictions provided in the attributes or rule set, will confuse the software and decisions made may be totally unreliable. The detail explanation of the software is presented in Appendix II and output generated using software is given in Appendix V.

The round-up chapter which summarizes the integrated design facility is given in Chapter 10.

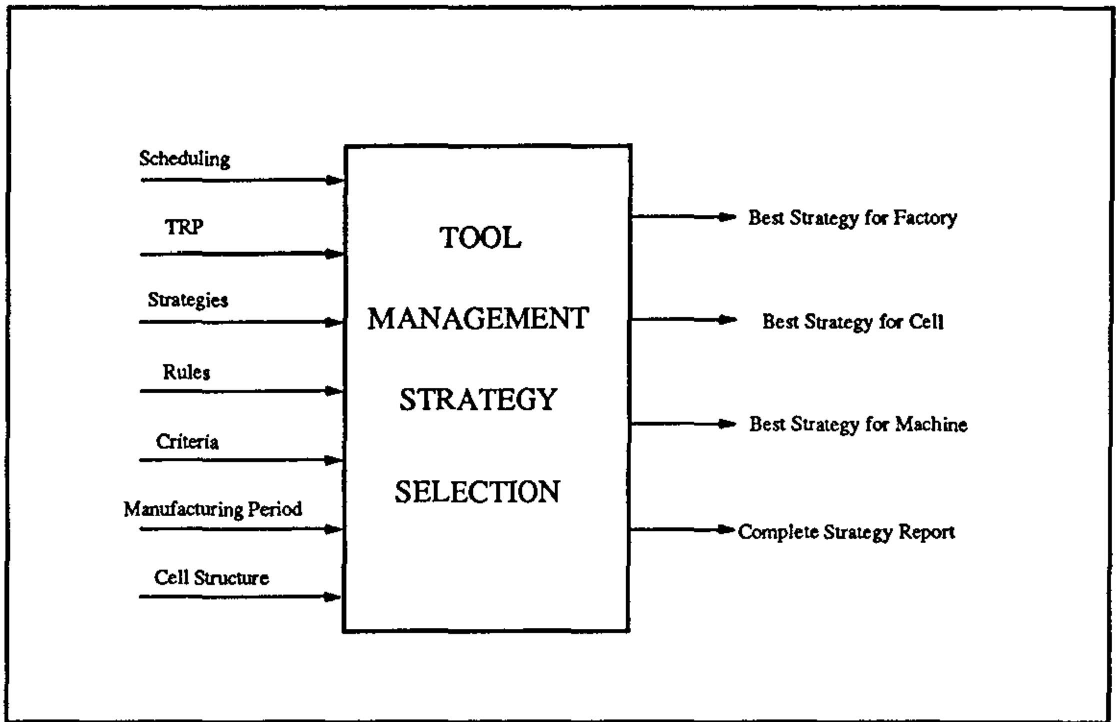


Figure 8.1	General Inputs and Output of Strategy Selection Module	LUT-FMS Research Group

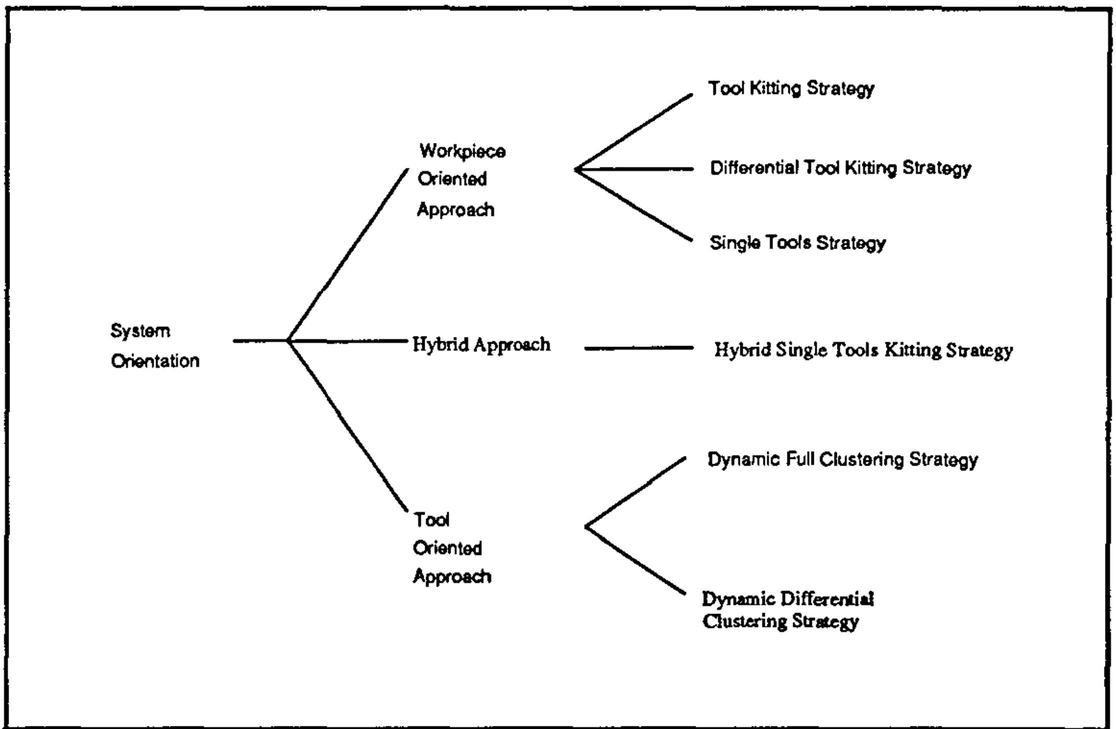


Figure 8.2	Strategies Tree to select 'Best' Strategy	LUT-FMS Research Group

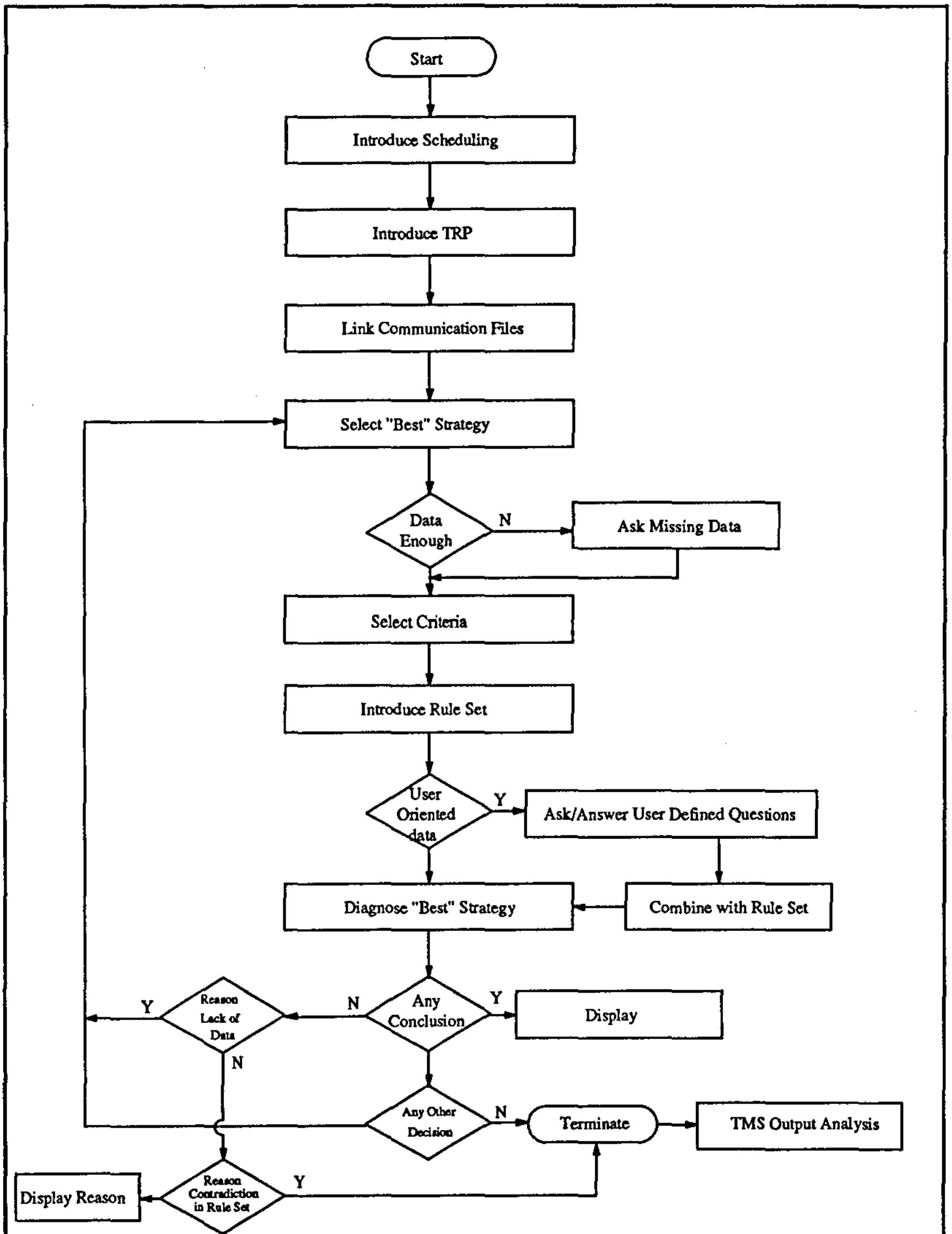


Figure 8.3	Logic Diagram of Strategy Selection	LUT-FMS Research Group

Chapter 9

Output Analysis

9.1 Introduction

The purpose of this chapter is to introduce the reader to the tool management output analysis. The structure and working mechanism of the module is presented. Finally the function of the module in the integrated design facility is explained.

9.2 Output Analysis

When a system is developed or designed, the question of reliability is one of the first which is expected to be answered. This is especially true when developing systems in which many different interacting parameters are involved and uncontrollable parameters can create an uncertain environment. The validation and testing of the system is part of the design process and should be done using a reliable design and analysis tool.

Knowledge-based methodology is largely accepted as design tool [175]. However, since it calls for validation and testing during each iteration, it is used more as diagnosis and analysis tool especially when developing systems for uncertain environment. [9]

The knowledge-based tool management output analysis has been developed to assess the tool management design performance in flexible manufacturing systems. Since a very large number of outputs are generated by the design facility, regarding the many different tool management activities in a multi-level manufacturing environment, it is needed to test the reliability of the design facility.

Since many rules, strategies and decisions are involved and small but important steps are taken in a tool management design effort, it is important to have expert advice at each step of the design process. The design facility and meeting the system requirements using the design facility must be reliable in order to solve the problem adequately. It is difficult to find source of problems especially in chain events and in environments in which many factors are involved. Also, it is equally difficult to implement the available set of knowledge correctly, all at once, without of further review and modification. As knowledge is collected and stored into the knowledge-base, it must be evaluated and tested against the system requirements as well as the expectations of how the system is to perform and/or what knowledge the system is to contain. [9] Thus, during the each step of the design process, the design decisions must be validated and supported by an expert for analysis of the available design process output. Figure 9.1 shows the basic inputs which are collected from the other design modules reported in earlier chapters via the manufacturing database and the attributes which are embedded in the classified rules. Each class of rules is devoted to one analysis and reported in the next section. The outputs are generated by processing of these inputs as well as the rule sets.

9.3 Structure of Output Analysis

The system is two fold. One is for TMS performance analysis and the other is for TMS fault detection and diagnosis. The output analysis is part of the integrated design facility and is fed and updated through other design modules as well as the manufacturing database.

9.3.1 TMS Performance Analysis

The system performance analyser measures the output collected from the scheduling, TRP and strategy selection modules for the overall system, individual cells, workstations, tool stores and tool transporters against the user accepted tolerance limits. The knowledge-based output analysis module makes the analysis easier by recognizing similarities between the real system requirements and the interpretation of real system in the rule based environment. The system always compares the output gathered from the other modules against the user requirements. At this stage, the user requirements and specified tolerance limits play a crucial role to assess the system output.

System output can be tested against formally proven and reliable real company output and justified by comparison against the real manufacturing system output or specified limits.

The performance analysis has been classified into seven groups:

* **Manufacturing Workstation Utilization**: Since workstations are the major ingredients of an automated manufacturing system, it is common sense as well as a logical conclusion that the machine utilization is very important and that high utilization is one of the indicators of the success of the manufacturing system.

* **Central Tool Store (CTS) Utilization**: This research work primarily considers tool management issues. Therefore, it is important to consider the CTS as a basis of performance analysis which indicates the degree of tool flow and tooling activities at factory level. (Ref. to Figure 5.2)

* **Secondary Tool Store (STS) Utilization**: STS is designed as a bridge between individual machines and CTS and it has two way traffic as well as being the place where the main cell level tooling activities take place. (Reference to Figure 5.2) Thus, it is important to consider STS performance as a major part of the TM design facility

* **Primary Tool Store (PTS) Utilization**: PTS is the machine level tool store and supplies the tools that are used directly in operations. PTS is one of major system design constraints which may cause tool flow bottlenecks or serious production bottlenecks on the machine. It is the unique performance indicator for tool management at machine level.

* **Tool Utilization:** Tool utilization mostly depends on the adopted tool issue strategy. It significantly affects tool inventory and tool flow level and it is one of the most important factors in TMS design.

* **Transport Utilization:** Since all the hardware elements are integrated with each other in FMS, the failure of one element may cause serious problems in the system. In order to apply the tool issue strategies, the hardware requirements must be satisfied. Tool transport mechanism is one of the unique parts of the TMS design facility which is constrained by several factors such as capacity, speed and form of transport. It is thought that transportation should be considered as a basis of performance analysis.

* **Throughput and Lead Time Report:** Throughput time is not only a criteria for TMS design but for the whole manufacturing system. Since it is the basis of all the time related activities, throughput time and its extension, lead time, are accepted as performance criteria.

The system gives a broad report for the key criteria for the applied strategy which has been selected/suggested by the KBTMSS module, (Ref.to Chapter 8)

The system starts by giving a menu of the listed alternatives for examination of the desired manufacturing system parameters. For example, if the first alternative, workstation utilization is chosen, the output analysis module triggers the machine utilization section. This first determines the number of machines available in the system and then determines which machine belongs to which cell if the manufacturing system is a multi cell system. After the identification of machine numbers and machine groups, output analysis lists the knowledge about each individual machine giving the utilization percentage, cumulative worked time, processed jobs, sister tools used and spent tools.

It is a great help to have this level of information about the system which gives an opportunity to the user to intervene with the system if needed. The jobs and the tools distributed to each machine and each cell can be easily envisaged. The other design parameters can be viewed with the same level detail.

9.3.2 TMS Identification of Operation Problems and Fault Detection

TMS operation problem and fault detection is the second main function of the output analysis module, designed to support the design facility by providing feedback for both hardware and organizational problems. Since operational issues are dynamic, the knowledge stored in the module requires updates from the other feeding modules, i.e, scheduling, TRP and KBTMSS. This is achieved through the relational database, ORACLE, which links the three supporting modules to the output analysis module as shown in Figure 9.2. An optional data file which is fed by the three modules can also feed into the output analysis module.

The module supports four main hardware and operational problems, these are:

* manufacturing cell problem,

* manufacturing workstation problem,

* tool store problem,

* tooling problem.

First, the most likely problem areas with the supporting questions and possible solutions are stored in the global attributes section. When the initial menu has triggered the related problem area, to be able to make a decision, the rules section fires the related attributes as well as the associated questions. Answers may be selected from among the output provided by the other modules, or, if the user does not want to answer a relatively large number of questions, the output gathered from other modules can be attached as a default value to the related questions to prevent asking questions.

The rule section will reach a conclusion according to the given answer or specified default values. Since every possible problem stored in the knowledge base is answered by another rule, if the user asks the output analysis to provide a solution for the related problem, output analysis will prompt the related rule and will suggest a solution for the problem faced. Also, the problem as well as the solution can be justified by asking output analysis.

One of the related attributes is given below,

*** Attributes**

manufacturing problem:sgl

(transport capacity not large enough,

pallet quantity insufficient,

due date not met,

wrong strategy selected,

....

The same type of attributes are provided for cell, tool store and tooling operations. One of the problem rules is:

flexible manufacturing cell rule1:

J:jobs

if

J>kit size gt J>picked station>pts capacity and

J>picked station>pts capacity # 0

then

reassert tool store problem = tool magazine capacity insufficient.

endif.

The following rule is provided as a solution to the problem rule presented above:

\The following rules provide solutions for the manufacturing problems

Tool magazine insufficient problem solution:

if
 tool store problem = tool magazine capacity insufficient
then
 reassert remedy = reduce the transfer batch size<0.4>/
  remove the worn_broken_or_not needed tools from magazine<0.3>/
  increase the usable tool life percentage<0.1>/
  increase the tool magazine capacity<0.1>.
endif.

Possible problem areas may be different to each organization and it is straightforward to change, add or delete any attribute as well as changing solutions attributes. Also, any rule can be easily changed, deleted or added to make the output analysis module compatible with the system worked in.

9.4 Software Capability

The output analysis has the capability of analysing output generated by the tool management system design facility. The output is justified against a pre-determined set of criteria. These criteria could be user specified or formally proven company output and because of the software flexibility, they can be easily replaced or changed. The software could be used entirely as an interactive analyser cancelling pre-determined default values which as a result of this process might be asked tens of questions depends on the system size analyzed. Also, when the default values are specified to the attributes it is possible to analyze entire system without answering a single question.

The second major part of the module is designed to solve the major TMS design problems. Problem recognition is based on internal problem classification. These are, cell, workstation, tool store and tooling problems. The software has the flexibility which lets the user specify his/her own criteria, problem areas and analysis areas. Therefore, the software can easily be restructure inserting a new set of attributes as well as rule sets. Thus, the software can be made more compatible with the working environment. Figure 9.3 and 4 depict typical output analysis and fault detection outputs.

The detail of the software is explained in Appendix II and the output generated from one of the examples is illustrated in Appendix VI .

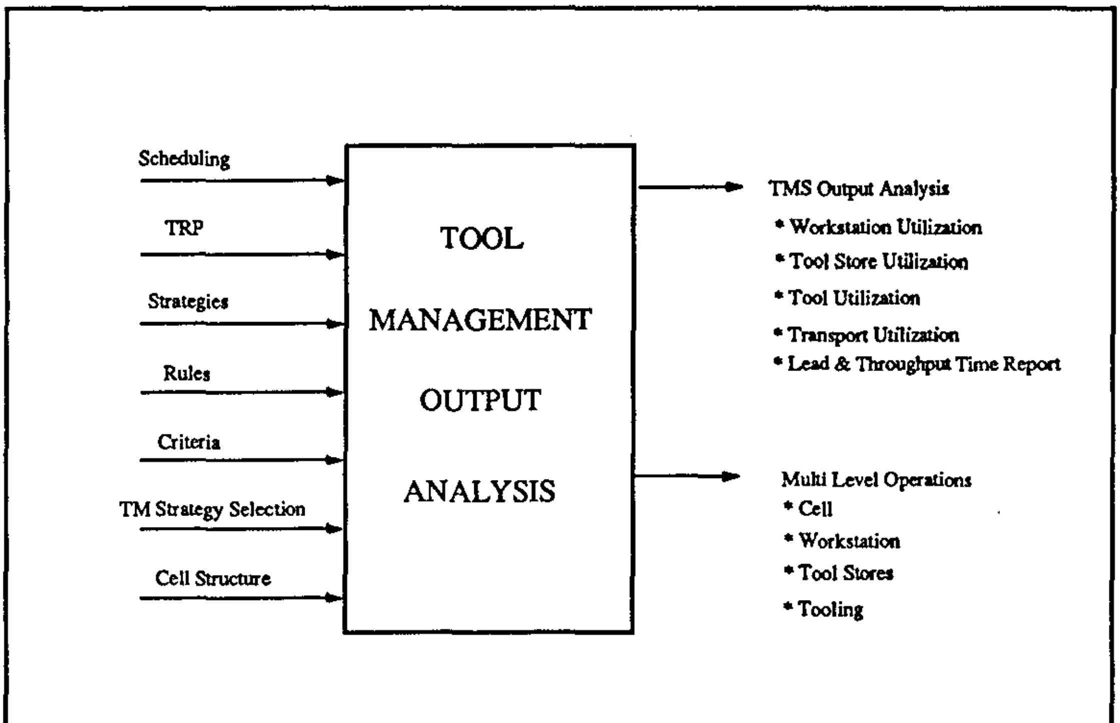


Figure 9.1	General Inputs and Output of TM Output Analysis Module	LUT-FMS Research Group

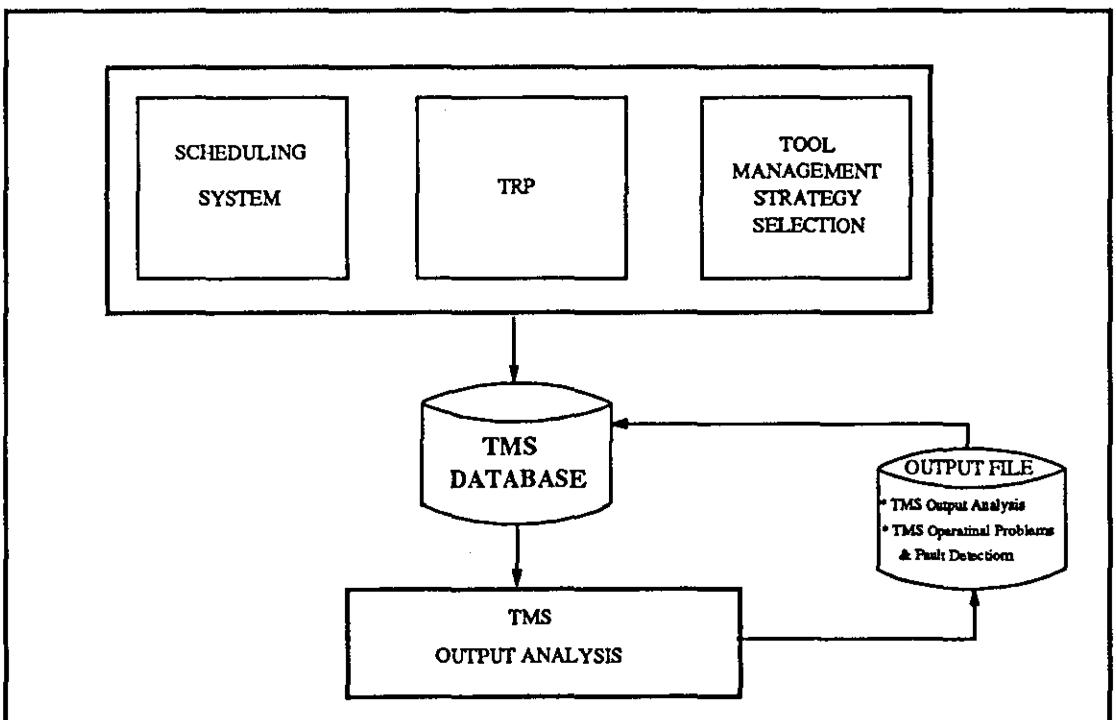


Figure 9.2	Integration of Tool Management Output Analysis with Design Facility	LUT-FMS Research Group

What would you like to do ?

1.Manufacturing Workstation Utilization
2.CTS Utilization
3.STS Utilization
4.PTS Utilization
5.Tool Utilization
6.Transporter Utilization
7.Throughput and Lead Time Report

=? 1

******** STATION UTILIZATION TABLE ********

Station	:	Station 1	Station	:	Station 2	Station	:	Station 3
Group	:	1	Group	:	1	Group	:	1
Jobs Done	:	3	Jobs Done	:	6	Jobs Done	:	4
Utilization	:	73.254	Utilization	:	99.185	Utilization	:	92.85
Worked	:	1054.86	Worked	:	1625.08	Worked	:	1337.15

Figure 9.3 Sample Output of TM Output Analysis Module — LUT-FMS Research Group

What would you like to do ?

1. Manufacturing Cell Problem
2. Manufacturing workstation problem
3. Tool store problem
4. Tooling problem
5. Justify manufacturing problem
6. Justify workstation problem
7. Justify tool store problem
8. Justify tooling problem
9. Provide solution
10. Justify solution
11. Exit

=? 4

What amount of_tool should be available for next batch?
(Enter a number)
= 730

What size is the company tool inventory ?
(enter a number)
=? 300

Current critical tool size ?
(enter a number)
=? 30

Current sister tool size ?
(enter a number)
=? 150

****
No tooling problem has been discovered
****

Type 'c' to continue or 's' stop.

Figure 9.4 Sample Output of TM Fault Detection Function of the Output Analysis Module — LUT-FMS Research Group

Chapter 10
The Tool Management Design Facility

10.1 Introduction

The purpose of this chapter is to present the hardware and software configurations used in the development of the tool management design facility based on the models presented through chapters seven to ten. The modelling approach, techniques, data inputs and the modelling outputs are also discussed.

10.2 The Design Task and the Functionality of the TMS Design Facility

The four integrated modules in the TMS design facility are:

1- the part batching and scheduling module,

2- the tool requirements planning module,

3- the tool management strategy selection module,

4- the tool management output analysis module

Detailed explanations of each one of these modules are presented in Chapters 6,7,8 and 9 respectively. The functionality, structure and the usage of the software are presented in Appendix II for each stage, together with views of screens with the purpose of guiding users. The outputs generated by the modules are presented in Appendices III, IV, V and VI respectively. The overall configuration of the modules is illustrated in Chapter 5, Fig.3.

The design facility is aimed at providing a powerful design and forecasting tool for tool management. It acts as an aid to cell management which could either work alongside a currently operating cell oriented tool management system or be used to assess a tool management solution within a cell or a total factory environment.

The modules which form the design facility are integrated both with each other and through a manufacturing database. Each module and the database has its own interfaces. Therefore, each of the modules could be used either in a standalone mode as a sub-design facility for a particular problem or as an integrated design facility. The prototype software is currently mounted on a SUN SPARC IPC workstation.

The design facility centres on four modules which are derived from the hierarchical representation of a tool management system, (Reference to Figure 5.2). Therefore, it is possible to model from single workstation to multi-cell, multi-machine systems. The design facility has been validated through a large number of experiments. The method of the design of experiments and the results are presented in chapter 12 to 17. The facility permits powerful tool flow solutions to be achieved and the rules and the strategies which the modules are based on are embedded in the each one of design chapters.

The modelling system has been created using the power of both algorithmic and knowledge based approaches, (Ref. to Chapter 5). Therefore it is possible to model some details of a tool management system as well as making decisions with the help of a rule based environment.

10.3 The Modelling Capability

Considerable detail, involving complex relationship between system elements, has been built into the modelling through the use of rules and strategies. The aim is to create a design facility which can produce detailed, accurate and realistic output as well as making decisions as accurately as possible at the right place and time.

The TRP module, which is the core of the entire design facility, treats each one of the three different TM approaches separately. These are discussed in Chapters 13, 15 and 17.

The modelling of each of the approaches is capable of producing all the necessary output needed by a tool management system such as maximum, minimum and actual tool requirements, tool inventory, kit size, sister tool requirements, worn tool list, machine and transportation utilisation as well as throughput time for the job list. The modules are fed by either an internal database or by the manufacturing database.

The modelling addresses not only problems such as calculation of tool requirement, tool inventory etc. but also managerial problems such as which tool issue strategy should be used, why it should be used, what is the best solution for a particular hardware environment among the alternatives and also the justification for the decision made. The modelling also allows the determination of tool inventory levels and the prediction of the tool requirement for long term manufacturing period as well as size of the secondary and primary tool stores. TMS strategy selection output is presented in Appendix V.

The models can produce the maximum and minimum tool requirements as well as the actual tool requirement for a particular production period in order to demonstrate the performance of the currently applied tool management strategy. This allows the user to justify the system beforehand without going to detail modelling and interrogation. It is also possible to produce an inventory cost report. A detailed output generated by a model is presented in Appendix IV.

Each machine is represented by a separate file specifying and updating the content of the primary tool store so that it is possible to trace the individual tool movement in the manufacturing system. Other output could also be generated such as tool life usage, sister tools, spent tools, how long each tool stayed on a machine and when it is changed. This is a great help, especially when there is a lack of a control mechanism or low level control situations.

The output analysis module interrogates the output collected from each of the modules and justifies them based on one or more user selected criteria. The model could also be used to assess workstation, central tool store, secondary tool store, primary tool store and tool transportation utilization as well as throughput time.

The modelling is also capable of fault diagnosis. This is designed to solve major and widely met manufacturing problems within the tool management context. First, problems are classified as manufacturing, cell, machine and tooling problems and then a set of solutions is provided for each problem that is likely to be met. Problem discovery mostly depends on the tolerances that are accepted by the user. A detailed output generated by the output analysis module is presented in Appendix VIII.

The modelling facility theoretically has the ability to model a limitless number of machines and limitless time horizon. The only restriction imposed is the computer and software platform and the run time of the prototype software.

The influences of part batching and scheduling functions have been added to provide a balanced prototype facility and the work is described in Chapter 6. This work has been included so as to construct an ordered machining list for each machine as well as meeting the constraints imposed by hardware facilities such as magazine and transporter capacities.

All the modules can be run individually or as a wholly integrated design facility.

10.4 Overview of Data Inputs

Databases are defined as the collection of information that can be accessed by both end-users and application programs[66]A large amount of data for parts, tools, machines, operations, cells and other ancillary functions has to be manipulated among several computer programs in the TMS design process. The data set has to have a certain format and a logical relationship with other parts of the data set. It has to be easily updated, deleted, changed, stored, transferred and reached. Therefore a relational database management system (RDBMS) is one of the major parts of the tool management design facility.

A commercial database system, ORACLE, has been used to store the TMS data set and to support the other design models. The database serves as a store for all those parameters common to all the modelling tools. The shared information essentially includes jobs, work-stations, tools, tool stores and cell data organised in a relational hierarchy such that for example, tools are related to jobs and jobs may be related to workstations.

The database management system has been configured into 10 blocks. These are the cell block, part block, tool block, workstation block, jobs block, operation block, pallet block, primary tool store block, secondary tool store block, batch block, and system block. Each block is connected through one or more reference data.

All the blocks can be run in any sequence and for any number of times, so that each block can be processed individually without going to detail. Once the data has been input, it is possible to edit any individual data entry without requiring the whole data record again.

Each block has its own menu system and access to data is done by querying the data. Also, the next and previous record can be easily reached by soft-key dialogue. The data handling, queering and referencing related data in another block is made much easier because of the software used.

The data set used in this research has been obtained from a Peterborough based manufacturing company [201] and a complete list of the data is given in a complementary data book. Some of the sample parts data and the tool list are presented in Appendix I. The interface and the structure of the manufacturing database is introduced in Appendix II.

A detailed worked example which illustrates the use and usefulness of this design facility is included in Appendices II to VIII, based on the data set contained in the supplementary data book. The example chosen is for a relatively short manufacturing period so that the total output can be reasonably contained in the body of the thesis.

The appendix containing the worked example includes the step by step explanation of the insertion of data and the study of output data which comes from the use of the TMS design facility.

Chapter 11
TMS Design and Performance Parameter Interactions

11.1 Introduction

This chapter addresses the need to understand the relationships between key design parameters with the help of major computational experiments which are based on realistic manufacturing data and a representative flexible manufacturing cell configurations where hardware and design/operation rules are variable.

11.2 The Scope

The use of the design software reported in the earlier chapters to create computational experiments offer valuable support for the design of TMS. However, since there are a large number of design parameters that participate in the tool management design process and there are complex relationships between parameters, it is difficult to explain the parameter interactions. The scope of this chapter is to explore a better way of understanding the interactions between major design parameters in TMS using the tool management design facility.

An attempt is made in this thesis to carry out a balanced set of experiments based on the use of a unique body of data. This will help give an understanding of the interactions between the key parameters.

It would be a great help to TMS design if a deterministic or even a statistical pattern of behaviour could be found among the parameter interactions. However, the problem faced is that interactions may not follow such pattern. Therefore, it is necessary to explore many relationships in order to give a broad sense of direction to tool management design practice.

While there are some other design platforms available (Reference to Chapter 2 and 5) a unique approach to design and analysis has been used. The approach adopted in this thesis is used to design software, as reported in earlier chapters, for searching a family of realistic situations and hence providing structured and detailed output. This is illustrated in the subsequent chapters. The output forms the basis for the research.

This approach, although valuable, has one weakness i.e. it considers only a limited amount of part and tool data. This data set, which consists of 70 part-types and a 76 tool-type matrix, has been listed in the supplementary data book. Some representative data and figures are illustrated in Appendix I. It is noted that the reader must make an assessment of the work based on the data provided. The reader must bear in mind the strengths and weaknesses of using one data set.

11.3 The Cell

The cells described below adequately represent the purpose of this work,i.e. to study a substantial range of tool management parameter interactions that are subjected to a practical performance target.

The focus of the calculations carried out in the subsequent chapters is an FMS cell structure of well established form. It is assumed that the cell can be configured with from three to eight machine tools. This is consistent with the state of the art. It can also be considered on occasion to be two physically separate four machine cells. These types of installation are used within manufacturing industry. Figure 11.1 depicts the cell layout used as a hypothetical work environment for the computational experiments.

It is assumed that tool and part transport flow paths are separate within a cell layout. The computational algorithms are not designed to deal with shared tool and part transport systems. In such systems bottlenecks may occur.

No attempt is made in this work to differentiate between STS and a central warehouse within a factory. In some of the computational experiments, therefore, tool inventory may be assumed to be stored, for a particular manufacturing period, in either a small capacity STS, a larger capacity STS or in the warehouse.

11.4 Parameter Modification

In the initial definition of the research program a wide range of manufacturing periods, ranging from one to ten shifts was considered. As work has progressed it has been found that the computational results gained from very short runs have limited value. The research reported in the next chapters therefore only considers manufacturing periods which spans from three shifts to ten shifts. For the same reasons the LPT and GRP scheduling rules have proved to be an incorrect choice especially with short term manufacturing periods. In the latter experiments these two scheduling rules have not been included. In the light of initial computational experiments it has been found that the five machine and seven machine cells have produced very similar results to the six and eight machine cells. The five and eight machine cells have therefore been excluded from the latter experiments.

Besides the planned experiments, one long term computational experiment, for a 58-shift period, has been studied. This highlights the total factory organization tool inventory and is reported in the concluding discussion chapter (Ref. to Chapter 18).

The loading of the cell with work follows a pattern laid down by the company who provided the data. Three families of work requirements are identified and these are documented in the supplementary data book supplied with the thesis. The families are repeatedly used, both separately and in combined form to construct the longer manufacturing period.

11.5 The Research

In this thesis an attempt is made to study this engineering activity. An approach is made in the form of a series of experiments based on the use of computer models that simulate particular machining facilities. Many parameters have been discussed in Chapter 4, however it has been decided that only a short list of performance parameters can be given a high priority. These are considered in order to gain an understanding of the computational experiments. These performance parameters are:

* Tool Inventory
* Tool Requirement
* Machine Utilization
* Throughput Time

The following parameters may then be considered as a secondary list of performance criteria:

* Tool Life Utilization
* Transportation Utilization
* Tool Distribution

The work is split into three major areas; that dominated by

* workpiece-oriented flow,
* tool-oriented flow and
* hybrid flow.

Hybrid flow is a composite of workpiece and tool oriented flows. Work flow is subject to different loading rules and tool flow is subject to one of six specific tool issue strategies.

It is expected that the reader can form an opinion, based of the interpretation of the results of the merits of the different strategies required for a particular machining cell application. However, it is considered that the results are broadly applicable.

Whilst the next five chapters assist in understanding the parameter interactions in response to different strategies applied, attention should be drawn to the concluding discussion (Ref. to Chapter 18). Here the individual strategies' results are studied and have been brought together for comparative assessment. A core set of experiments and additional outputs help to further understanding of the interactions of the parameters.

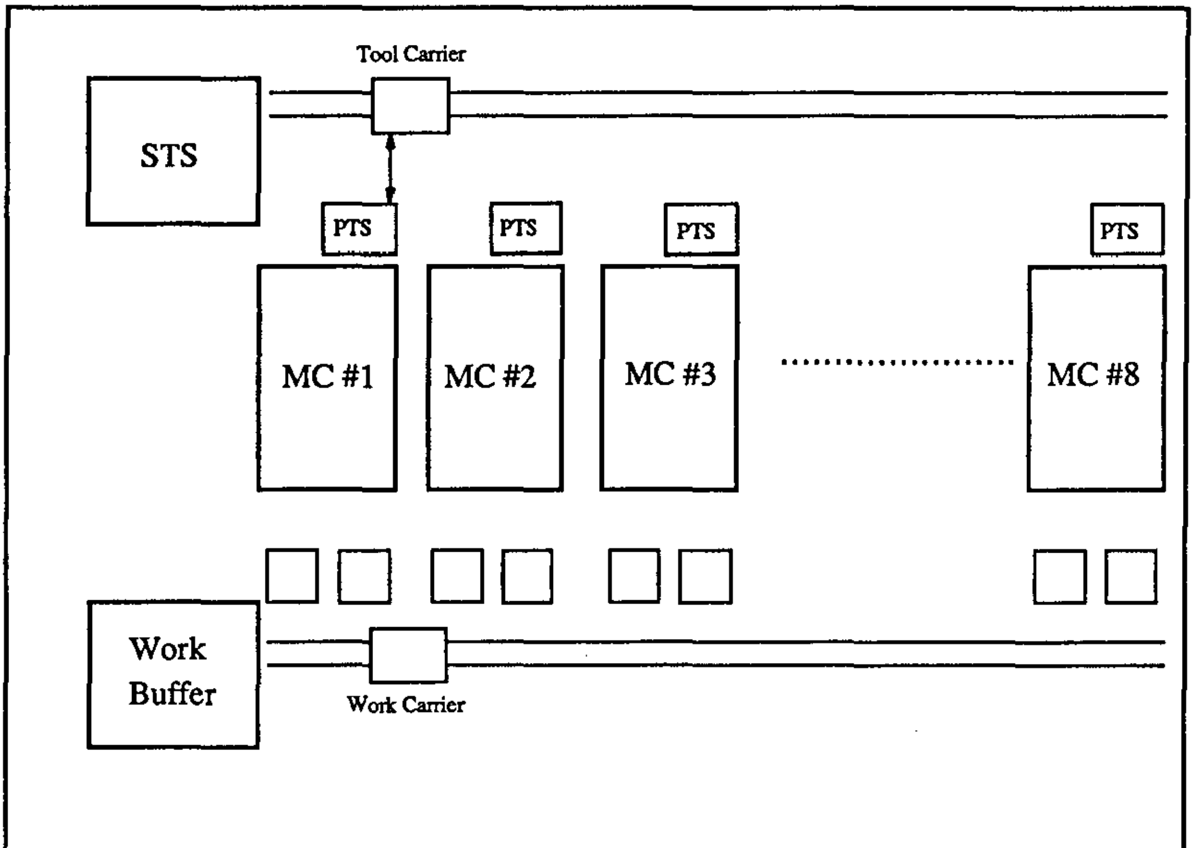


Figure 11.1	Hypothetical Cell Layout where Experiments Practiced	LUT - FMS Research Group

Chapter 12
Design of Computational Experiments

12.1 Introduction

This chapter presents an overview of the complete family of experiments presented in the subsequent chapters. The chapter also presents the method used to create the computational experiments, design stages and decisions made.

12.2 Factors Involved in Computational Experiments

A number of factors are involved in the computational experiments. These are tool issue strategies, work family, work scheduling rules, batch size, number of machines, manufacturing period, permissible tool life and magazine capacity. (Ref. to Chapter 4). Since tool issue strategies have unique characteristics and each strategy has a different approach for the design of TMS, the design of computational experiments is basically centred on tool issue strategies. Therefore, the six tool issue strategies are grouped under three main headings according to the approaches adopted (Ref. to Chapter 4) and the computational experiments are also grouped according to main approaches. These are:
- workpiece-oriented approach experiments
- tool-oriented approach experiments
- hybrid-approach experiments

Table 12.1 depicts the factors involved and the level of variables of each main factor. Each main group of experiments uses only the related variables and the parameter set involved in each group is depicted in Tables 12.2, 12.3 and 12.4 in each appropriate section.

12.3 Design of Computational Experiments

When there are several factors of interest in an experiment, a factorial design could be used which permits every possible alternative to be investigated. However, when the number of factors involved is increased each with a wide range variables, the possible number of combinations is exponentially increased. To set up such a large amount of experiments is impractical or exorbitant in terms of time, effort and cost. [196]

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Kitting	Diff.Kitt.	Single T.	Full Clus.	Diff.Clus.	Hybrid Single T.
B: Part Scheduling Rule	EDD	SPT	LPT	GRP	Internal	
C: Part Family	Family 1	Family 2	Family 3			
D: Number of Machine	3	4	5	6	7	8
E: Manufacturing Period	1-Shift	3-Shift	10-Shift			
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%	75%	50%			
H: Magazine Capacity	60	120				

Table 12.1 Main design factors involved in computational experiments

From the table 12.1, the possible combinatorial of maximum number of experiments is 7776. Therefore, a design methodology is required which prevents the need for a such a large number of experiments as well as suggesting a disciplined way to design and conduct the experiments.

The Taguchi method has been introduced to reduce this very large number of possible experiments to a relatively small number of the most effective minimum experiments. However, this small number of experiments allows valuable information to be learned about the design concept. Also the method suggests a disciplined way to conduct as well as analyse the design experiments. See Appendix VII for the detail of the Taguchi Method.

Since three families of work requirements are identified, in each main experiment group, the experiments are designed to cover all work families. Also in the workpiece and hybrid-oriented approach experiments, the work load is determined by an external scheduling system which employs four different scheduling rules (Ref. to Chapter 6). The second main parameter with work family are the two key factors that mainly determine the shape of the experiments.

In the light of experience gained from the initial experiments, the Taguchi method has been found to be inadequate in terms of gaining more understanding from the proposed computational experiments. Therefore, a new extended set of experiments has been designed and conducted.

Some of the parameters have been excluded in the extended set of experiments to create more adequately combined computational experiments. (See Chapter 11) The new set of experiments are designed to especially consider the specific combination of design parameters which is more helpful in the analysis of the effect of the design parameters. This is in contrast to letting the design technique used select the parameter combinations, which sometimes might suggest very unpractical combinations.

The experiments reported in this thesis and the analysis to gain understanding from the experiments are based on this extended set of computational experiments. Although the Taguchi method suggested experiments have been found less helpful and have been used less in the analysis, they have been presented in the supplementary output book as reference.

12.4 Design of Workpiece-Oriented Approach Experiments

Eight design factors are identified in the workpiece-oriented approach each with a different level of variables as listed in Table 12.1. The possible combinations using eight factors with up to six variables each give a total of $(6^1 \times 4^1 \times 3^4 \times 2^2) = (6 \times 4 \times 81 \times 4) = 7776$ experiments. To establish this many experiments is highly impractical.

The major benefit of the Taguchi method is to reduce this total to a manageable set of 32 experiments, which should still provide the same understanding from the body of factors and variables. The L_{32} orthogonal array and the matrix which has been modified and suited to the design structure are given in Appendix VII Tables 1 and 2 respectively.

The first experiment is conducted using the first level (Level 1) variables in order to identify which one of eight possible controllable factors are statistically significant. A detailed explanation of the Taguchi method suggested experiments is given in Appendix VII

Through the description of individual design experiments, it is seen that a Taguchi design experiment can contribute to the selection of the most important different configurations of the design experiments. However, some of the results of the Taguchi suggested design alternatives are easily predictable and although they have already been conducted, some additional design experiments are separately created to gain some more critical understanding from the experiments. These additional experiments and configurations are tabulated in Chapter 13, Tables 3 and 4 respectively.

The new reduced form of parameter set is depicted in Table 12.2. All the experiments created apart from the Taguchi method in the workpiece-oriented group are based on this parameter set. Also the analysis of workpiece-oriented experiment results is based on these experiments.

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Kitting	Diff.Kitt.	Single T.			
B: Part Scheduling Rule	EDD	SPT				
C: Part Family	Family 1	Family 2	Family 3			
D: Number of Machine	4	6	8			
E: Manufacturing Period	3-Shift	10-Shift				
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%					
H: Magazine Capacity	60	120				

Table 12.2 Parameter set with reduced alternatives in Workpiece-oriented experiments

12.5 Design of Tool-Oriented Approach Experiments

Since the tool-oriented approach which is the dynamic cluster analysis approach, has its own internal scheduling system, the external scheduling rules used in workpiece-oriented experiments are excluded. Thus seven factors with a maximum of three level variables are identified as listed in Table 12.3. The possible combinations total of $(3^3 \times 2^4) = (27 \times 16) = 432$ experiments.

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Full Clustering	Diff. Clustering				
B: Part Scheduling Rule	Internal					
C: Part Family	Family 1	Family 2	Family 3			
D: Number of Machine	4	6	8			
E: Manufacturing Period	1-Shift	3-Shift	10-Shift			
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%	75%				
H: Magazine Capacity	60	120				

Table 12.3 Main design factors involved in Tool-oriented experiments

3 factors with 3 variables 6 DOF
4 factors with 2 variables 4 DOF
1 factor with 1 variable 0 DOF
Total DOF = 10.

As indicated in Table 12.3, the total degree of freedom (DOF) is 10 for the tool-oriented approach experiments and the nearest 2-level array is L_{12}. Thus, the Taguchi method suggests that a design of 12 experiments instead of 432 is sufficient.

The experience gained from the design of the workpiece-oriented experiments proved that because of the unique nature of a tool management system, the suggested computational experiments have limited value and it is not possible to fully understand the interactions and trends from such a limited number of experiments. Therefore, instead of conducting the Taguchi method suggested computational experiments, all the tool-oriented experiments have been designed separately. Special care has been given to the machine number and batch size parameter combinations which makes it easier to draw conclusions as well as giving more logical configurations.

Further, during the execution of the computational experiments a possibility emerged to issue the cluster sets in a more effective and powerful way, resulting in the creation of a new tool issue strategy. Therefore, a number of alternatives were added or removed from the initial design parameters which affected the shape of experiments. All the experiments created for the tool-oriented approach have been designed completely separately from the Taguchi method and the analysis of the experiment results is based on this set of experiments.

The tool-oriented approach experiments are explained in Chapter 15 and the experiments conducted are given in Tables 15.2, 15.3 and 15.4 respectively.

12.6 Design of Hybrid Approach Experiments

The hybrid approach was invented during the execution of the workpiece-oriented and tool-oriented approaches experiments and it is treated as a different approach because of its working nature (Ref. to Chapter 17). The approach employs only one tool issue strategy which is the hybrid single tools kitting strategy.

Since the complete list of parameters have resulted with some less useful experiments design in the workpiece oriented approach experiments the main design parameters in the hybrid approach experiments are the same as the reduced parameter set used in the workpiece-oriented approach experiments as shown in Table 12.4. The possible number of experiment combinations is $(6^1 \times 4^1 \times 3^3 \times 2^2) = (6 \times 4 \times 27 \times 4) = 2592$ for the hybrid approach.

1 factor with 6 variables 5 DOF
1 factor with 4 variables 3 DOF
3 factors with 3 variables 6 DOF

2 factors with 2 variables 2 DOF
1 factor with 1 variable   0 DOF
Total DOF = 16

From the Table 12.4 total degree of freedom (DOF) is 16 for the hybrid approach factors and the nearest 2-level array is L_{16}. For the Hybrid experiments the Taguchi method has suggested 16 experiments instead of 2592 experiments.

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Hybrid Single T.					
B: Part Scheduling Rule	EDD	SPT	LPT	GRP		
C: Part Family	Family 1	Family 2	Family 3			
D: Number of Machine	3	4	5	6	7	8
E: Manufacturing Period	1-Shift	3-Shift	10-Shift			
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%	75%	50%			
H: Magazine Capacity	60	120				

Table 12.4 Main design factors involved in Hybrid experiments

With the same reasons stated for the workpiece and tool-oriented approaches, the experiments have been designed independently from the Taguchi method and the analysis of results is based on this independent set of experiments. The complete list of computational experiments and the detail explanation of the hybrid approach are presented in Chapter 17.

Chapter 13
Design of Workpiece-Oriented Approach Computational Experiments

13.1 Introduction

This chapter addresses the design effort for the workpiece-oriented approach computational experiments, the parameter set used and the rules and decisions made. The chapter further presents the method used to create computational experiments.

13.2 Scope of Workpiece-Oriented Experiments

The workpiece-oriented experiments are planned to test the design approach capability and the effectiveness against the major TMS performance criteria listed in Chapter 4 to gain more understanding in the design of TMS.

The experiments are basically centred on three main design parameters. These are: the family of jobs, tool issue strategies and part scheduling rules. The three tool issue strategies are full kitting, differential kitting and single tools kitting, and have been explained in detail in Chapters 4 and 7. The other design parameters determine the shape of the experiments and are placed around the three main parameters.

In the design and planning of the workpiece-oriented experiments, primary consideration is given to gaining understanding of the major parameter interactions and their influence. The experiments are used to find the effective solutions to TMS design problems.

13.3 Design of the Taguchi Method Suggested Experiments

Since a number of design parameters with different levels of variables are involved in design, the possible factorial computational experiments which cover all parameter combinations is 7776. (Ref. to Chapter 12) Due to the impracticality of designing all the possible experiments, a new design methodology has been introduced which is aimed at reducing this number of possible experiments to an affordable number whilst still covering all the key issues involved in the workpiece-oriented approach. The reason for this is to gain more understanding from the available experiments. The design parameters and the level of variables involved in the workpiece-oriented approach are listed in Table 13.1.

As indicated in Table 13.1 since each factor has two or more level of variables, it is preferable to use an array from the 2-level series of the Taguchi design method. Because there are 18 degrees of freedom, (DOF) the array must have 18 or more rows where each row indicates

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Kitting	Diff.Kitt.	Single T.			
B: Part Scheduling Rule	EDD	SPT	LPT	GRP		
C: Part Family	Family I	Family 2	Family 3			
D: Number of Machine	3	4	5	6	7	8
E: Manufacturing Period	1-Shift	3-Shift	10-Shift			
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%	75%	50%			
H: Magazine Capacity	60	120				

Table 13.1 Main design factors involved in Workpiece-oriented experiments

1 factor with 6 levels of variable gives DOF = 5

1 factor with 4 levels of variable gives DOF = 3

4 factors with 3 levels of variable each gives DOF = 8

2 factors with 2 levels of variable DOF gives 2

Thus Total DOF = 18

and the nearest 2-level Orthogonal Array L_{32}

an experiment combination. The most convenient 2-level of array, L_{32}, has been selected to establish the computational experiments which suggest altogether 32 experiments instead of 7776.

However, since this 32-row orthogonal array contains a maximum of 31 parameters with 2-level variables, it is necessary to modify this standard array to suit the workpiece-oriented parameters which contain 8 parameters with maximum 6-level variables. (See Table 13.1.) The detail of the Taguchi method suggested orthogonal array and the modified orthogonal array are tabulated in Appendix VII

The parameter combinations of the first experiment conducted which is extracted from the 8-parameter orthogonal array, column 1, is tabulated in Table 13.2 as an example.

Main factors	Level and Value of Variables	
A: Tool Issue Strategy	Level 1	Kitting
B: Part Scheduling Rule	Level 1	LPT
C: Part Family	Level 1	F1
D: Number of Machine	Level 1	3
E: Manufacturing Period	Level 1	1-Shift
F: Batch Size	Level 1	<=4
G: Permissible Tool Life	Level 1	90%
H: Magazine Capacity	Level 1	120

Table 13.2 Design Parameters and Value of Parameters according to the Taguchi Method

The complete list of the Taguchi method suggested experiments is presented in Tables 13.3.

13.4 Extended Workpiece-Oriented Computational Experiments

After conducting the 32 Taguchi method suggested experiments, it was apparent that most of the results, although they have some value, were either easily predictable or inadequate to deduce valuable conclusions. Therefore, it has been necessary to extend the number of computational experiments. After a careful analysis of the experiments conducted, it could be seen that much of the inadequacy comes from the parameter combinations especially the degree of levels of variables. Therefore, with the experience gained from the initial experiments, some of the parameter levels have been modified. Distorting causes such as very short manufacturing periods and the LPT, and GRP scheduling rules have been excluded from the initial parameter set (Ref. to Chapter 10) and a new reduced set has been created. The modified and reduced parameter set is tabulated in Table 13.4.

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Kitting	Diff.Kitt.	Single T.			
B: Part Scheduling Rule	EDD	SPT				
C: Part Family	Family I	Family 2	Family 3			
D: Number of Machine	4	6	8			
E: Manufacturing Period	3-Shift	10-Shift				
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%					
H: Magazine Capacity	60	120				

Table 13.4 Parameter set with reduced alternatives in workpiece-oriented experiments

In order to draw satisfactory conclusions from the experiments, it is necessary to have sufficient evidence. Therefore, it is necessary to have more computational experiments. This new set of extended experiments, thus, has been designed outside of the Taguchi method but with insight gained from the initial experiments. These extended experiments are aimed at gaining more understanding from the design of TMS permitting comprehensive parameter interaction analysis. The complete list of the extended workpiece-oriented experiments is given in Tables 13.5a and 13.5b.

Family	Job List	# MC	Batch Size	Prod. Peri.	Strat.	Schd. Rule	Perm. Tool Life	Magz. Capa.	X Ref.	Exp. No	Tool Inv.	MC Util.	Make-span	TRP
F1	15	3	4	1	K	LPT	90	120		T1	221	93	563	182
F1	15	3	4	1	K	LPT	90	60		T2	221	93	563	182
F1	15	3	50	1	K	SPT	90	120		T3	49	45	734	46
F1	15	3	50	1	K	SPT	90	60		T4	49	45	734	46
F1	15	4	4	1	K	GRP	90	120		T5	263	91	735	252
F1	15	4	4	1	K	GRP	90	60		T6	263	91	735	252
F1	15	4	50	1	K	SPT	90	120		T7	65	42	771	62
F1	15	4	50	1	K	SPT	90	60		T8	65	42	771	62
F1	15	4	50	1	DK	GRP	90	60		T9	60	62	635	60
F1	15	4	4	1	STK	GRP	90	60		T10	211	90	598	204
F1	15	4	4	1	STK	SPT	90	60		T11	59	94	687	60
F1	15	4	4	1	DK	SPT	90	120		T12	59	94	687	60
F2	40	5	50	1	DK	LPT	90	60		T13	45	46	611	41
F2	40	5	50	1	DK	LPT	90	120		T14	45	46	611	41
F3	70	5	8	1	STK	SPT	90	60		T15	385	85	734	380
F3	70	5	8	1	STK	SPT	90	120		T16	385	85	734	380
F3	70	5	50	3	STK	SPT	75	120		T17	387	84	1484	380
F3	70	5	50	10	STK	SPT	75	60		T18	464	72	4705	380
F2	40	5	8	3	DK	SPT	50	120		T19	492	87	1500	461
F2	40	5	8	10	DK	SPT	50	60		T20	746	82	2977	673
F3	70	6	50	3	STK	EDD	50	120		T21	456	87	1601	456
F3	70	6	50	10	STK	EDD	50	60		T22	606	89	3142	527
F2	40	6	8	3	DK	EDD	75	120		T23	469	96	1459	440
F2	40	6	8	10	DK	EDD	90	60	C21	T24	517	89	2246	496
F3	70	7	8	3	K	EDD	75	60		T25	771	75	1423	704
F3	70	7	8	10	K	EDD	75	120		T26	1108	75	3635	1038
F2	40	7	50	3	DK	EDD	50	60		T27	321	61	1519	234
F2	40	7	50	10	DK	EDD	50	120		T28	595	56	2724	464
F2	40	8	8	3	K	SPT	50	60		T29	648	78	1436	577
F2	40	8	8	10	K	SPT	50	120		T30	817	50	2976	706
F3	70	8	50	3	DK	SPT	75	120		T31	359	77	1396	347
F3	70	8	50	10	DK	SPT	75	120		T32	580	77	1396	496

Table 13.3 The Taguchi Method suggested computational experiments

Family	Job List	# MC	Batch Size	Prod. Peri.	Strat.	Schd. Rule	Perm. Tool Life	Magz. Capa.	X Ref.	Exp. No	Tool Inv.	MC Util.	Make-span	TRP
F1	15	4	4	3	DK	EDD	90	60	C13	W1	324	92	1374	309
F2	40	4	8	10	DK	EDD	90	60	C15	W2	529	97	3120	465
F3	70	4	8	3	DK	EDD	90	120		W3	292	95	1580	244
F1	15	6	50	3	DK	EDD	90	60	C37	W4	164	88	813	138
F2	40	4	50	10	DK	EDD	90	120	C39	W5	353	95	2840	299
F3	70	6	50	10	DK	EDD	90	120	C42	W6	520	96	2905	459
F3	70	8	50	10	DK	EDD	90	120	C26	W7	527	87	2410	465
F1	15	4	4	3	DK	SPT	90	60		W17	311	95	1520	296
F2	40	4	8	10	DK	SPT	90	60		W18	530	95	3192	483
F3	70	4	8	10	DK	SPT	90	120		W19	857	96	4396	822
F3	70	4	50	10	DK	SPT	90	120		W20	509	95	4494	442
F2	40	4	50	10	DK	SPT	90	120		W21	365	94	2810	311
F1	15	4	50	3	DK	SPT	90	60		W22	168	87	1237	140
F3	70	6	50	10	DK	SPT	90	120		W23	521	95	2981	454
F3	70	8	50	10	DK	SPT	90	120		W24	525	86	2459	460
F3	70	8	8	10	DK	EDD	90	120	C24	W25	836	91	2474	811
F3	70	4	8	10	DK	EDD	90	120	C17	W41	791	93	4859	756
F3	70	4+4	8	10	DK	EDD	90	120	C54	W47	837	92	2474	812
F3	70	4+4	50	10	DK	EDD	90	120	C53	W49	527	89	2261	468
F1	15	3	4	3	DK	EDD	90	60		W62	214	97	1473	197
F1	15	6	4	3	DK	EDD	90	60	C19	W63	357	96	956	341
F1	15	8	4	3	DK	EDD	90	60	C20	W64	393	92	754	385
F1	15	8	50	3	DK	EDD	90	60	C34	W65	162	72	742	143
F1	15	4	50	3	DK	EDD	90	60	C38	W66	167	88	1214	142
F1	15	3	50	3	DK	EDD	90	60		W67	169	93	1542	143
F1	15	3	4	3	DK	SPT	90	60		W68	283	98	1978	264
F1	15	6	4	3	DK	SPT	90	60		W69	314	92	1051	302
F1	15	8	4	3	DK	SPT	90	60		W70	272	90	809	264
F1	15	3	50	3	DK	SPT	90	60		W71	170	91	1564	138
F1	15	6	50	3	DK	SPT	90	60		W72	174	70	1013	150
F1	15	8	50	3	DK	SPT	90	60		W73	160	65	822	146

Table 13.5a Complete List of Extended Computational Experiments (1)

Family	Job List	# MC	Batch Size	Prod. Peri.	Strat.	Schd. Rule	Perm. Tool Life	Magz. Capa.	X Ref.	Exp. No	Tool Inv.	MC Util.	Make-span	TRP
F2	40	3	8	10	DK	EDD	90	120		W74	466	95	4235	443
F2	40	8	8	10	DK	EDD	90	120	C22	W75	561	90	1676	519
F2	40	3	50	10	DK	EDD	90	120		W76	351	91	3968	297
F2	40	8	50	10	DK	EDD	90	120	C36	W77	368	72	1878	314
F2	40	6	50	10	DK	EDD	90	120	C40	W84	358	78	2316	304
F2	40	3	8	10	DK	SPT	90	120		W78	499	95	4291	477
F2	40	6	8	10	DK	SPT	90	120		W79	520	72	2841	498
F2	40	8	8	10	DK	SPT	90	120		W83	539	93	1648	517
F2	40	3	50	10	DK	SPT	90	120		W80	359	97	3618	305
F2	40	6	50	10	DK	SPT	90	120		W81	363	93	1896	309
F2	40	8	50	10	DK	SPT	90	120		W82	371	75	1748	321
F3	70	3	8	10	DK	EDD	90	120		W90	567	96	4898	546
F3	70	6	8	10	DK	EDD	90	120	C23	W91	827	95	3181	804
F3	70	8	50	10	DK	EDD	90	120		W92	433	97	4846	381
F3	70	4	50	10	DK	EDD	90	120	C41	W93	507	95	4415	446
F3	70	3	8	10	DK	SPT	90	120		W94	820	96	5140	790
F3	70	6	8	10	DK	SPT	90	120		W95	866	89	3161	859
F3	70	8	8	10	DK	SPT	90	120		W96	860	87	2439	850
F3	70	3	50	10	DK	SPT	90	120		W97	455	95	4936	408
F2	40	6	8	3	DK	EDD	75	120		T23	469	96	1459	440
F2	40	6	8	10	DK	EDD	90	60	C21	T24	517	89	2246	496
F3	70	8	50	3	DK	EDD	75	120		T31	359	77	1396	347
F3	70	8	50	10	DK	EDD	75	120		T32	580	70	3021	496
F3	70	3	50	10	DK	EDD	90	120		W92	433	97	4846	381
F3	70	4	8	10	DK	EDD	90	120		W45	527	97	4164	466

Table 13.5b Complete List of Extended Computational Experiments (2)

Chapter 14
Interpretation of Workpiece-Oriented Approach Output

14.1 Introduction

This chapter introduces the reader to the interpretation and observations deduced from the workpiece-oriented approach computational experiments output which have been produced using the TMS design facility.

The output has been interpreted using primary and secondary sets of criteria which based on common sense as well as manufacturing practice.

14.2 Computational Experiments and Interpretation Criteria Sets

The experiments are centred around the tool issue strategies as well as the work families in both the Taguchi method suggested and extended experiments. Since most of the Taguchi method suggested experiments' results are less useful, the main body of interpretations is based on the extended computational experiments. In the reference to experiments, [W] refers to extended experiments and [T] refers to Taguchi method suggested experiments. The complete list of experiments with the reference numbers for both extended and the Taguchi method are given in Chapter 13.

During the execution of the workpiece-oriented approach computational experiments, a new form of tool issue strategy has been discovered and since it is potentially very effective in terms of tool requirement and tool inventory, this strategy has been named the Hybrid approach and is reported in a separate chapter. (Ref. to Chapter 17)

Two sets of criteria have been used as the basis of interpretation. The primary criteria which are given high priority:

* Tool inventory
* Machine utilization
* Tool requirements
* Makespan

The secondary criteria are:

* Tool life utilization
* Tool transportation utilization

The selection of the criteria is based on the literature survey (Ref. to Chapter 2) and manufacturing practice (common sense). They have been used consistently for every observation on the results of the experiments.

14.3 Analysing Output

Since the parameters participating in the design process make their contribution to design as well as interacting with each other, there are many conclusions to be drawn from the experiment results. Therefore, in order to draw clear conclusions it is necessary to structure the analysis. The analysis has been classified into three main areas. These are:

1. Tool Issue Strategies
2. Cell Structure
3. Manufacturing Requirements

Each of the areas has a number of sub-categories for detailed analysis. All the categories have been analysed against the primary and secondary criteria. The aim is to deduce clear, understandable and distinctive conclusions from the design of TMS research as well as to draw guidelines for designers.

14.4 Observations on the Result of Computational Experiments

The following observations have been made from the results of the computational experiments. In this section, primary and secondary criteria have been used to assess the output. The comparisons and the performance parameter results are tabulated in tables 14.1, 14.2 and 14.3. Each table is devoted to one family of parts and shows all fundamental comparisons, such as different machine groups, different batch sizes, different job scheduling rules and tool issue strategies. The tables contain the main reference data for this chapter and they are discussed in the text.

14.4.1 Tool Issue Strategies

a) Full Kitting Strategy - Due to the nature of this strategy, which concerns a complete tool exchange for each job, a large number of tools and tool inventory are required. Therefore, tool flow is very high especially when jobs are sent in small batches. This creates extensive tool traffic between STS and PTSs unnecessarily (Ref. to Experiments T25, T26, T29, T39) with too many sister tools involved in the tool traffic the majority of which are used very lightly. (Ref. to Supplementary output book - all the reported maximum tool requirements are calculated using the full kitting strategy therefore, when a referred is made to the maximum tool requirement it is a reference to the full kitting strategy as well). The strategy puts extensive pressure on tool transportation mechanism. Since a machine must be stopped frequently for the tool exchange, makespan is longer and machine utilization is less than for the other two workpiece-oriented strategies performance although not dramatically different. (Ref. to Experiments T1, T2, T5, T25, T26, T29, T30) The strategy is very flexible and does not need a sophisticated control system. Also, it is very easy to operate and implement. If there is a need, the strategy may be used considering two important points. First, if jobs are sent in small batches, the permissible tool life should be kept very low, 50% is recommended, to guarantee re-circulation of the complete tool list. (Ref. to Experiments T25, T26, T29, T30). Second, if it is intended to use tool life fully, the batch size should be large to increase the total operation times and use the tool life effectively. (Ref. to Experiments T3, T4, T7, T8)

b) Differential Kitting Strategy - As indicated in the Tables 14.1, 2 and 3, the strategy's primary characteristic, tool sharing between successive jobs leads to substantial tool savings in tool requirement and tool inventory. There is no significant change in makespan and machine utilization when the strategy is practised. However, since it requires less tool changing, the strategy gives a better performance in long period runs in terms of machine utilization and makespan. (Ref. to Experiments W18, W19, W20, W21, W23, W24, W25, W41)

The strategy largely depends on the part scheduling rules. If a scheduling rule assigns a very diverse list of jobs to the machines in terms of tool commonality, then the differential kitting strategy may perform poorly (Ref. to Experiments T24, W2, W18, W19, W41). Also a large number of machines increases the risk of ineffective differential kitting because there will be less tool commonality between successive batches assigned to the same machine. Table 14.1,2 and 3 show the differential kitting performance in different machine groups which prove that the large machine groups require more tool inventory despite less throughput time. The strategy needs a sophisticated control system to trace the common tools' remaining life. Since the strategy shares the available tool life between successive batches, tool life utilization is more effective in comparison to full to full kitting strategy. For example in Table 14.1, for three machine case, differential kitting requires less than one third of the tools full kitting strategy required whereas for eight machine case the differential kitting strategy saves virtually 50% of tools required by full kitting strategy.

c) Single Tools Strategy - Since all the tool types are assigned at the beginning of the manufacturing period, the strategy guarantees tool availability. However a sophisticated control mechanism is required to trace tool life and signal when tools become worn. The strategy uses tool life effectively especially in long term runs and for small size cells. When the number of machines is increased, the strategy's performance begins to decline in terms of tool requirement and tool inventory because of the assignment of identical tools to every machine, Table 14.1,2 and 3.

Since large batch applications consume tool life quickly, they put a great pressure on tool exchange which leads to extensive tool traffic between STS and PTS. Therefore, large batch applications give poorer performance with the single tools strategy in terms of tool transportation, (Ref. to Experiments T10, T11, T15, T16, T17) Since all the tool types required in production are assigned to every machine, the part scheduling rules do not affect the strategy dramatically.

14.4.2 Cell Structure

a) Number of Machines - One of the dilemmas faced in tool management is the number of machines in the cell. When the number of machines is increased, the tool requirement and tool inventory dramatically increase (Ref.to W6, W7, W23, W24, W25,W41, W47, W49). However, this depends somewhat on the part scheduling rule adopted. On the other hand, makespan begins decreasing and depending on the batch size, machine utilization may also decrease in large a machine group. Table 14.1, 2 and 3 indicate the different machine group response to key performance parameters. The observations on the result of large machine groups experiments can be summarized as follows:

- tool inventory increases
- tool requirement increases
- spent tools decreases
- tool life sharing decreases
- sister tools increases
- tool traffic between PTSs and STS increases
- overall average machine utilization decreases

- makespan decreases

(Ref. to Experiments, W6, W7, W23, W24, W25, W41, W75, W79, W83, W91, W91, W95, W96, T32).

b) Number of Cells - As observed in the large machine group experiments, the number of cell affect the tool requirements and tool inventory dramatically (Ref. to W47, W49). Since, in the multi-cell experiments, job scheduling is harmonized (any job, any cell, any machine) then the machine loading is also balanced and utilization and makespan performance have given even better results.

c) Permissible Tool Life - High permissible tool life results less tool requirements and tool inventory in large batch applications (Ref. to W4, W20, W21, W22, W23). Low permissible tool life has resulted high tool requirements and tool inventory. (Ref. to Experiments T20, T22, T32) However, if small the batch is in practice, a low permissible tool life gives a better result and guarantees the re-circulation of tools, (Ref. to Experiments T30, maximum column in W83). Low permissible tool life is a better solution for full kitting applications because of the control problem and complete change requirement (Ref. to Experiments T25, T26, T29, T30). High permissible tool life is a better solution for large batch applications because of high total operation times (Ref. to W5, W6, W65, W66, W67). It is also a better solution for differential kitting and single tools applications because tool life sharing is permitted (W20, W21, W22, W23).

There is no dramatic change in machine utilization or makespan performance in low permissible tool life applications because of frequent tool exchange (Ref.to T19, T20, T21, T22). Over long manufacturing periods both performances start to decline (Ref.to T18, T28, T30, T32). Also, in low permissible tool life applications over a long manufacturing periods, there is pressure on the transporter (Ref. T28, T30). Low permissible tool life gives better performance in terms of tool life utilization in both large and small batch applications (Ref. to Supplementary output book)

d) Machine Magazine Capacity - Two main parameters have played a major role in magazine loading. These are the machine work load and the tool issue strategies. Full kitting and differential kitting strategies always unload the magazine fully or partially for each new workload. Therefore there could be a very small possibility of a magazine capacity problem in large batch applications. However, because of the relatively large magazine capacities (60 and

120), used in the experiment, no magazine capacity problem has occurred. Although single tools by nature of strategy already needs large magazine capacity, even in the small magazine capacity applications it is not come across any magazine capacity bottleneck because of relatively balanced work load. The experiments have proved that a 60 tool magazine capacity for each machine is sufficiently large to run an 8 machine cell for up to a 10-shift manufacturing period (Ref. to T18, T20, T22, T24).

14.4.3 Manufacturing Requirements

a) Batch Size - It is found that batch size is one of the most important design factors which influences tool management system design. Using a small batch size gives great flexibility to balance the machine load and gives better performance in terms of machine utilization and throughput time, (Ref.to Table 1, 2 and 3 small batch size section). However, it is observed that all the poor performances in terms of tool requirement and tool inventory have been caused by using small batch size (Ref. to T25, T26, T30, W19, W25, W41, W47, W94, W95, W96). In particular full and differential kitting strategy applications, a small batch size caused an extensive tool inventory, very high tool traffic between STS and PTSs and a large number of sister tool requirement (Ref.to T25, T26, T29, T30). This also results in very ineffective tool life utilization and a heavy pressure on the transporter (Ref. to Supplementary Output book). The single tools strategy shows a better performance in small batch applications because of total small sub-operation times which require less and infrequent tool exchange.

Using a large batch size, however, gives poorer performance in terms of machine utilization and makespan because there is of less flexibility in machine loading. It is observed however, that large batch size gives better performance in terms of tool requirements and tool inventory because of high tool life utilization. Full kitting and differential kitting strategy applications can work with large batch applications successfully. In single tools strategy applications, because of unique nature of strategy which requires tools individually, there is a pressure on tool transportation. The Tables 14.1, 14.2 and 14.3 give a clear comparison of the small and large batch size applications performance.

b) Work Scheduling Rules:

Shortest Processing Time (SPT) - This rule schedules the jobs with shortest processing time first, therefore too many jobs with a great variety of tools are sent first, (Ref. to Experiments W18, W19, W20, W23, W24, W79, W83, W95, W96). This leads to releasing many jobs, with sometimes a very large number of tool requirements in the early shifts. Tool traffic is extensive and tool exchange very frequent. Rule has given poorer performance with the single tools strategy because of heavy pressure on the tool transporter. SPT works with short term manufacturing successfully in terms of machine utilization.

Workload density is not balanced and too many jobs with short process times put a strong pressure on tooling demand, tool changing and tool transportation in the early shifts of a multi-shift manufacturing period. However, in the later shifts, tool requirements and tool inventory decrease, consequently a light pressure is put on tool demand, tool changing and tool transportation, tools stay on the magazine longer and the initial magazine conditions are sufficient to meet the requirements. Graph 14.1. depicts the tool requirements distribution per shift for a 10-shift run.

Longest Processing Time (LPT) - This rule schedules the jobs with longer processing time first and hence a relatively small number of jobs are scheduled in early shifts in comparison to SPT. The pressure on the tool changing, tool requirements intensity and tool transportation is relatively very light and the initial magazine contains are sufficient to run in early shifts. However, the work load is unbalanced and the late shifts need more tools and tool changing instances.

Earliest Due Date (EDD) - Despite the great time pressure on the jobs, this rule delivers jobs in a more balanced manner, therefore the tool requirements in EDD rule applied experiments are relatively well balanced among the shifts in comparison with the previous two strategies. Graph 14.2 indicates the tool requirements per shift in an EDD application. Consequently, makespan and machine utilization have give a better performance in this scheduling rule.

However, the rule may send very a diverse jobs list which use a great variety of tools to the same machine because of due date pressure. This can cause a very high tool demand and affect the tool issue strategies which share tool life among the jobs such as differential kitting, and single tools strategies. Therefore, it may also cause very ineffective tool life usage simply because of the potential diversity of tool requirements in successive jobs regardless of what type of tool issue strategy is used (Ref. to Experiments W2, W6, W7, W25, W41, W74, W75, W90, W91, T24, T32). Despite the negative points above, this rule gives better performance overall in terms of tool requirements, tool inventory, makespan and machine utilization as well as transportation utilization (Ref. to W1, W2, W3, W4, W5, W6, W7).

Grouped Parts in Terms of Tools Used (GRP) - The GRP rule is effective only if the conditions are specifically designed to apply such a rule where grouped parts are sent strictly to the same machine and due date pressure is completely relaxed. (Ref.to Chapter 6 and 15) . Otherwise, does not give any preferable performance (Ref.to Experiments T5, T6, T9, T10) therefore this rule has been excluded in the extended experiments.

c) Work-Tool Matrix - The overall performance of tool management depends mostly on work-tool list used in the experiments. Since a matrix with only 70 part types and 76 tool types is used in the experiments one should be aware of this reality. However, the tool distribution is mostly homogeneous, except for more demand on finishing tools. Hence the work-tool list has not affected performance radically. Three part families have been used in all experiments (Ref. to Chapter 4). Since Family 1 contains only 15 part types, the large batch - large machine group experiments give poor results because of a lack of work load balance. (Ref. Table 14.1) Family 2 has performed rather strangely and most of the unexpected utilization figures have been generated by this family. For example, the general trend is towards poorer results when the number of machines is increased. However, using Family 2, the 4 and 6 applications give better performance using large batches rather than small batches. Family 3 has the most balanced work list, hence it gives an overall better performance in comparison to Family 1 and 2. The work-tool matrices used in this research are depicted in Appendix I, Tables 1a, 1b and 1c respectively.

d) Manufacturing Period - Although the manufacturing period has no significant direct effect on the performance of tool management except for natural gradually increasing demand in parallel with longer periods. The short manufacturing period, i.e 1-shift, did not give very useful results in the initial experiments to explore the TMS issues, therefore, it has been excluded in the extended experiments, (Ref. to Chapter 11). The manufacturing period has a serious interaction with part scheduling rules and it is found that the SPT rule has puts great pressure on the short manufacturing period and on tool requirement as well as tool transportation. In longer periods, this pressure is decreased in the late shifts or more balanced throughout.

# MC	Criteria	<=4						<=50					
		EDD			SPT			EDD			SPT		
		K	DF	STK	K	DF	STK	K	DK	STK	K	DK	STK
3	Tool Inventory	632	214	173	640	283	163	172	169	183	187	170	188
	MC Utilization (%)	97	97	97	96	98	98	83	93	83	92	91	92
	Makespan	1523	1473	1476	1497	1973	1441	1483	1542	1483	1564	1564	1565
	TRP	612	197	153	627	264	153	142	143	153	152	138	153
4	Tool Inventory	542	324	226	689	311	224	188	167	240	182	168	234
	MC Utilization (%)	97	92	97	95	95	96	89	88	88	87	87	87
	Makespan	1509	1374	1479	1553	1520	1501	1214	1214	1221	1238	1237	1240
	TRP	520	309	204	669	296	204	152	142	204	152	140	204
6	Tool Inventory	685	357	322	681	314	318	185	164	339	176	174	330
	MC Utilization (%)	96	96	96	92	92	93	63	88	62	71	70	71
	Makespan	992	956	957	1102	1051	1051	1139	813	1167	1013	1013	1047
	TRP	669	341	305	669	302	305	152	138	305	152	150	305
8	Tool Inventory	685	393	424	677	272	424	171	162	427	166	160	422
	MC Utilization (%)	92	92	93	89	90	90	56	72	55	66	65	65
	Makespan	793	754	754	885	809	832	967	742	1003	822	822	851
	TRP	669	385	408	669	264	408	152	143	408	152	146	408

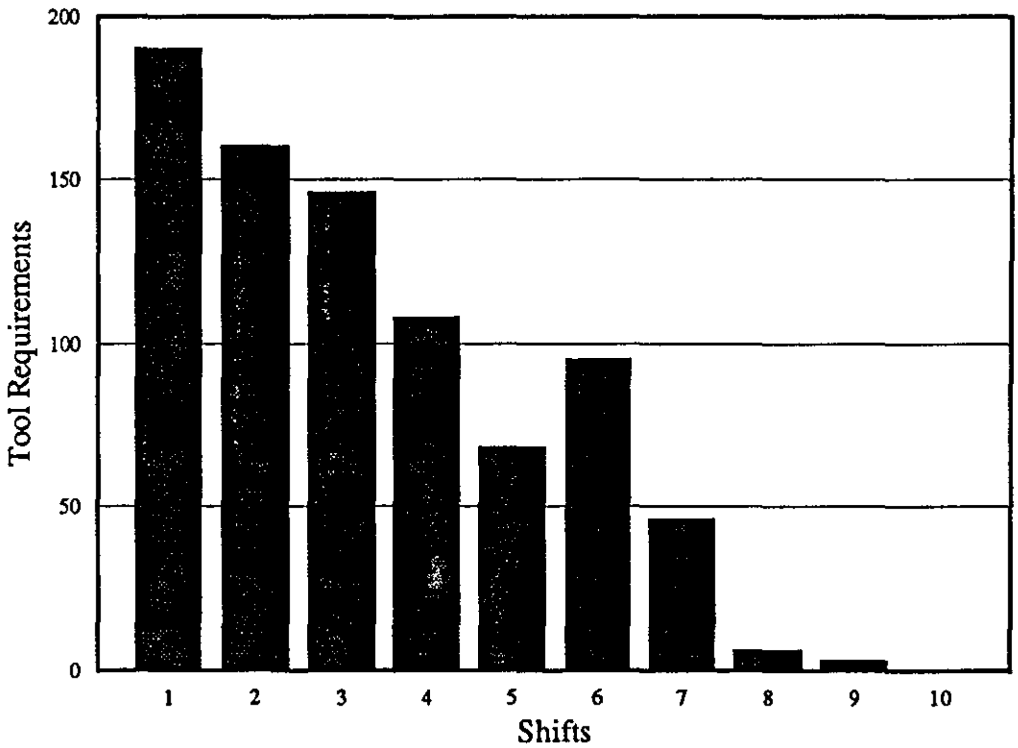
Table 14.1 Family 1 Comparison Table

# MC	Criteria	<=8						<=50					
		EDD			SPT			EDD			SPT		
		K	DF	STK	K	DF	STK	K	DK	STK	K	DK	STK
3	Tool inventory	688	466	226	688	499	235	385	351	267	398	359	267
	MC Utilization (%)	96	95	96	95	95	95	91	91	91	97	97	97
	Makespan	4247	4235	4227	4321	4291	4254	3973	3968	3941	3638	3618	3603
	TRP	665	443	213	665	477	213	331	297	213	344	305	213
4	Tool inventory	709	529	348	724	530	278	385	353	338	399	365	338
	MC Utilization (%)	97	97	97	72	95	77	95	95	95	94	94	94
	Makespan	3147	3120	3102	4191	3192	4017	2842	2840	2837	2817	2810	2808
	TRP	665	465	284	659	483	284	331	299	284	344	311	284
6	Tool inventory	686	517	447	688	520	448	385	358	480	399	363	490
	MC Utilization (%)	90	89	90	72	72	75	78	78	77	93	93	91
	Makespan	2249	2246	2234	2871	2841	2776	2321	2316	2364	1902	1896	1912
	TRP	665	496	426	665	498	426	331	304	426	344	309	426
8	Tool inventory	707	561	610	688	539	580	385	368	622	394	371	618
	MC Utilization (%)	90	90	90	93	93	93	72	72	71	75	75	75
	Makespan	1692	1676	1691	1661	1648	1653	1881	1878	1904	1751	1748	1779
	TRP	665	519	568	665	517	568	331	314	568	344	321	568

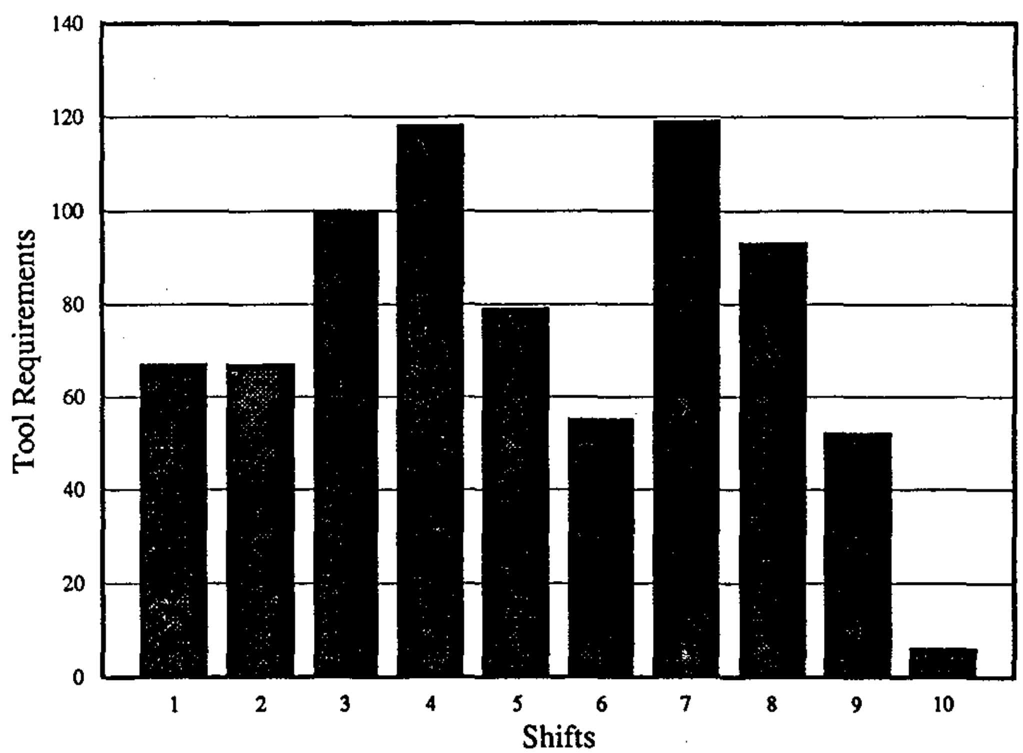
Table 14.2 Family 2 Comparison Table

# MC	Criteria	<=8						<=50					
		EDD			SPT			EDD			SPT		
		K	DF	STK	K	DF	STK	K	DK	STK	K	DK	STK
3	Tool Inventory	840	567	249	857	820	262	485	433	280	557	455	275
	MC Utilization (%)	97	96	98	97	96	97	97	97	98	95	95	96
	Makespan	4917	4898	4811	4903	5140	4811	4851	4846	4802	4911	4936	4858
	TRP	819	546	213	823	790	213	433	381	213	510	408	213
4	Tool Inventory	1063	791	331	1062	857	339	567	507	365	577	509	371
	MC Utilization (%)	92	93	95	97	96	98	95	95	96	95	95	96
	Makespan	4913	4859	4761	4412	4396	4245	4423	4415	4373	4471	4494	4411
	TRP	1038	756	304	1027	822	304	510	446	304	510	442	304
6	Tool Inventory	1051	827	625	1036	866	465	571	520	517	577	521	523
	MC Utilization (%)	94	95	95	89	89	92	96	96	96	95	95	95
	Makespan	3213	3181	3167	3202	3161	3054	2913	2905	2907	2989	2981	2982
	TRP	1038	804	450	1027	859	450	510	459	450	510	454	450
8	Tool Inventory	1063	836	633	1037	860	618	572	527	670	575	525	673
	MC Utilization (%)	92	91	92	87	87	87	87	87	87	86	86	85
	Makespan	2502	2474	2417	2477	2439	2396	2418	2410	2434	2466	2459	2507
	TRP	1038	811	598	1027	850	598	510	465	598	510	460	598

Table 14.3 Family 3 Comparison Table



Graph 14.1 - Tool Requirements in 10-Shift period in an SPT application.



Graph 14.2 - Tool Requirements in 10-Shift period in an EDD application.

Chapter 15
Design of Tool Oriented Approach Computational Experiments

15.1 Introduction

This chapter concerns with the design of tool oriented approach computational experiments and the role of cluster analysis. There are considerable differences between the parameter variables used for the tool oriented and workpiece-oriented experiments, resulting in a less extensive number of computational experiments for dynamic cluster analysis.

The chapter further explains the planning and development of the family of computational experiments.

15.2 Scope of the Tool Oriented Experiments

The tool-oriented approach experiments employ strategies based on a cluster analysis. The strategies have been developed from previous research work in the laboratory.

The original model developed by De Souza and Bell [67] has the capability to cluster tools and parts but model has severely limited capacity which does not consider multiple machines, transfer batch size, magazine capacity or the manufacturing period. Also the original model clusters the part-tool matrix once only which, most of the time, does not produce acceptable cluster sets.

In this research, a new cluster analysis approach has been developed using the same algorithm. The analysis has been made dynamic by adding the capability to cluster any number of times and reorganize the initial part-tool matrix. (Ref. to Chapter 7) The new form of dynamic cluster analysis (DCA) considers new parameters such as the number of machines, transfer batch size, manufacturing period and magazine capacity which makes the model more realistic. DCA has proved to be a valid, efficient and alternative solution to TMS design problems.

The tool-oriented experiments are aimed at testing the design approach against the key points of TMS performance such as tool requirement planning, effective tool life utilisation, tool inventory, tool transportation and hardware planning (PTS, STS and transporter capacities) to gain more understanding in the design of TMS.

The design and planning of the family of computational experiments, is focussed on the areas of curiosity that should be examined such as multi-clustering in different manufacturing configurations and the behaviour of cluster analysis in such systems. The experiments are used to find how cluster analysis is an effective solution to TMS design problems.

Cluster analysis depend mostly on the job list structure as well as the manufacturing system hardware configuration. The identification of cluster sets is much more dependent on user experience and the assumptions allowed at the beginning of the experiment. Since there is no widely accepted rule set governing the application of cluster analysis it is intended to set a range of rules to make cluster analysis more powerful and structured.

15.3 The Design of Cluster Analysis Computational Experiments

The tool-oriented computational experiments using DCA have been created using the experience gained from the previous computational experiments in which the Taguchi method was used as a primary design tool. A similar logic has been applied to that used in the Taguchi aided workpiece-oriented approach experiments.

In order to cover the wide range of systems available in practice and since not all the job lists give obvious cluster sets, three sets of job lists and different hardware configurations are used to build up the experiments. The number of machines and transfer batch size are two important factors which affect TMS design considerably. The experiment design is planned to specifically test these two factors' influences as well as test other influences on dynamic cluster analysis.

The parameter set and the variation of parameters are tabulated in Table 15.1. The computational experiments created are tabulated in Tables 15.2a, 2b and 2c. The tables are grouped according to the part families applied in the experiments. These experiments which overlap with the workpiece-oriented experiments are cross referenced. The conclusions drawn from the computational experiments are given in the next chapter (Ref. to Chapter 16).

15.4 Basic Concepts of Dynamic Cluster Analysis

As indicated in Figure 15.1a, the workpiece-oriented approach simply distributes the jobs to any available machine, according to a predetermined schedule. This it helps to reduce throughput time and increase machine utilization by of balancing the work load.

By contrast, cluster analysis has a fundamentally different approach to job assignment to machines since it creates its own job schedule. In the simple clustering approach, once jobs and parts are clustered, the cluster sets and associated jobs could be sent to any associated idle machine as depicted in Figure 15.1b. Although this way increase the total throughput time, a considerable saving in tools can be achieved in comparison to the workpiece-oriented approach.

In order to increase the efficiency of clustering analysis in terms of the basic performance criteria, i.e. tool inventory, tool requirement, etc. another concept has been introduced. In this lean inventory approach, the clustered tools and associated jobs may be sent to only one machine depending on each cluster set's throughput time. The approach is depicted in Figure 15.1c and although it may increase the throughput time and may decrease machine utilization, the approach saves the tool inventory further and offers a powerful economic tooling solution. The idea is implemented in two steps. First, the algorithm checks each emergent cluster throughput time. If the throughput time is equal or less than remaining manufacturing period for machine, the cluster is sent to that machine as a whole. If the cluster set's throughput time is longer than this time, the cluster set must be split into smaller sets which are sent to different available machines in the same manner.

The rule set which is embedded in the structure and mechanism of the DCA concept is described in the next section.

15.5 Rule Set

A set of rules have been developed to make dynamic cluster analysis more standardised as well as more powerful. The rules are listed below:

1. A tool which is a member of a cluster set may be used by different jobs on the same machine as long as enough tool life is available,

2. If there is 50% commonality between the tool lists required by jobs, then the tool lists are included in a cluster set.

3. If the job's batch size is large and causes either a magazine capacity or a machine bottleneck problem, this batch may be split further into smaller transfer batches which use exactly the same tools types.

4. A cluster set may be formed by jobs of a single part type.

5. If the time to process the jobs in a with cluster set is longer than the planned/remaining manufacturing period, the cluster set may be split into smaller cluster sets which can be sent to different machines.

6. After the first clustering attempt, the emerging cluster sets are distributed to the available machines. Then the allocated jobs are removed from the part-tool matrix thus creating another smaller matrix for the next clustering attempt. This process is repeated until all the cluster sets and associated jobs are distributed to the machines.

7. In a cluster set, there may be several associated jobs. The sequence of jobs may be created according to one of the sequencing rules, (i.e. SPT, LPT, EDD, FIFO, etc.)

8. If the tool population of a cluster set is more than the available machine magazine capacity, the cluster set may be split into smaller sets by reducing either the batch size of jobs or by removing one of the associated jobs from the set.

9. If there is commonality between cluster sets scheduled to the same machine successively, available tool lifes are checked. If there are tools which are common and have enough life, these tools are kept on machine and the rest are removed. This technique forms a separate strategy and is called *the dynamic clustering differential kitting strategy (DCDK).*

10. If emergence of obvious cluster sets is blocked by some jobs which use diverse tools, these jobs may be scheduled individually until a cluster set emerges.

11. If no obvious cluster set emerges because of the job list structure, some of the jobs which have a larger than specified batch size, may be split into several jobs which have small batch sizes.

10. The cluster set and the associated jobs are sent to the least utilised idle machine.

11. All the suboperations of the jobs are processed on the same machine.

15.6 Dynamic Clustering Full Kitting

Some of the cluster analysis computational experiments are devoted to full kitting experiments. The logic of the operation of the dynamic clustering full kitting strategy has been given in Chapter 7 and is described in the flowchart Figure 15.2. Tool sharing is not permitted between successive cluster sets and when a new cluster set is assigned to a machine, the previous tool cluster set is always removed regardless of tool commonality and empty pockets in the magazine.

15.7 Dynamic Clustering Differential Kitting

Dynamic clustering differential kitting is an enhanced form of the full kitting strategy. The approach allows tool life sharing and concentrates on the commonality of tools between successive cluster sets on each machine. If there is commonality between the previously assigned cluster set and the new cluster set, then the remaining tool life is checked. If there is sufficient life, strategy keeps the previous tools and removes the uncommon tools to create space in the magazine for the new tools. Figure 15.3 depicts the logic of the algorithm applied. Differential kitting uses the available tool life further improving the effectiveness of the strategy.

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	Full Clustering	Diff. Clustering				
B: Part Scheduling Rule	Internal					
C: Part Family	Family I	Family 2	Family 3			
D: Number of Machine	4	6	8			
E: Manufacturing Period	1-Shift	3-Shift	10-Shift			
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%	75%				
H: Magazine Capacity	60	120				

Table 15.1 Main design factors involved in Tool-oriented experiments

Family of Run	Job List	Manuf. Period	# MC	Batch Size	Strat.	Magaz. Cap.	Perm. Tool Life	Exper. No.	X Refer.	# Cluster Trial	Tool Invent.	MC Utilis.	Make-span (min)	Tool Requi.	Additional Comment
F1	15	3	4	4	FC	60	90%	C1		8	277	92	1787	258	
F1	15	3	6	4	FC	60	90%	C7		8	264	95	1153	245	
F1	15	3	8	4	FC	60	90%	C8		8	267	77	948	248	
F1	15	3	4	4	DC	60	90%	C13	W1	8	205	92	1787	192	
F1	15	3	6	4	DC	60	90%	C19	W63	8	234	95	1153	216	
F1	15	3	8	4	DC	60	90%	C20	W64	8	236	77	948	218	
F1	15	3	8	10	FC	60	90%	C27		15	176	85	682	154	
F1	15	3	6	10	FC	60	90%	C28		15	176	91	852	154	
F1	15	3	8	10	DC	60	90%	C29		15	159	85	682	144	
F1	15	3	6	10	DC	60	90%	C30		15	153	91	852	138	
F1	15	3	8	50	FC	60	90%	C33		5	128	70	713	112	
F1	15	3	8	50	DC	60	90%	C34	W65	5	128	70	713	112	
F1	15	3	6	50	DC	60	90%	C37	W4	5	124	77	860	104	
F1	15	3	4	50	DC	60	90%	C38	W66	5	119	81	1235	97	
F1	15	3	8	124	DC	60	90%	C43		6	183	48	1364	139	
F1	15	3	8	62	DC	60	90%	C44		6	150	81	708	122	
F1	15	3	8	25	DC	60	90%	C45		8	164	81	713	151	

Table 15.2a Complete List of Family I DCA Computational Experiements

Family of Run	Job List	Manuf. Period	# MC	Batch Size	Strat.	Magaz. Capac.	Perm. Tool Life	Exper. No.	X Refer.	# Cluster Trial	Tool Invent.	MC Utilis.	Make-span (min)	Tool Requi.	Additional Comment
F2	40	10	4	8	FC	120	90%	C3		22	333	89	3062	263	
F2	40	10	6	8	FC	120	90%	C9		22	335	82	2251	270	
F2	40	10	8	8	FC	120	90%	C10		22	351	77	1720	278	
F2	40	10	4	8	DC	120	90%	C15	W2	22	312	89	3062	242	
F2	40	10	6	8	DC	120	90%	C21	T24	22	304	82	2251	242	
F2	40	10	8	8	DC	120	90%	C22	W75	22	331	77	1720	258	
F2	40	10	8	10	FC	120	90%	C31		15	334	73	1801	272	
F2	40	10	8	10	DC	120	90%	C32		15	334	73	1801	272	
F2	40	10	8	50	FC	120	90%	C35		15	336	85	1677	268	
F2	40	10	8	50	DC	120	90%	C36	W77	15	319	85	1677	249	
F2	40	10	4	50	DC	120	90%	C39	W5	15	315	93	2880	240	
F2	40	10	6	50	DC	120	90%	C40	W84	15	321	88	2044	246	
F2	40	10	8	124	DC	120	90%	C46		15	309	85	1957	245	
F2	40	10	8	62	DC	120	90%	C47		15	296	92	1506	232	
F2	40	10	8	25	DC	120	90%	C48		15	306	83	1683	248	

Table 15.2b Complete List of Family II DCA Computational Experiments

Family of Run	Job List	Manuf. Period	# MC	Batch Size	Stra.	Magaz. Capac.	Permis. Tool Life	Exper. No.	X Refer.	# Cluster Trial	Tool Invent.	MC Utilis.	Make-span (min)	Tool Requi.	Additional Comment
F3	70	10	4	8	FC	120	90%	C5		24	561	92	4653	458	
F3	70	10	6	8	FC	120	90%	C11		24	535	86	2980	433	
F3	70	10	8	8	FC	120	90%	C12		24	515	83	2428	429	
F3	70	10	4	8	DC	120	90%	C17	W41	24	513	92	4653	410	
F3	70	10	6	8	DC	120	90%	C23	W91	24	484	87	2980	382	
F3	70	10	8	8	DC	120	90%	C24	W25	24	488	83	2428	402	
F3	70	10	8	50	FC	120	90%	C25		13	466	78	2552	393	
F3	70	10	8	50	DC	120	90%	C26	W7	13	425	78	2552	360	
F3	70	10	4	50	DC	120	90%	C41	W93	13	422	96	4329	342	
F3	70	10	6	50	DC	120	90%	C42	W6	13	428	88	2651	350	
F3	70	10	8	62	DC	120	90%	C50		13	426	89	2211	342	
F3	70	10	8	25	DC	120	90%	C51		19	469	95	2116	409	
F3	70	10	8	10	DC	120	90%	C52		22	424	90	2314	351	
F3	70	10	8	PRC	DC	120	90%	C49		11	460	74	2646	360	
F3	70	10	4+4	50	DC	120	90%	C53	W49	14	444	77	2537	360	
F3	70	10	4+4	8	DC	120	90%	C54	W47	24	496	89	2428	401	

Table 15.2c Complete List of Family III DCA Computational Experiments

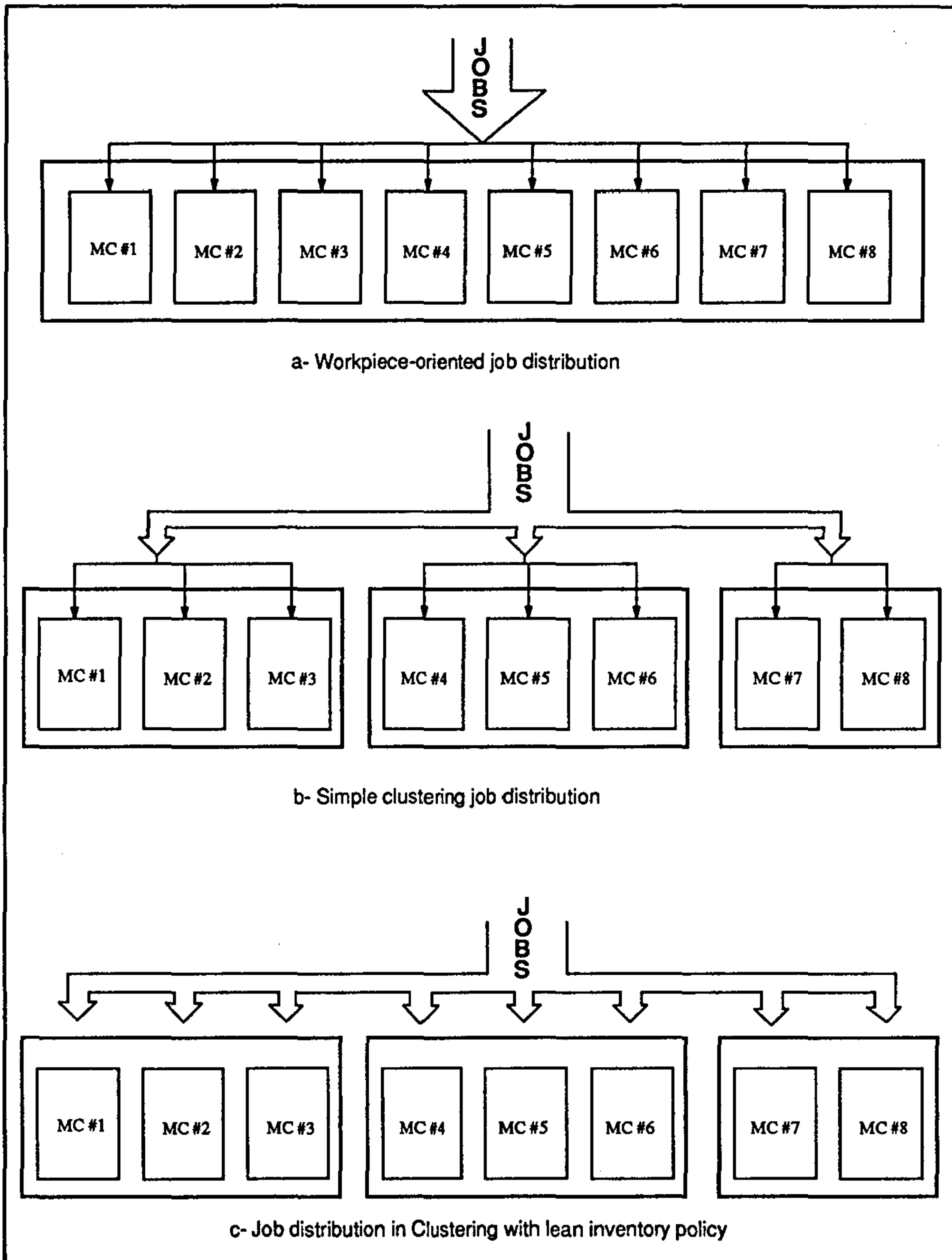


Figure 15.1 Job Distribution Concepts in Workpiece-Oriented and Cluster Environment — LUT - FMS Research Group

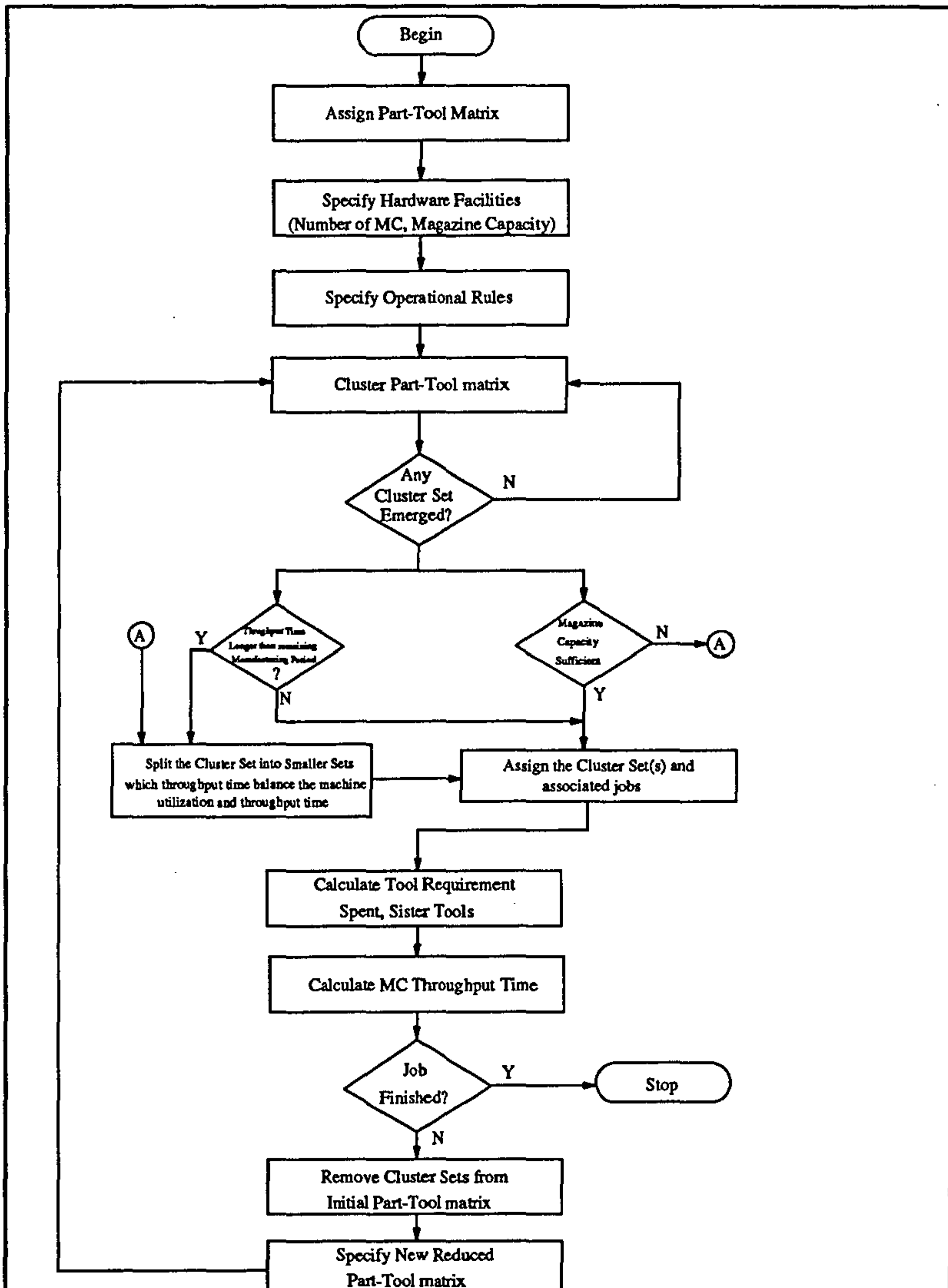


Figure 15.2	Dynamic Cluster Analysis (Full Kitting)	LUT-FMS Research Group

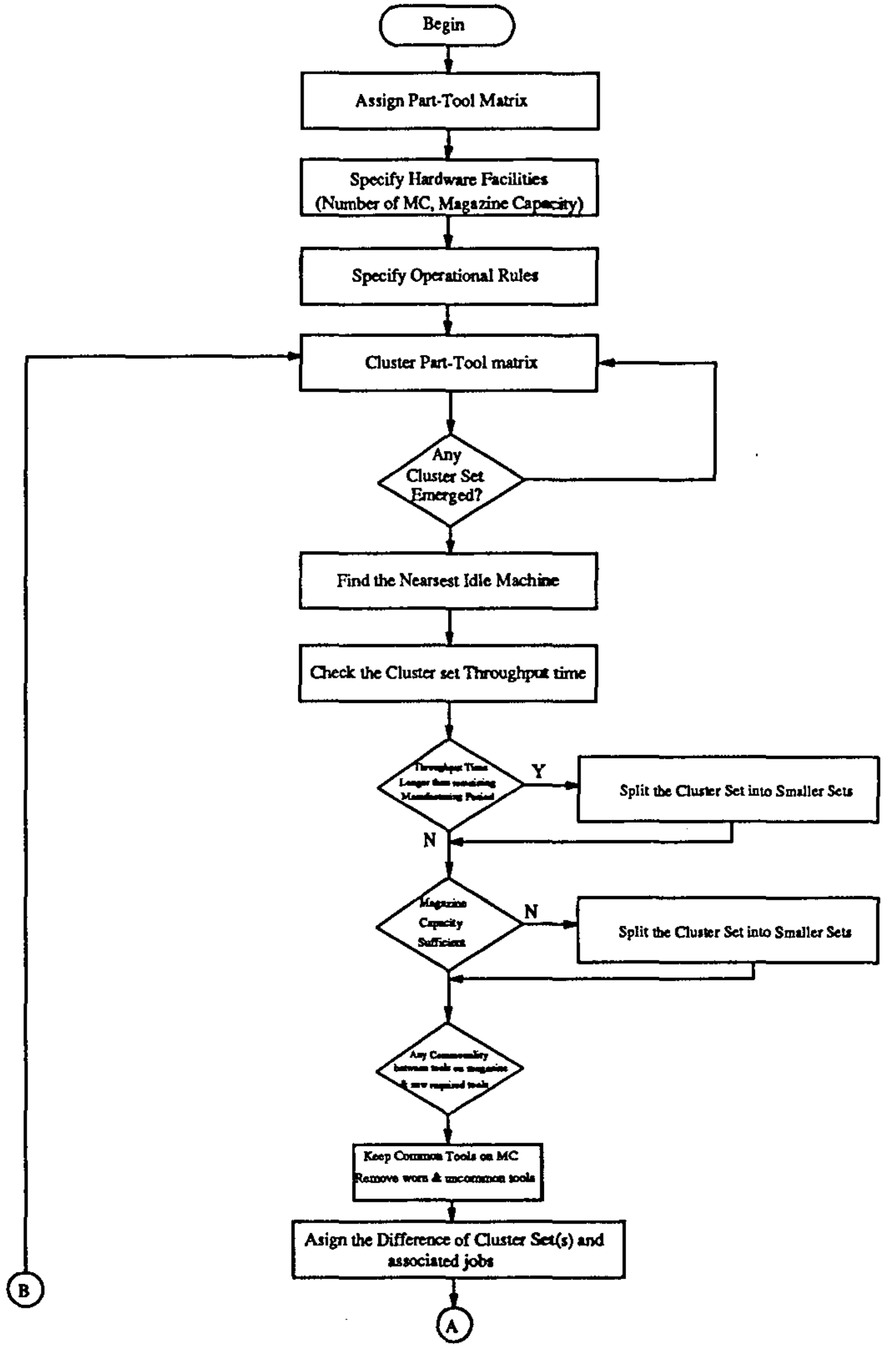


Figure 15.3a	Dynamic Cluster Analysis - Differential Kitting	LUT-FMS Research Group

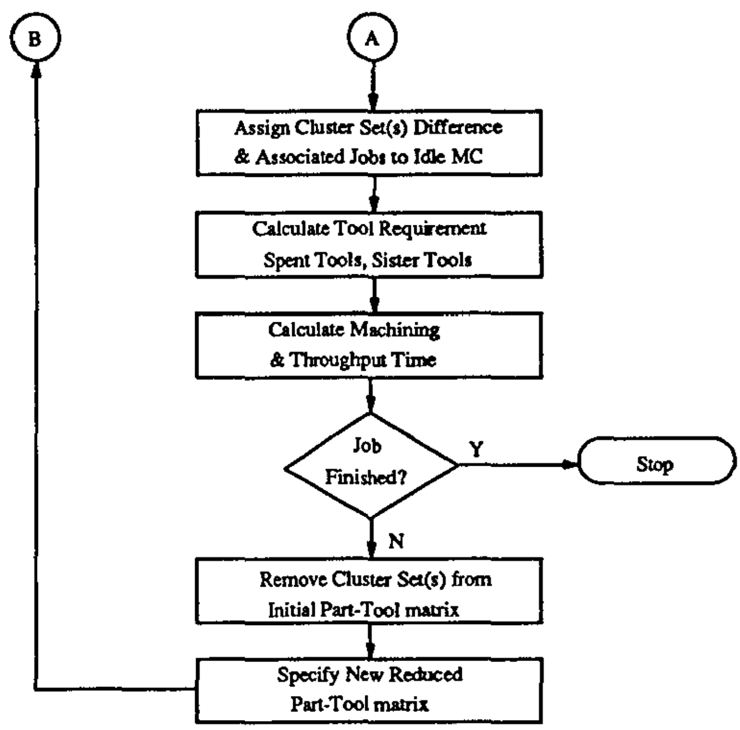


Figure 15.3b	Dynamic Cluster Analysis - Differential Kitting	LUT-FMS Research Group

Chapter 16
Interpretation of Tool-Oriented Approach Output

16.1 Introduction

This chapter presents the interpretation of the tool-oriented approach computational experiments output which have been produced using the Dynamic cluster analysis design facility. Output is interpreted using the primary and secondary sets of criteria, as for the workpiece-oriented approach results interpretations (Chapter 14).

16.2 Clustering Techniques

The cluster analysis approach [67] has been enhanced by making it dynamic and more realistic by adding new design parameters. (Ref. to Chapter 15) Two strategies have been applied to the tool-oriented approach experiments, dynamic clustering full kitting (DCFK) and dynamic clustering differential kitting strategies (DCDK). At the end of the initial analysis it was realized that differential kitting is more efficient in terms of tool inventory and tool requirement, therefore most of the experiments have been practised using this strategy. The experiments' output proved that this strategy further enhances the already powerful approach, cluster analysis, and gives better results in terms of tool inventory, efficient use of tool life and machine utilisation.

Both strategies have been applied under the strict control rule set which has been invented to make the cluster analysis approach generally applicable and more powerful.

16.2.1 The Issue of Rule Set

For the task of dynamic cluster analysis further basic points have to be identified within the base of evidence provided in this research. It is not possible to carry out clustering across the diverse range of conditions without a set of rules.

An ad hoc rule set has been invented and set out in Chapter 15, based on the experience gained in the research. Since dynamic cluster analysis needs user interaction and decisions for the justification of emerging cluster set(s) throughout the clustering (Ref. to Chapter 15), a rule set is needed to make dynamic clustering standardised and more powerful as well as making the procedure less complex.

Further, the rules have been invented to overcome the difficulties imposed by either manufacturing requirements such as, large batch size and scheduling rules or the cell structure such as the number of machines and the number of cells. (Ref. to Chapter 15). The rules are vitally important to achieve streamlined clustering. They have been set out to make the clustering approach generally applicable in different conditions where the parameter interactions might force the consideration special conditions.

16.2.2 Dynamic Clustering Full Kitting - Dynamic Clustering Differential Kitting

Two clustering strategies have been applied in dynamic cluster analysis using the same parameter set, full kitting and differential kitting. (Ref. to Chapters 7 and 15).

As indicated in Table 16.1 the DCDK is proven to be more efficient and give better result in terms of tool inventory and effective usage of tool life. This strategy can save tool requirement and tool inventory by up to 26% compared with DCFK strategy, (Table 16.1, Experiments 1,13). DCDK is very effective especially when a small batch size-small machine group is practised (Ref. to Table 16.1, Experiments 13, 15, 17, 21) (Ref. to Section 16.4.1) Both approaches give virtually the same performance when a large batch is practised, (Table 16.1, Experiments 25/26). However, DCDK still has an advantage even when a large batch is practised, due to the possibility of tool commonality and tool life sharing between successive cluster sets. (Ref. to Experiments 35, 36 in Table 16.1)

The DCDK uses available tool life very effectively which makes the strategy very efficient and powerful, so that it is a powerful solution to TMS problems. Further, the strategy supports high machine utilisation and less tool transport visits to machines due to less tool load/unload interruptions It is more suitable for uninterrupted production where in most cases workstations are equipped with a medium size magazine (60-tool capacity) which is sufficient to hold all the tools needed for the entire manufacturing period or at least for a three-shift manufacturing period.

16.2.3 Frequency of Clustering

In the development of cluster analysis, there are different conditions to be considered. It is necessary to consider a number of decisions which are made to establish and re-establishing clustering during the manufacturing period required. This has led to the view that the cluster analysis is a dynamic process.

Whilst an efficient result may be obtained, a balance has to be drawn between clustering infrequently and inefficiently and clustering more frequently which might lead to the other extreme point of putting pressure on the work-tool list within the cell.

Dynamic clustering is a broadly more effective technique and some results produced show the significance of the frequency of dynamic clustering (Ref to. Table 16.1, Experiments 5,11,12,17,23,24). Figure 16.1 shows number and frequency of the clustering decisions made in approximate per shift in a dynamic clustering experiment.

When a frequent clustering approach is adopted, to avoid putting too much over pressure on cell as well as attempting to balance the work load on the machines, jobs are not allocated to every machine unless a perfect cluster set emerges and idle machine is available. Frequent clustering, in reality, does not put too much pressure on the cell. Instead, it refines the cluster sets which would be created by an infrequent clustering approach where jobs are grouped in a limited repetition, mostly distorting the quality of cluster set. Figure 16.2 compares the cluster set quality achieved by frequent and infrequent clustering decisions.

16.3 Analysing the Tool-Oriented Approach Output

The key interactions between four primary performance indicators namely, tool inventory (TI), machine utilisation (MU), makespan (M) and tool requirements (TR) have been considered as the primary criteria for analysis. TI/MU/M/TR have been considered as functions of fundamental design parameters. The level of interactions as well as understanding from the interactions are presented, based on the experiments designed. Further, to gain more understanding from the results a secondary set of performance criteria has been used as in the analysis of the workpiece-oriented experiments results.

16.3.1 Clustering Techniques

Tool utilisation is further improved when DCDK strategy is practised. As a result tool requirement, sister tool requirement and tool inventory are significantly reduced, (Ref. to Table 16.1. Experiments 1/3, 3/15, 5/17, 7/19). As a result of less tool requirement, the transportation is used less in comparison to full kitting. Graph 16.1 shows the transportation visits approximately per shift, over a 10-shift period, for a 4 machine DCDK strategy experiment.

Due to the need for less tool changing (loading/unloading) using DCDK, the machine down time is reduced. In a short manufacturing period, this is not significant, but in a longer term manufacturing period, it is believed that less tool changing may make an important contribution increased machine utilisation and to reduced throughput time.

16.3.2 Frequency of Clustering

Although the frequency of clustering depends more on the size and structure of work-tool list, it has a significant effect on handling cluster analysis and the result of the cluster analysis.

Due to diversity in the work-tool list clustered, some of the jobs may block emerging cluster set(s) which may cause very poor grouping. These type of low quality cluster sets can cause very inefficient tool utilisation, high tool inventory and longer throughput time. In order to overcome this difficulty and to improve the quality of the cluster sets, repeated clustering is an efficient solution and makes clustering more realistic as well as more applicable to any work-tool list.

Since repeated clustering increases the quality of cluster sets, the use of tool life is increased and the tool requirement and tool inventory are decreased. Although there is no remarkable change in machine utilisation when either of the strategies is applied, over longer term manufacturing periods, depending on the quality of the cluster sets created, frequent clustering gives a better performance than infrequent clustering.

16.3.3 Cell Structure

The interactions between, hardware parameters such as the number of machines and cell have significant effects on the performance of a tool management system.

16.3.3.1 Number of Machines

One of the most important factors that affects the TMS performance is the number of machines available in the manufacturing system.

As indicated in Table 16.2 dynamic cluster analysis works very efficiently in a small group of machines because of the high possibility of identical jobs or jobs that have high tool commonality, visiting the same machine. This results in high tool utilisation, less tool requirement, less tool inventory as well as high machine utilisation. In a large machine group, although overall throughput time is dramatically decreased, the tool requirement and tool inventory are increased, machine utilisation and tool life utilisation are decreased. This is regardless of the magazine policy practised, e.g. for instance, in Table 16.2, tool inventory is 205 and the machine utilisation is 92% in 4 machine cell processing family 1, whereas tool inventory is 234 and 236 and the machine utilization is 95% and 77% in the 6 and 8 machine cells respectively.

In a large machine group, often at the expense of increased tool requirement and tool inventory, some perfect cluster sets have to be divided into smaller cluster sets and sent to different machines in order to balances the machine load increase the machine utilisation. In contrast to the machine load balancing problem, if it is intended to increase the tool utilisation and reduce the tool inventory, this might be achieved at the expense of poor machine utilisation. For example in Table 16.2 for Family 3, 3 machine large batch application machine utilization is 96 % and requires 422 tool for inventory whereas the same family in 8 machine group cell requires 428 tool for inventory but the machine utilization has decreased to 78%.

Since machine load balancing is relatively easy in a small machine group, and generally there is no need to further divide cluster sets performance is better in terms of tool and machine utilisation performance. Further, although throughput time is longer than for large machine group cases, the machine utilisation as well as tool life utilisation is dramatically increased. The

DCDK strategy in particular works very efficiently due to high tool life sharing. For example, in Table 16.2, the machine utilization is 92%, 89%, and 92% for all families which all have 4 machine cells respectively.

16.3.3.2 Number of Cell

As indicated in Table 16.3 dynamic cluster analysis reacts to a multi-cell situations virtually the same way as it reacts to a reacted to multi-machine situation. It is observed that it is less efficient in a multi-cell environment in terms of tool utilisation and tool inventory but gives a better performance for machine utilisation. The throughput time does not change between a single and multi-cell situation.

Since there is no cell restriction for the cluster sets (any cluster set to any cell) the performance parameters have not been affected radically and they have reacted to multi-cell as reacted large machine group. But it is believed any route restriction will affect the performance radically.

16.3.3.3 Permissible Tool Life

Since lower permissible tool life is applied where there is a lack of control to trace available tool life, especially when small batch size and diverse jobs are practised, to increase tool life utilisation allowing the use of a certain percentage of tool life which guarantees a certain percentage of unused tool life and re-circulates the same tools.

Dynamic cluster analysis is aimed at using a high percentage of available tool life. Therefore, a lower permissible tool life does not have a significant effect on tool requirement and tool inventory and dynamic cluster analysis by nature already needs a sophisticated control mechanism to trace available tool life.

When the DCDK strategy is practised, the use of available tool life is very high and keeping permissible tool life low increases the sister tool flow. The large batch size applications have a similar influence on permissible tool life since there will be an increased number of identical components which will use the same tool type. This helps to increase the tool life utilisation as for DCDK applications and keeping permissible tool life low increases the circulating tools on the shop floor.

16.4 Manufacturing Requirements

Four of the factors in the parameter set used to design the experiments all concerned with the manufacturing requirements, and have a significant effect on the design of TMS. Some of the parameters that are involved in the design may be manipulated by the user. This can give an opportunity to experiment with different levels of parameters which gives more understanding in the relationships of the parameters.

Each of four parameters has been considered and tested against the key performance criteria. These are summarized in the following section.

16.4.1 Batch Size

One of the most critical parameters is batch size which influences the tool management system design remarkably. Working with two extremes of batch size, small and large, naturally has advantages and disadvantages.

Whilst working with a small batch size can give high machine utilisation and shorter throughput time, the use of tool life is not very effective, especially in the application of DCFK strategy resulting in high tool requirement and tool inventory. The DCDK strategy gives a better performance in terms of tool requirement and tool inventory in small batch applications (Ref.to Experiments C13, C19, C29, C30, C15, C21, C24, C26).

In Table 16.2 which is for DCDK small and large batch applications respectively, the tool inventory is 205 and 119 for Family 1, 312 and 315 for Family 2 and 513 and 422 for family 3 respectively in four machine applications.

The short makespan of individual jobs due to small batch size makes it easier to manipulate machine load balancing and hence supports high machine utilisation and short throughput time (Ref. to Experiments C1, C3, C5, C7, C17, C13, C19). However, great divisions among the process batch reduce the chance of identical jobs visiting the same machine which will cause higher tool inventory (Ref. to Experiments C5, C11, C12, C17, C23).

A small batch size may be an effective solution to the problems that may be faced when working with a diverse work-tool list. The problem in poor quality clustering which is the main source of poor tool utilisation and high tool inventory. Breaking large process batch sizes into smaller batch sizes which create identical jobs is an efficient way to resolve the problem of poor quality clustering.

On the other hand, a large batch size has a reverse influence on the design parameters. Since it is difficult to balance the machine load due to resultant long job makespans, machine utilisation is significantly affected and gives a poor performance. However, tool life utilisation is significantly improved since a large number of identical components will visit the same machine. As a result of high tool life utilisation, tool requirement as well as tool inventory is significantly reduced. Overall throughput time is longer and the utilisation difference between machines is higher than the case where a small batch is practised (Ref. to Experiments C33, C34, C37, C38, C35, C36, C39, C40, C25, C26, C41, C42).

In terms of machine utilisation, for instance in Table 16.2 for the large batch cases, utilisations change in parallel to number of machines and range from 70% to 96%. Basically when large batch coupled with large machine group gives the worst performance.

It is observed that dynamic cluster analysis is very sensitive about the batch size. Previously designed large (<=50) batch experiments have resulted in generally poorer performance in terms of machine utilization and makespan, (Table 16.2). This parameter has further been explored and a group of computational experiments have been designed to gain more understanding about the influence of batch size in dynamic cluster analysis.

First, dynamic cluster analysis has been run with complete process batches of parts (no batch split). Then the largest process batch, which is 124 in all families, has been split into two equal transfer batches. In the third step the largest batch size is fixed at a maximum of 50 components which have created a number of transfer batches. In the forth step, the largest batch is fixed at a maximum of 25 components. Finally, the case is examined where the largest batch is fixed at a maximum of 10 components. All the experiments are run until all the jobs finish completely. For all the experiments the number of machine is fixed to 8 machines, the permissible tool life is 90% and the magazine capacity is 60 for family 1, an 120 for Family 2 and 3. The strategy for all experiments is dynamic cluster differential kitting. The results are tabulated in Table 16.4.

Generally, it is found that the larger batch experiments result in a poorer performance in terms of machine utilization and makespan. For example, as indicated in Table 16.4, the two lowest machine utilizations are seen for the process batch applications. These are 48% for Family 1, and 74% for Family 3. When the batch is split the performance immediately improves.

However, a rather interesting result has been obtained in the 50 batch size application and one of worst performance figures has been seen in these experiments. In contrast to the 62 batch size application the machine utilization drops and makespan increases again, while tool inventory gives a better performance in Family 1, increased in Family 2 and stays virtually the same in Family 3. In the third step, when batch size is split into a maximum of 25 components, the machine utilization and makespan have a better performance in Family 1 and Family 3 and virtually the same result in Family 2. However tool inventory is increased in Family 1 and Family 3 but decreased in Family 2.

In the fourth step when the batch is split into a maximum of 10 components, the machine utilization increases in Family 3 and drops in Family 2 and Family 3. Further one of the worst utilization figure as seen in this step for Family 2. Tool inventory decreases in Family 1 and Family 3, but increases in Family 2.

From the above analysis, it is difficult to specify that when the batch size is split into smaller batch sizes, all the performance figures give a better performance. However, there is still a general improvement in all performance figures except for a few cases where in contrast to expectations performance start declining.

16.4.2 Scheduling

Cluster analysis groups the jobs as well as tools. It works at the same time as a scheduling system that identifies the jobs/tools to be released.(Ref. to Chapter 6) Due to this nature of the cluster analysis approach, if there is strict due date pressure on a short term manufacturing period, cluster analysis job delivery may not match to specified due date. If there is no strict pressure on work scheduling and the manufacturing period is long enough to schedule all the planned jobs, cluster analysis may give both scheduling and tooling solutions at the same time.

16.4.3 Work-Tool List

The overall success of dynamic cluster analysis mostly depends on the work-tool list used. Since there is not always a possibility of working with identical jobs and common tools, the clustering approach may not always be a very suitable solution to tool management problems. However, one solution to this problem is to break the larger batches into small batches which creates more identical jobs and increases tool commonality, thus making the cluster analysis applicable (Ref.to Section 16.4.1) Another solution may be to cluster repeatedly, i.e dynamic clustering as it is practised in this research work. This may assign the diverse jobs which block the good quality clustering to the machines individually. This process refines the diverse jobs from the work-tool list (Ref. to Section 16.2.3) The same three part families have been used in the dynamic clustering experiments. As for the workpiece-oriented experiments, since there are very limited number of part types in Family 1, especially in large machine groups, overall performance is poorer than for the other two families because of unbalanced work. Again, Family 2 generally gives poorer performance than Family 3 but better than Family 1. One explanation for this poor performance is that the Family 2 part list contains more unbalanced large batches than Family 3 does. Since Family 3 has a more balanced part list in comparison to Family 1 and Family 2, the overall performance is better than the other two, and further it is widely predictable how it reacts to any hardware configuration.

16.4.4 Manufacturing Period

The manufacturing period has no significant effect on the efficiency of dynamic cluster analysis. However, since jobs are sent in groups instead of individually released, the makespan of a group is longer than individual jobs and a very short manufacturing period such as one shift is not long enough to get the full benefit out of dynamic cluster analysis.

In the long manufacturing period, convenient cluster sets emerge and are distributed at the beginning of the manufacturing period. Then, when approaching the end of the manufacturing period, the jobs which have virtually no commonality remain and cluster analysis loses its advantage since no proper sets emerge.

Exp. No.	Full Clustering		Differential Clustering		Tool Inventory
	Tool Invent.	MC Utili.	Tool Invent.	MC Utili.	Diff.Clust./Full Clust.
1/13	277	0.92	205	0.92	**0.74**
3/15	333	0.89	312	0.89	**0.93**
5/17	561	0.92	513	0.92	**0.91**
7/19	264	0.95	234	0.95	**0.88**
820	267	0.77	236	0.77	**0.88**
9/21	335	0.82	304	0.82	**0.90**
10/22	351	0.77	331	0.77	**0.94**
11/23	535	0.86	484	0.87	**0.90**
12/24	515	0.83	488	0.83	**0.94**
25/26	466	0.78	425	0.78	**0.91**
27/29	176	0.85	159	0.85	**0.90**
28/30	176	0.91	153	0.91	**0.86**
31/32	334	0.73	334	0.73	**1**
33/34	128	0.70	128	0.70	**1**
35/36	336	0.85	319	0.85	**0.94**

Table 16.1 Comparison of Full and Differential Clustering Strategies

	Criteria	Small Batch (<=8)			Large Batch (<=50)			
		F1	F2	F3	F1	F2	F3	
4	Tool Inventory	205	312	513	119	315	422	Strategy is DCDK
	MC Utilization(%)	92	89	92	81	93	96	
	Makespan	1787	3062	4653	1235	2880	4329	
	TRP	192	242	410	97	240	342	
6	Tool Inventory	234	304	484	124	321	428	Strategy is DCDK
	MC Utilization(%)	95	82	87	77	88	78	
	Makespan	1153	1720	2980	860	2044	2651	
	TRP	216	258	382	104	246	350	
8	Tool Inventory	236	331	488	128	319	425	Strategy is DCDK
	MC Utilization(%)	77	77	83	70	85	78	
	Makespan	948	1720	2428	713	1677	2552	
	TRP	218	265	402	112	249	360	

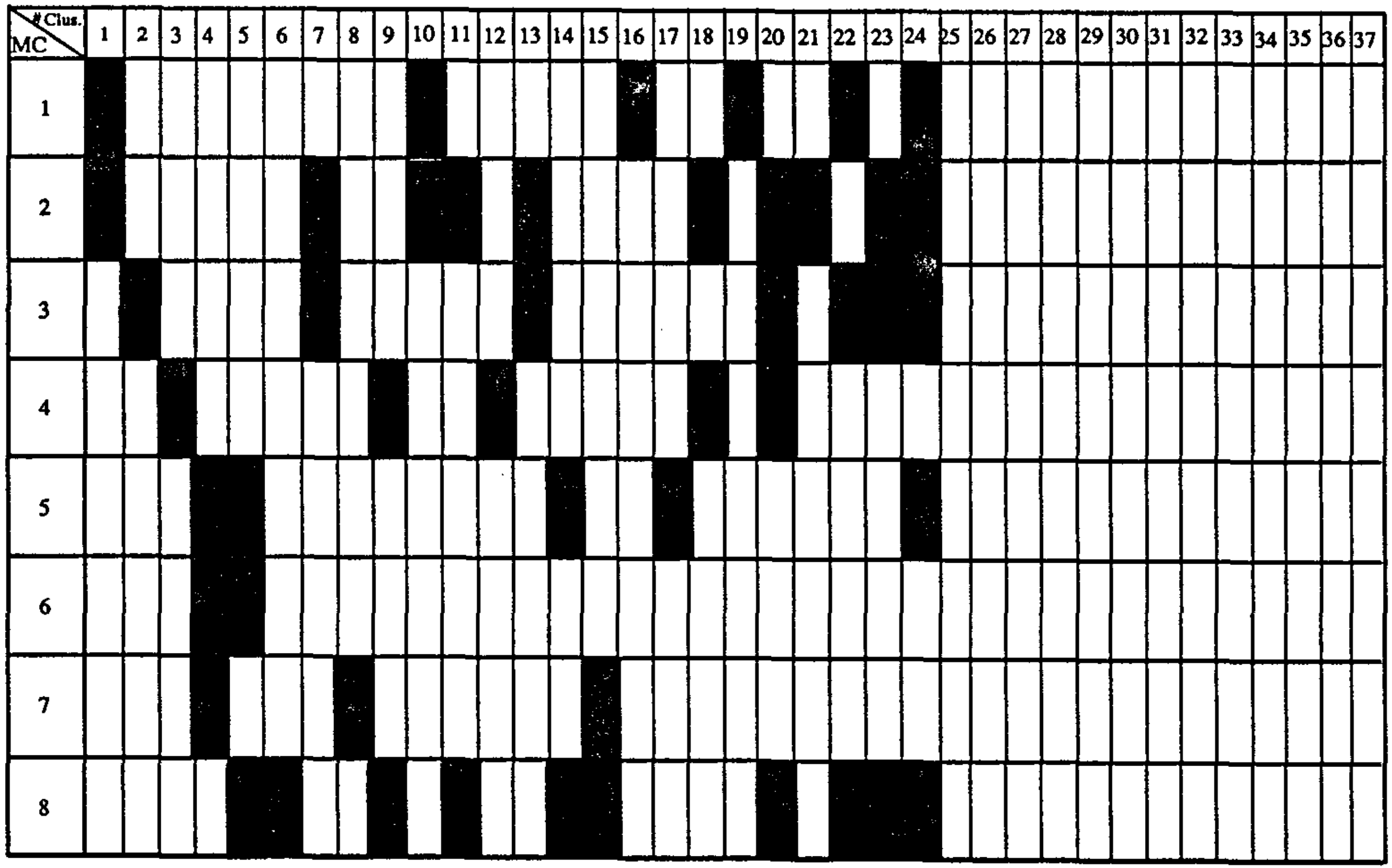
Table 16.2 Comparison of Different Machine Groups

Cell	<=8				<=50			
	TI	MU(%)	Makespan	TRP	TI	MU(%)	Makespan	TRP
Single 8 MC	488	88	2428	402	466	78	2552	393
Two 4+4 MC	496	89	2428	401	444	77	2537	360

Table 16.3 Single and Two Cell Performance Comparison

Batch	Criteria	F1	F2	F3	Comment
Process	Tool Inventory	183	309	460	Strategy is DCDK Number of Machine = 8
	MC Utilization(%)	48	85	74	
	Makespan	1364	1957	2646	
	TRP	139	245	360	
<=62	Tool Inventory	150	296	426	Strategy is DCDK Number of Machine = 8
	MC Utilization(%)	81	92	89	
	Makespan	708	1506	2211	
	TRP	122	232	342	
<=50	Tool Inventory	128	319	425	Strategy is DCDK Number of Machine = 8
	MC Utilization(%)	70	85	78	
	Makespan	713	1677	2552	
	TRP	112	249	360	
<=25	Tool Inventory	164	306	469	Strategy is DCDK Number of Machine = 8
	MC Utilization(%)	81	83	95	
	Makespan	713	1683	2116	
	TRP	151	248	409	
<=10	Tool Inventory	159	334	424	Strategy is DCDK Number of Machine = 8
	MC Utilization(%)	85	73	90	
	Makespan	682	1801	2314	
	TRP	144	272	351	

Table 16.4 Comparison of Dominant and Broken Batch Size



Part Types : 70 Batch Size :8 Manufacturing Period: 10

Figure 16.1	Number of Clustering and Cluster Sets Distribution to Machines	LUT-FMS Research Group

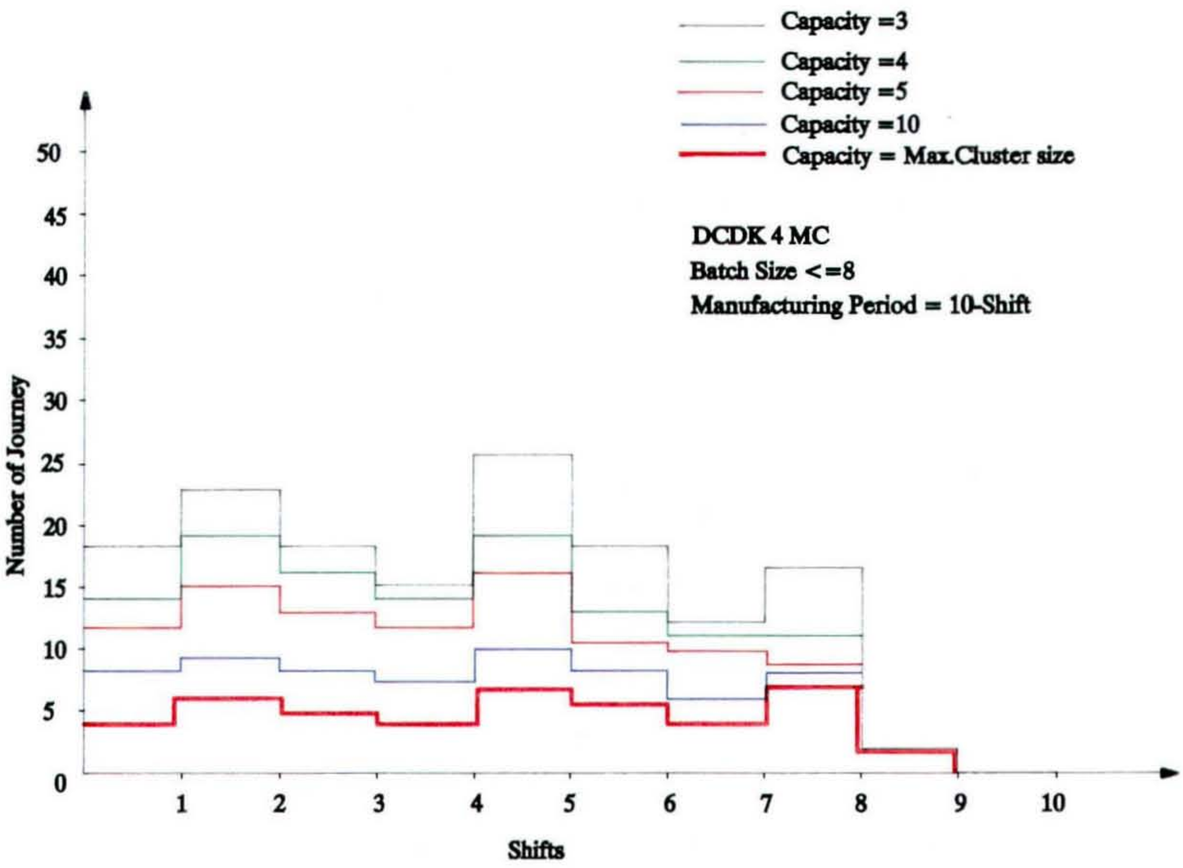
A	A	B	C	D	E	F	G	H	I	J
1										
2										
3	5	1	1	1	1	1	1			
4	13	1	1	1	1	1	1			
5	9	1	1	1	1	1	1			
6	2	1	1	1	1	1	1			
7	55	1	1	1	1	1	1			
8	43	1	1	1	1	1	1			
9	22	1	1	1	1	1	1			
10	28							1	1	1
11	19							1	1	1
12	14							1	1	1
13	11							1	1	1
14	20							1	1	1
15	31							1	1	1
16	24							1	1	1
17	15									
18	6									
19	17									
20	8									
21	29									
22	3									
23	71									
24	42									

Frequent Clustering Secreen

A	A	B	C	D	E	F	G	H	I	J
1										
2										
3	5	1	1	1	1	1	1			
4	33	1	1	1	1	1	1	1	1	1
5	3							1	1	1
6	41	1	1					1	1	1
7	27	1	1	1	1	1	1			
8	16			1	1	1	1			
9	17	1	1	1	1	1	1	1	1	
10	8									1
11	9				1	1	1			
12	11				1	1	1	1	1	
13	44							1	1	
14	58									1
15	14				1	1	1			
16	26				1	1	1			
17	35	1	1							
18	73	1	1							
19	71							1	1	
20	18									
21	19									
22	20									
23	21									1
24	22									1

Infrequent Clustering Secreen

Figure 16.2	Cluster Set Quality in Frequent and Infrequen Dynamic Clustering	LUT-FMS Research Group



Graph 16.1 Transportation Journey in DC Differential Kitting

Chapter 17
Hybrid Single Tools Approach

17.1 Introduction

This chapter presents a novel tooling strategy as well as the tool management system design approach. The chapter explains the strategy's structure, the experiments designed using the strategy and the interpretation of the results obtained from the computational experiments.

17.2 Scope and Structure of Hybrid Approach

This approach has been invented during the computational experiments and since the approach has characteristics of both the workpiece and tool oriented approaches, it is called the '*hybrid*' approach. The strategy is proven to be very effective and powerful in terms of tool inventory and tool requirements.

Since it is aimed at designing more powerful, efficient and economic systems, the approach offers a powerful solution to the design problems. The strategy uses an external scheduling system to assign jobs as it happens in workpiece-oriented approaches and then assigns the tool kits. However, in contrast to differential kitting strategy it does not remove the tools from the magazine as long as there is sufficient space in the magazine. The magazine is gradually filled to capacity which is an unstatistical clustering, loading only unavailable tools in the magazine. The strategy only exchanges tools if they become worn and they are still needed for the current operation. Figure 17.1 depicts the a logic diagram of the hybrid approach.

Since the strategy keeps the previously assigned tools in the magazine, there is always a good possibility to meet the requirement with one of the tool which is already in the magazine. If the tool needed is not available, this tool is assigned individually, therefore the strategy is called the '*hybrid single tools kitting strategy*'. This strategy has the great advantage of using tool life effectively because of tool pooling. Therefore it works very efficiently and economically in terms of tool inventory and tool requirements as well as tool life utilization.

17.3 Design of Hybrid Approach Experiments

The hybrid approach computational experiments have been designed with the experience gained from the previous two main design approaches and the complete set of experiments has been designed outside of the Taguchi method. The reduced parameter set used for the extended workpiece-oriented approach with the replacement of tool issue strategies, is used for the hybrid approach experiments depicted, Table 17.1. Although 23 experiments have been conducted, the experiments are widely sufficient to gain understanding from the design approach. The complete list of experiments is given in Table 17.2 with cross reference to appropriate workpiece-oriented experiments.

17.4 Interpretation of the Hybrid Experiments Output

The same set of performance criteria used in both the workpiece and tool oriented approaches, for the same design parameter interactions are used. The section titles below are similar to previous two approaches (Ref. to Chapter 14 and 16) to make easier the comparison between the three approaches.

17.4.1 Tool Issue Strategy

The approach uses only one strategy which is hybrid single tools kitting. It is found that the strategy is very effective and powerful in terms of tool requirement, tool inventory and tool life utilization. Since the strategy gradually builds up the magazine, especially in the late period of the manufacturing time, the strategy may not need any new tool which severely affects the tool inventory and tool requirement. It is observed that there is no significant effect on makespan and machine utilization, however, it is believed that in the long term, due to decreased tool exchange and machine down time, these two performances may improve further. The strategy gives a better tool requirement, tool inventory and tool life utilization performance when large batch size is applied (Ref. to Experiments H5, H16, H6, H4, H7 H9). However, machine utilization is always down when it is compared to small batch experiments (Ref. to Experiments H1/H5, H11/H16, H3/H4).

Transportation utilization has a similar trend to the workpiece-oriented single tools strategy experiments and it is more sensitive against batch size. (See supplementary output book for detail data)

The overall strategy performance is very competitive when it is compared to the workpiece and tool oriented approaches. (Ref. to Chapter 18)

17.4.2 Cell Structure

a) Number of Machines - The strategy reacts to the number of machines in a cell as seen in other two approaches. When number of machines is increased tool requirement, tool inventory and tool life utilization performance give a poorer performance (Ref. to Experiments H8, H7, H9, H13, H10, H18). When large machine group is coupled with large batch size, overall performance is further decreased (Ref. to Experiments H14, H17, H18 and H4, H7, H9 and H6, H8).

As can be seen from Table 17.2, the strategy is very effective for small machine groups since it builds up the magazine quickly due to more frequent job visits. The effective tool life utilization then saves tool requirement and tool inventory considerably (Ref. to Experiments H15, H14, H17, H18). Graph 17.1 shows the tool life requirements performance in this approach for one example, (Ref. to H19). (See also tool usage column in experiments output)

c) Number of Cells - As happened in previous two approaches, when the number of cell increased the tool inventory and tool requirement increased. Since there is no job route or specific machine technology restriction (any job any cell, any machine) in the experiments designed in this research, machine utilization and makespan has not been affected radically and sometimes gives better performance (Ref. to Chapter 14). In the hybrid experiments machine utilization and makespan have virtually the same performance as for a single cell large machine group. Table 17.3 compares single cell and multi-cell experiments performance.

d) Permissible Tool Life - Since permissible tool life interaction is easily predicted in the previous two approaches and the hybrid approach aimed at using high tool life percentage, it was not considered necessary to use different permissible tool life rates throughout the experiments. However two examples are given (Ref.to Experiments H13, H23). As it is seen in the performance parameters, tool requirement and tool inventory rise radically but machine utilization and makespan are not affected in comparison to full life utilization experiments (Ref. to H7).

e) **Magazine Capacity** - It is expected to have a magazine bottleneck problem in this strategy because of aiming to work with as large number of tools as possible so as to reduce tool exchange as well as using available tool life effectively. However, partially because of the relatively well balanced work and partially from using a relatively large magazine capacity, this problem has not occurred in any experiments. It should be noted that this strategy is sensitive to magazine capacity because of tool pooling during the manufacturing period.

17.4.3 Manufacturing Requirements

a) **Batch Size** - As indicated by the previous two approaches, batch size is one of the most influential factors in the entire tool management design process regardless of which approach is applied. A small batch size results in a large tool inventory and tool requirement but high machine utilization shorter makespan, whereas a large batch size resulted in less tool inventory and tool requirement, but poorer machine utilization and longer makespan (Ref.to Experiments H1/H5, H11/H16, H2/H6, H12/H15). Also a small batch causes poorer tool life utilization. However, in small batch applications the number of spent tool is relatively less than in large batch applications, so tool exchange is lower and therefore, less pressure is put on the tool transporter. Graph 17.2 shows the number of transportation journey in a small batch application in the hybrid approach. In comparison a large batch uses tool life very effectively, therefore tool consumption (spent tools) is higher and consequently more pressure is put on the tool transporter. (Ref.to Hybrid experiments results in supplementary output book)

b) Work Scheduling Rules

Shortest Processing Time (SPT) - SPT puts a great pressure on the early shifts by releasing many jobs with short operation times. However, since the tooling operations are short, the strategy has balances the part scheduling rule pressure by using the same tools for many short operations. Therefore, tool inventory and tool requirement are balanced after a few shifts. Although there is a great pressure in the early shifts, the machine utilization and makespan are not affected radically. In a short manufacturing period, the pressure on the transporter is heavy but this pressure gets lighter in the later periods.

Earliest Due Date (EDD) - EDD schedules the jobs in a more balanced manner compared to SPT. There is no particularly heavy pressure in any shift, therefore it is found that this rule is more convenient for streamlined manufacturing (Re. to Experiments H1, H2, H3, H4, H5, H7, H8, H9,H10). Therefore most of the experiments is designed using EDD rule. Tool inventory and tool requirement performance is close to SPT for longer period manufacturing and although machine utilization and makespan give sometimes better performance still they are close to SPT performance as well. (Ref.to Experiments H1/H11, H6/H15,) . However, in short term manufacturing, tool inventory and tool requirement have a better performance but machine utilization and makespan performance is poorer than for the SPT rule, (Ref. to Experiments H5 and H16). Further, since the work load is much more balanced, this rule does not put over pressure on the transporter in any shift.

c) Work-Tool List - The work-tool list used does not affect the hybrid approach particularly. The strategy reacts in the same way as for the other two approaches. Since Family 1 contains a relatively small number of part types, it has a very poor performance especially in a large machine group and with large batch size. Family 2 and Family 3 however have a better performance in comparison to Family 1 because of the longer and more balanced job list.

d) Manufacturing Period - It is observed that only when the short period is coupled with the SPT scheduling rule, there is a heavy pressure on the hybrid approach. But is not seen that any direct pressure on the strategy is caused by the manufacturing period except a natural demand in parallel to increased manufacturing period.

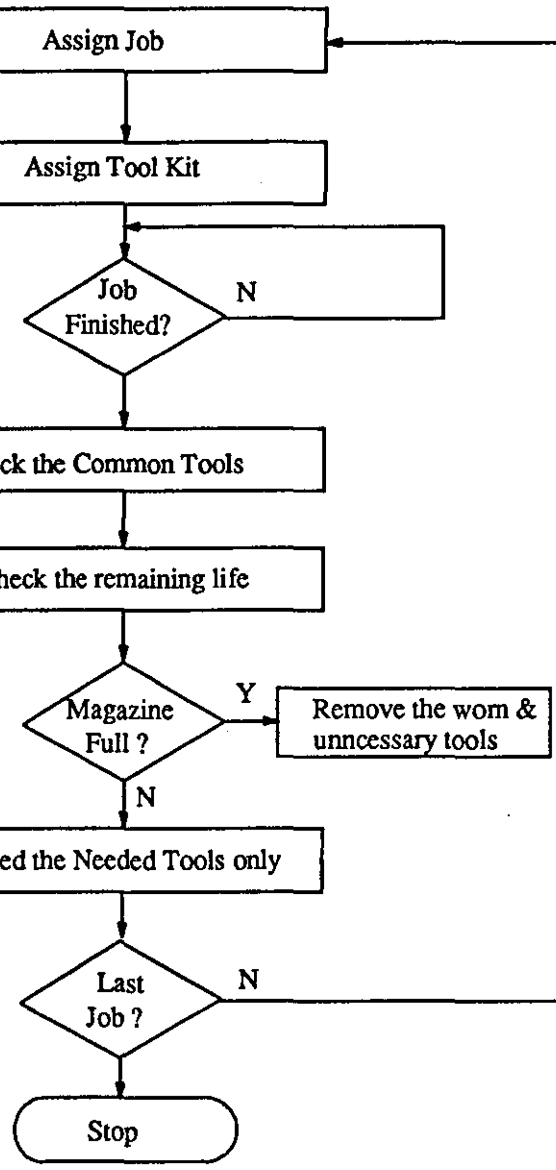


Figure 17.1	Hybrid Single Tools Kitting Strategy	LUT-FMS Research Group

Main factors	Level of Variables					
	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A: Tool Issue Strategy	HSTK					
B: Part Scheduling Rule	EDD	SPT				
C: Part Family	Family I	Family 2	Family 3			
D: Number of Machine	4	6	8			
E: Manufacturing Period	3-Shift	10-Shift				
F: Batch Size	<=8	<= 50				
G: Permissible Tool Life	90%					
H: Magazine Capacity	60	120				

Table 17.1 Parameter set with reduced alternatives in Hybrid approach experiments

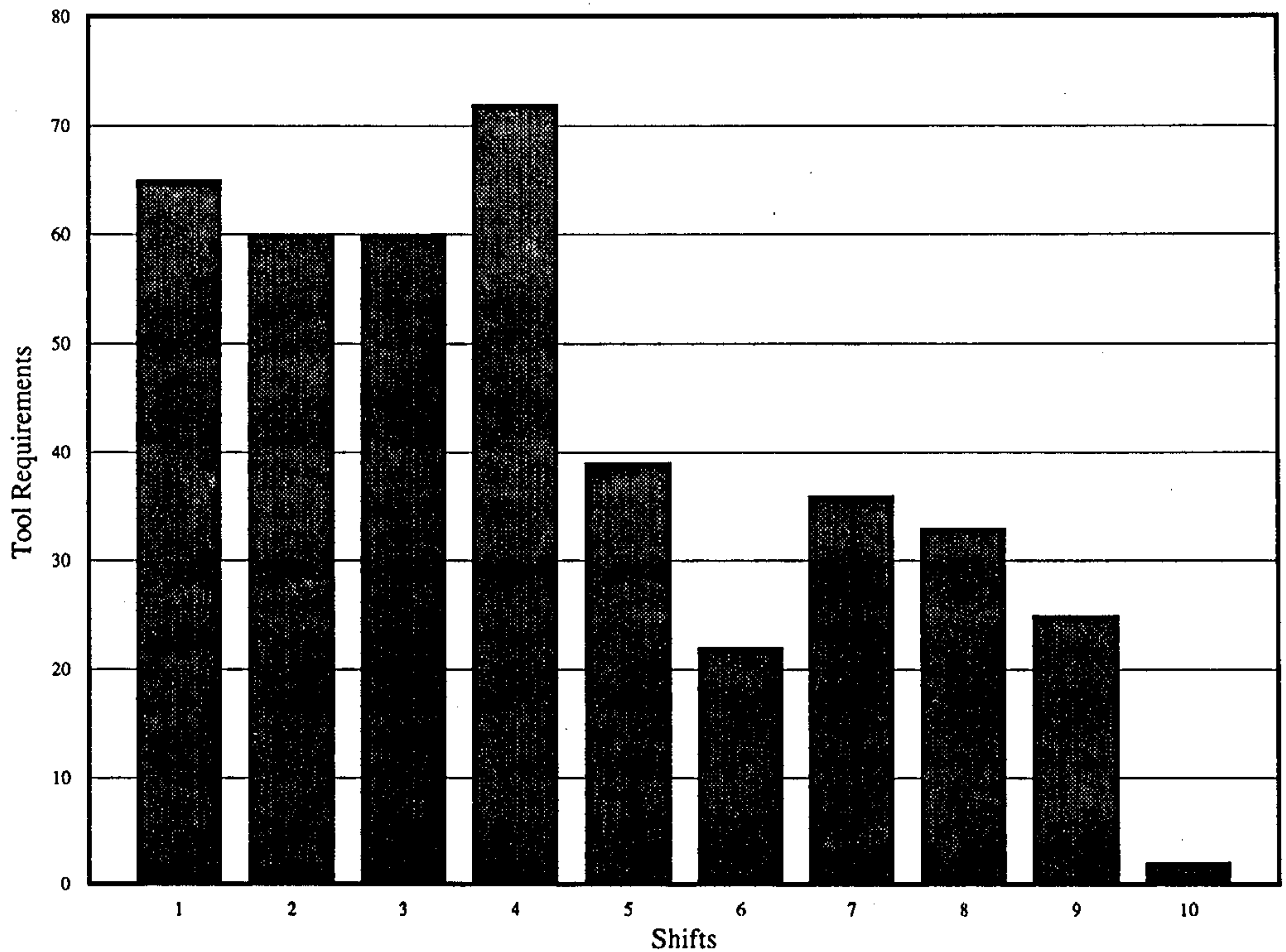
Ref. No	Family	# MC	Part Sche.	Batch Size	Manuf. Period	Magaz. Capa.	Permis. Tool Life	Tool Inven.	MC Util. (%)	Throughput Time	TRP	X Refr.
H1	F1	4	EDD	4	3	60	90	234	95	1483	213	W1
H5	F1	4	EDD	50	3	60	90	155	84	1306	127	W66
H11	F1	4	SPT	4	3	60	90	211	92	1560	196	
H16	F1	4	SPT	50	3	60	90	159	90	1340	128	
H2	F2	4	EDD	8	3	120	90	239	95	1636	204	
H6	F2	4	EDD	50	3	120	90	211	96	1695	154	
H8	F2	6	EDD	50	3	120	90	308	88	1477	244	
H12	F2	4	SPT	8	10	120	90	455	96	3167	395	
H15	F2	4	SPT	50	3	120	90	157	90	1448	147	
H3	F3	4	EDD	8	3	120	90	239	95	1636	204	
H4	F3	4	EDD	50	3	120	90	211	89	1520	159	
H7	F3	6	EDD	50	3	120	90	308	88	1477	244	
H9	F3	8	EDD	50	10	120	90	423	85	2465	362	W7
H13	F3	6	EDD	50	3	120	50	419	87	1601	309	
H23	F3	6	EDD	50	10	120	50	715	87	2465	496	W6
H10	F3	8	EDD	8	10	120	90	537	91	2470	515	W25
H20	F3	4+4	EDD	50	10	120	90	446	88	2465	387	W49
H14	F3	4	SPT	50	3	120	90	158	92	1694	144	
H17	F3	6	SPT	50	3	120	90	248	85	1640	228	
H18	F3	8	SPT	50	3	120	90	408	86	1644	347	
H19	F3	4	EDD	8	10	120	90	439	97	4623	414	W41
H21	F3	4	EDD	50	10	120	90	418	95	4413	357	W93
H22	F3	4+4	EDD	8	10	120	90	543	92	2470	512	W47

Table 17.2 Complete list of Hybrid approach computational experiments

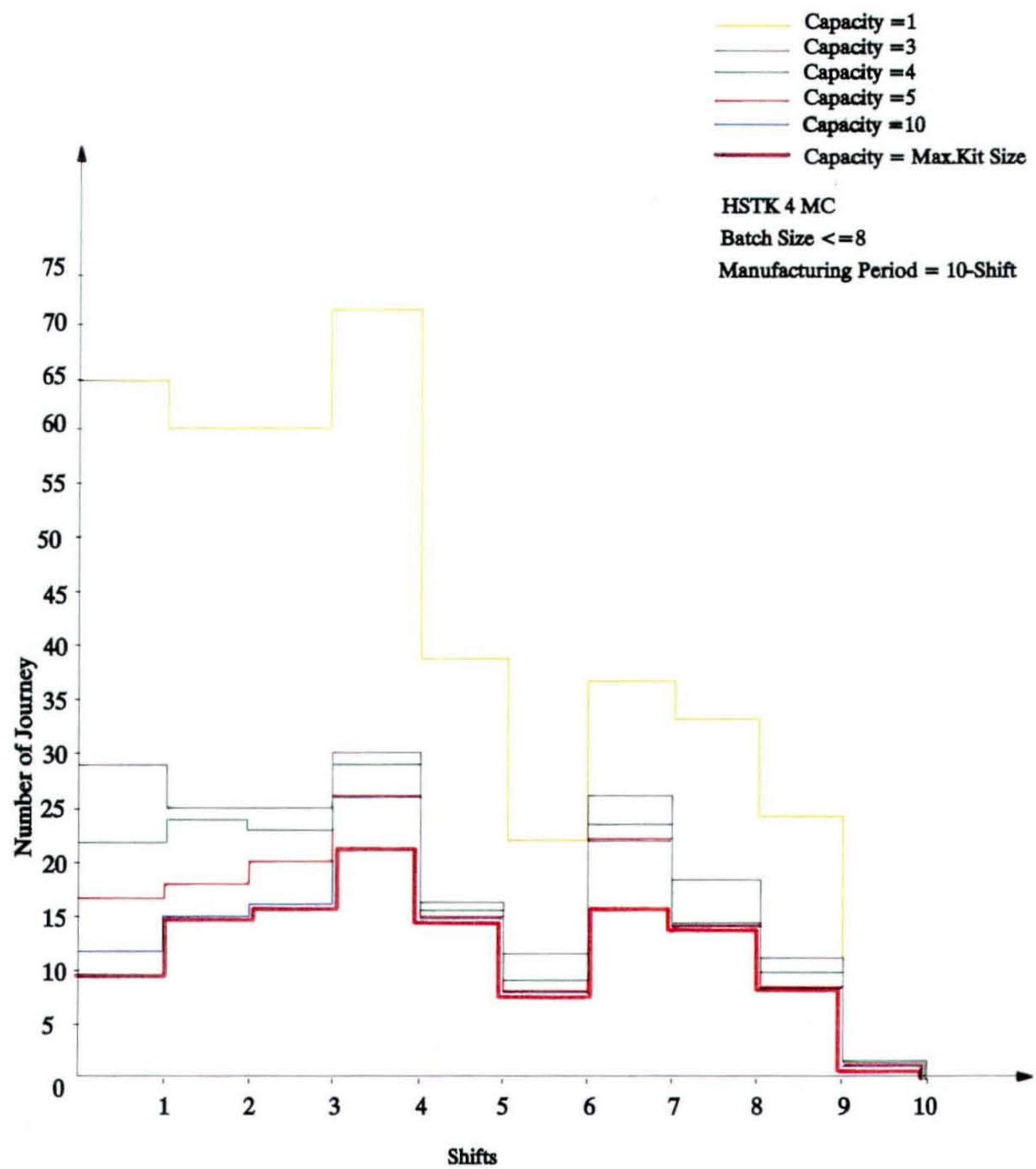
Cell	<=8				<=50			
	TI	MU(%)	Makespan	TRP	TI	MU(%)	Makespan	TRP
Single 8 MC	537	91	2470	515	423	85	2465	362
Two 4+4 MC	543	92	2470	512	446	88	2465	387

Table 17.3 Single and Two Cell Performance Comparison

The Hybrid Approach Experiment No.19 - Tool Requirements in Per Shift



Graph 17.1 Tool Requirements in Hybrid Single Tools Kitting Strategy



Graph 17.2 Transportation Journey in Hybrid Single Tools Kitting

Chapter 18
Concluding Discussion

18.1 Introduction

In this chapter the work on both the design method software and the research experiments are discussed in order to allow a set of conclusions to be reached in Chapter 19. The design methodology is reviewed and comments are made on the effectiveness of the experimental software.

The competitive elements of the results produced in the research experiments reported in chapters 13 through 17, concerned with the specific strategies, are further assessed. An example of the extended computation of the manufacturing period is also included to illustrate further points.

18.2 Design of TMS

A design methodology has been devised comparing the use of algorithmic methods of modelling supported by an expert system. Four software models have been introduced whose interactions provide a facility for system designers. The adequately detailed use of model and system data software will produce a comprehensive range of outputs which will allow designers to check virtually every issue involved in the design of TMS.

The use of performance parameters allow decisions to be made on the suitability of a design and a comparative assessment of that design.

The four primary parameters identified, are:

* tool inventory
* machine utilization,
* makespan, and
* tool requirement planning

A number of secondary parameters are also available for assessing design. These include:

* tool utilization spectra which provide detailed information on each tool type for a particular period of manufacturing, providing data on spent tools and tool utilization.
* individual machine utilization

* transporter utilization which is based on the number of transportation activities
* job throughput time
* tool distribution

It is worth noting that, in the past, tool management strategies have been linked with the choice of tool carrier system that has been involved. In this work, a somewhat different approach has been used where the tool issue strategy has been assumed to define the carrier but in many cases it is still left open to the system designer to see the impact of tool carrier capacity.

Overall it is the consideration of the primary and secondary parameters that provide the system designer with complete support when required to carry out a cost effective high performance system design for TMS.

The issue must be pointed out that this design work is based on a number of strategies each one of which is regarded as a simple stereotype. However, in practice it will be necessary to modify these strategies to some degree to accommodate the rules required by a particular company for operation of the TMS. Machining practice varies considerably and the design system will lose its impact if it is required simply to inflict stereotype solutions on real systems. It will be shown later in this chapter that the significance of the tool carrier capacity can be readily introduced and throw interesting light on the interpretation of competitive tool issue strategy performance figures.

Other aspects of tool transporters are somewhat influenced by the simplification used in the model, reported in Chapter 7. In order to reduce the run time of the model it has been assumed that an average tool transportation visit time can be used. Whilst this does not adversely affect the effectiveness of the use of the model, in general, it does have some effect on prediction of the utilization for the tool transporter.

On reflection it is considered that the design method and implementation indicated here are more effective than any other approaches traced in the current literature. There are many authors that have produced partial solutions, some analytical [45],[53],[173], some using simulation modelling methods [99],[162],[220],[252], but none of them have embraced the whole issue of tool management as the work reported in this thesis has done.

18.2.1 Software

The major choices on the use of software platform for the design methodology were decided some three years ago. At that time, the earlier work reported by De Souza [66] and Zhang [272] had shown the power of algorithmic methods, but also indicated clearly that the computational time required by fully detailed algorithmic models was excessive and also that algorithmic modelling needed to be capable of being extended to include operational rules.

The work done initially in close collaboration with De Souza on the experimental software used in this work chose to rely primarily on the Lotus 123 spreadsheet and KES expert system. Initially this work was based on IBM AT personnel computer and later was transferred to a Sun 386i workstation in order to accelerate the performance. However this move failed to produce the advantages that were sought as it was never found possible to obtain an appropriate Lotus 123 spreadsheet version for the Sun workstation itself. In this respect, the lack of availability of an appropriate product forced the use of a slower solution.

Looking to the future, the design method is broadly speaking correctly specified, but the software platform is unacceptably slow for major application to either industry or research. Some thought has been given to the possibility of rewriting the methodology in the C++ environment, which seems very attractive as it is likely to significantly reduce the processing time involved.

18.3 The Comparative Assessment of TMS Strategies

As stated above the initial choices made in the research reported in this thesis were to define individual strategies employed in their simplest form by offering stereotypes which would need some modifications when used in particular factories. This is thought be the way in which to approach the process.

The work on strategies has been reported in three sections, i.e. workpiece-oriented flow strategies, tool-oriented flow strategies, and the case of one strategy which is considered to be hybrid of the other two.

In the case of workpiece-oriented flow, the strategy is considered to consist of three options. Full kitting where each new job requires an issue of a complete kit of tools and therefore it is assumed that the tool provision system can make available a kit of tools which can vary up to the magazine capacity quoted in a particular instance. Differential kitting which requires fewer tools to be transferred, i.e. for each job is considered to require a differential set of tools thus making use of the tools already in place. Again, when it comes to tool provision, it is considered that a tool transporter system is available which can move a differential kit varying from the smallest single tool up to the maximum tool magazine capacity minus one tool. The third workpiece-oriented strategy is the single tools strategy where it is assumed that as work progresses, tools can be called up one at a time for delivery by the transporter system. This work was triggered off by observing the apparently successful use of this approach in a major industrial example. [140]

The work on the tool-oriented flow was considered with an investigation of the use of cluster analysis. Here the main emphasis has been given to dynamic clustering (Ref. to Chapter 7 and 15) supported by differential kitting, i.e each time a new clustering decision was made and work and tool relationships were modified across a number of machines. In some but not all cases new tools are required at a particular machine and in this case tools were considered to be required as a differential kit to supplement those tools already available. It is assumed a transport system is available of the appropriate capacity.

Finally the hybrid case, i.e the single tools kitting workpiece-oriented strategy supported by a set of rules which are a consequence of a hybridization between workpiece-oriented and tool-oriented flow as described earlier. This assumes that a tool carrier able to bring a single tool when required is available.

18.3.1 The Competitive Performance of the Strategies

In general it is thought that an adequate picture emerges from the experiments reported in this thesis for the projection of a broad view of the competitive performance of the major strategies.

Full kitting results are seen to provide a heavy demand on tool provision and cause a maximum tool inventory. It is thought that the case for this strategy is only really strongly made where very large batches are concerned, where a high degree of predictability is available and the use of full kitting simplifies the task of tool management. In these situations there is perhaps space for economising.

Differential kitting results were seen to offer greater tool inventory economy than was available using full kitting. This strategy is relatively expensive when one takes the tool inventory as the primary factor. However, at this point, it must be considered that it is assumed in this research that it is cost effective to use software to trace and control the flow of tools and have good data readily available, i.e. the use of a tool management software package and the use of an embedded chip in the tool holders. These refinements are considered to be cost effective, but this is a view not necessarily held by many industrial users of TMS.

When one looks at the approach to the selection of a strategy for work which is relatively varied in its content, then the choice appears to come down to either the dynamic clustering with differential kitting or use the single tools hybrid method.

The results shown in Table 18.1 summarize the results of the core of the experiments which have been carried out and reported in the earlier chapters. From a consideration of this table, it will be seen that in some situations, one of the strategies is clearly best but in a large number of other instances there is little to choose between two. If one had the ability to work with a relatively short tool list perhaps assuming a product designed in a CAD/CAM environment then hybrid single tools kitting would have major advantages. The clustering method has more a effective performance when there are significant changes in the length and make up of the tool list required in any instance. The issue of dominant batches in the list of jobs is a point which merits some consideration and the experiments in this work, the clustering, method seems to cope with large batches better with the aid of batch splitting.

The overview assessment which can be derived from Table 18.1 indicates in broad terms that the hybrid single tools kitting strategy offer short lead times and a good control of inventory. This is true if one seeks to manufacture a list of jobs which consists of considerable variety but is relatively dominated by large batches, and also where there is a long tool list with significant fluctuations in the make up of the list.

Dynamic clustering seems to be best when used over a relatively long manufacturing period with a relatively small cell and batch splitting produces good results, though a penalty is inferred in part, when one thinks of batch splitting.

A further factor which causes the dynamic clustering differential kitting (DCDK) system to produce delayed throughput time is the necessary consequence of the situation in dynamic clustering (DC) where it does not follow that all the jobs required to be processed immediately can be effectively clustered. It is appropriate to feed forward jobs for delayed machining in order to clarify the clustering decisions for the remainder of the jobs.

In total, however, this approach has the advantage of a flexible high performance technique which can perhaps deal with a larger range of contemporary situations than the hybrid single tools kitting (HSTK). Although, as design for manufacture improves and in cases where one does not have large inheritance of machining from much earlier product design, then HSTK would have an advantage.

An important point to be realized is that the current work reported in this thesis for the DCDK strategy is only really in its early stages. Whilst new ideas have been introduced and use of a rule set is found necessary, much remains to be done. If one considers the special requirements which an individual factor may require in tool management then the use of DC at best requires an automated process in carrying out the clustering decisions. Then the rule set would be further investigated and perhaps could be made capable of being re-developed for particular applications.

There is a reason to believe that inventory cost could be further reduced by introducing a variant of DCDK. If this is developed further it could result in possibly bringing together HSTK and DCDK into one composite strategy. However, this requires further work and possibly requires refinement in the clustering algorithm currently used.

18.3.2 Factors which influence effective implementation of preferred TMS strategies

The broad discussion above of the advantages and disadvantages of the two preferred tool management strategies was carried out at a high level. It can be better understood by carrying on the comparative study and referring to a limited number of secondary parameters.

18.3.2.1 Individual Machine Utilization

It is always important to maximize the machine performance. Within this work, efforts have been made in carrying out the experimental studies to seek the highest machine utilization. Some opinions suggest that machine utilization ought to be perhaps 80% allowing a manufacturing system to achieve the higher upper limit of performance when exceptional circumstances demand it. The others just simply take the view that the machine utilization should be maximized.

It is found in general that the workpiece-oriented strategies studies more readily gave high machine utilization figures compared to the clustering studies. Interpretations of the effective machine utilization have been quoted in the chapters discussing the results of major experiments. All the individual machine utilizations figures are given in Appendix IV and in supplementary data book. Table 18.2 presents an example of how individual machine utilization can be affected by carrying through DC process, in comparison to the workpiece-oriented approach and the hybrid approach.

18.3.2.2 Tool Utilization Spectra

A major insight into the performance of strategies can be achieved by going down to fine detail using the experimental software to obtain data on the utilization of individual tool types.

In general, good tool management strategies give a low tool inventory cost and provide every tool just before it is needed. A simple count of tool inventory on its own has not been found to be enough. In fact in some cases it is quite misleading. However, ideally a good strategy requires the minimum number of tools of a given type in a cell at any time and as many as of those to be as fully used as possible. This point is a useful check in the comparison of individual spectra. In general, the requirements for highly flexible performance do create considerable challenge in meeting these requirements.

The tool utilization spectra shown for particular experiments in Graph 18.1 highlights how much this factor varies. A further point has been added in this work by considering tool utilization which will help decision making the in effective operation of TMS.

If it is assumed that the model is not effective in the computation and the predictions of the tool requirement planning and spent tools are important, then the cell manager is offered what might be judged an exact figure for the tool complement required for the next manufacturing period over full spectrum of tool types. This may be somewhat uncomfortable choice for a decision maker and so it is found useful to introduce a secondary figure using the parameter tool inventory cautious, T_m (Ref. to Chapter 4). This figure, when used tool type by tool type allows the assessment of the potential hazard involved in relying on the dead reckoning of the system. (Some detail individual tool inventory calculations with a comparison to other performance criteria and their associated graphs are given in Appendix IV and in the Supplementary output book).

In general, it is thought that the design method reported in this thesis will be best applied when each of the detailed recommendations in tool inventory, as interpreted by tool utilization spectra, is augmented tool type by tool type, subject to the judgement of cell manager. This allows tool inventory to be increased marginally where the margin is judged to be the difference between the count for T_m and the corresponding T_s values.

18.3.2.3 Tool Life Utilization

The design process includes the result ranges of individual variables which include those specific to the machine tool and transport mechanism, but also include the issue of tool life. This variable can have a considerable impact on the output provided from a particular design study.

Tool life utilization has been included as a significant component in the studies which have been used to gain understanding about the performance of TMS. A simplified view has been taken of tool life which is simply related to increments of time and does not depend on the use of an algorithm by which utilization might be computed [66][272]. The use of simple time metering reduces the complexity of modelling. Results have been obtained in the experiments where the permitted upper limit of the tool life varies between 50% and 90% of the theoretical maximum value. These figures seem to have a significant effect on the projections of cell performance. A cross section of relevant experiments is shown in Table 18.3. When dealing with tool life one has to come to terms with the different attitudes of different companies. Some companies are willing in invest on tool tracking software and use embedded chip tooling, therefore they have a strong interest in the economy of tools and in the cycling of tools in the cell. Others would take an extreme view and not consider the use of tools once they are taken to the machine. It is hoped that the results of this piece of research would persuade an industrial reader of the work to follow the modern direction in tool management so that the full, effective use can be made of tools which keeps inventory cost down.

18.3.2.4 Tool Transportation

As reported earlier in this thesis the main tool issue strategies has been made independent of the choice of tool carrier. This was thought to be essential because in the past, developments in industry of TMS have been perhaps over constrained by the hardware used for moving tools about.

A view can be taken to see the implications of this issue tool management design by consideration of the Graphs 18.2a, 2b, 2c and 2d In this graphs experiments reported earlier in this thesis can be looked at again assuming that the tool carrier could have a capacity of 1,3,4,5, 10 tools or can carry maximum kit size at one visit. If the results of these experiments are restated for each of these conditions then the curves in the Graphs show some interesting results.

The prime conclusion is that any a particular case could be optimized by one choice of carrier capacity or another, however, in general, with a sensible selection of carrier capacity, tool transport implications for the major competitive solutions are reduced to an almost common solution. This result is considered to be significant as it leads one to suggest the TMS should be dominated by the use of effective control software able to trace tools and a fast small capacity transporter is then an economic solution which can be readily achieved.

18.3.2.5 Job Throughput Time

This issue is one that has been referred to earlier but due to the spread of data that can be discussed has not been given a lot of attention. It is considered sufficient at this stage to draw the reader's attention to some of the output from the experiments which is reported in Table 18.4. Consideration of this table shows that in general, use of the workpiece-oriented strategies can generate the shortest throughput times but in some cases with a relatively considerable tool inventory cost.

Clustering techniques as shown in Table 18.4 produced longer throughput times by pushing the jobs forward. The impact of the clustering techniques on the throughput time of particular jobs is a topic which needs careful assessment. There are two factors to consider. Grouping work and tools can impose some extended throughput time to particular job. In the particular case of significant batch splitting there is a definite increase in throughput time. As a consequence of efficient clustering decisions, some jobs are pushed forward to the next dynamic clustering decision time frame. All of these issues concerning throughput time have to be set in the context of the manufacturing strategy of the business. One point which stands out strongly in this thesis is that a total emphasis on shortest lead time can carry penalties in tool inventory.

18.3.2.6 Tool Distribution

One further point of significance to study the location of tools at a particular instant of time in a particular cell in the middle of manufacturing period. The question is the tools on the machine or in the STS ?

A number of results to highlight how situations can vary are included in Table 18.5. It will be seen that subject to the strategy used, tools present on the machine can vary considerably and the remainder of the tools are therefore considered to be present in the STS.

A particular strategy requires tools at different situations. The use of DC can be seen to keep the tool population on the machine relatively low whilst requiring higher tool population in the STS.

The use of STK and HSTK strategies give quite different results. Each of these strategies requires a virtually full population of tools on the magazine but a relatively STS capacity is required. It is however, total tool inventory (T_t) which is the dominant overall factor.

Two further points have to be given some attention. One is the choice of magazine capacity. This is of course a factor which is primarily decided by machine tool builders. Over the years the size of tool magazine which have been offered have gone from initially quite small capacities of 20, or 30 up to 120 tools or more on current machines. (This comment excludes very early machining centre installations) Lately design efforts have been made to offer a larger capacity of magazine where differential elements can be readily changed. These points have been touched upon in Chapter 3. The choice appears to be subject to the tool transportation solution employed in the cell, but the preferred solution is to use a relatively large magazine regardless of the strategy. In the case of STK, key decisions have to be made on sister tool utilization at full capacity. Alternatively, with DC, one has to take the view that the demand can occasionally be large and therefore spare pockets have to be available on the magazine.

The second point which requires further discussion is the limitation imposed on this work by boundaries placed on the design methodology. The software used in this research places constraints on modelling the cell only and does not allow higher levels of tool provision in the factory to be modelled. This has not been a significant hindrance to the research but leaves the same choices on the interpretations of STS population to be made. In some cases, the inference might be that a relatively large STS capacity is required, However, subject to the factory organization, some of the capacity would be better found in the central tool warehouse rather than in the STS.

To make this point, consider the results of the case where an extended manufacturing period of a 59 shifts has been computed. In this particular case of a differentially kitted cell, the three families of work used in the research were considered to be processed by a 4 machine cell in the following pattern, F1 F1 F2 F2 F3 F3 F2 F2 F1 F1. The result of the tool requirement is depicted in Graph 18.3a. The figure shows the gross inventory, and gross spent tools. As indicated in this figure, the population of the tools increases considerably due to the demand of the F3 part of the work string. It stabilizes in the latter period of manufacture but there is a gradual increase in spent tools. This information can be interpreted more significantly by referring to the second figure, Graph 18.3b. In which the figure, gross tool inventory is accompanied by a curve showing the net tool inventory and the net tool inventory plus spent tools. The plot also shows the rate at which tools enter and leave the cell. The net inventory required by cell at any time is shown to fall after the major demand of the F3 F3 manufacturing period is over. One could argue that many of these tools would be returned to the central tool store and not kept in the cell.

The design method can be readily extended to include a model of the higher level of tool preparation and it is considered important this should be the case in the future. In designing TMS it is thought essential to perhaps to cross check shorter manufacturing period based studies with some carefully chosen long period runs which will show up the longer range of the dynamics of tool provision.

18.4 Final Overview

The work reported in this thesis falls into two subsections. The first is the introduction of a design methodology which is being implemented in experimental software and has been shown to be a powerful aid to TMS design. However, of course this does not attempt to cover all the issues in flexible system design but does offer a major experimental study in which over 150 instances have been computed in order to develop a basis for understanding the performance of individual manufacturing strategies and their relative merits.

The design method will be more effective if it is enhanced to include higher levels of tool provision and preparation. The software platform needs to be reconsidered in order to a obtain faster facility for manufacturing system designers.

One side which has not been referred so far is the choice of manufacturing period used for a particular study. Initial work was considered to be carried out in balanced manufacturing period of 1, 3 and 10 shifts. It is found, however, that the studies done on short manufacturing period, whilst valid themselves, were not considerably significant for a wide range of comparative use. This is simply because the initial conditions which are assumed to apply at the beginning of the first shift have a very considerable effect on the cell performance over the short period of 1 shift.

Also the dynamics involved in TMS must be considered and results taken over the 10-shift period perhaps have the best value. In a major design study, there could be considerable value in considering one extended run to assess the economics of the total system, i.e. to see the interaction between the tool warehouse and tool preparation facilities and the cell level activities.

The work on the use of strategies has shown that a clear position can be taken on the relative value of a particular strategy. Two strategies which are considered new, were introduced in this work, i.e DCDK and HSTK, These very competitive strategies are applicable for use in cells where there is considerable demand for flexibility of performance. Each of these strategies has a varying vulnerability to key factors such as dominant batches or the length and variation of the tool list associated with particular machining requirements.

It is thought possible to take the work beyond the point reached in this thesis in the development of the preferred strategies and in particular it is thought it might be possible to blend these two strategies together to produce a definitive and highly economic solution for the management of tools for the flexible manufacturing cell.

# MC	Criteria	<=8						<=50						COMMENT
		Workpiece Oriented			Tool Oriented		Hybrid	Workpiece Oriented			Tool Oriented		Hybrid	
		K	DK	STK	FC	DC	HST	K	DK	STK	FC	DC	HST	
4	Tool Inventory	1063	791	339	561	513	439	571	507	365	422	422	418	
	MC Utilization(%)	92	93	94	92	92	97	97	95	97	96	96	95	
	Makespan	4917	4859	4789	4653	4653	4623	4166	4415	4111	4329	4329	4413	
	TRP	1038	756	304	458	410	414	510	446	300	342	342	357	
8	Tool Inventory	1063	836	633	515	488	537	571	527	670	466	425	423	
	MC Utilization(%)	90	91	92	83	83	91	89	87	89	78	78	85	
	Makespan	2544	2474	2411	2428	2428	2470	2255	2410	2261	2552	2552	2465	
	TRP	1038	811	608	429	402	515	510	465	608	393	360	362	
4+4	Tool Inventory	1063	837	633	521	496	543	571	527	667	524	444	446	
	MC Utilization(%)	90	92	92	82	89	92	89	89	89	77	77	88	
	Makespan	2544	2474	2411	2492	2428	2470	2269	2261	2272	2567	2537	2465	
	TRP	1038	812	608	441	401	512	511	468	608	417	360	387	

Table 18.1 Comparison of three main approaches

Ref	Approach	MC #1	MC#2	MC#3	Mc#4	Mc#5	MC#6	MC#7	MC#8
W25	WP-O	92	98	88	79	85	90	94	92
C24	T-O	88	92	90	82	76	71	81	83
H10	H	93	99	88	80	85	91	95	91

Table 18.2 Individual Machine Utilization in Three Approaches

Part family 3, Production period = 10-shift

	DK		K		K	
	90 %	75%	90%	50%	90%	75%
Tool Inventory	525	580	677	817	1037	1108
Machine Utilization	86	77	93	50	87	75
Makespan	2549	3021	1648	2976	2439	3635
TRP	460	496	666	706	1027	1038

Table 18.3 Different Permissible Tool Life Applications in Several Experiments

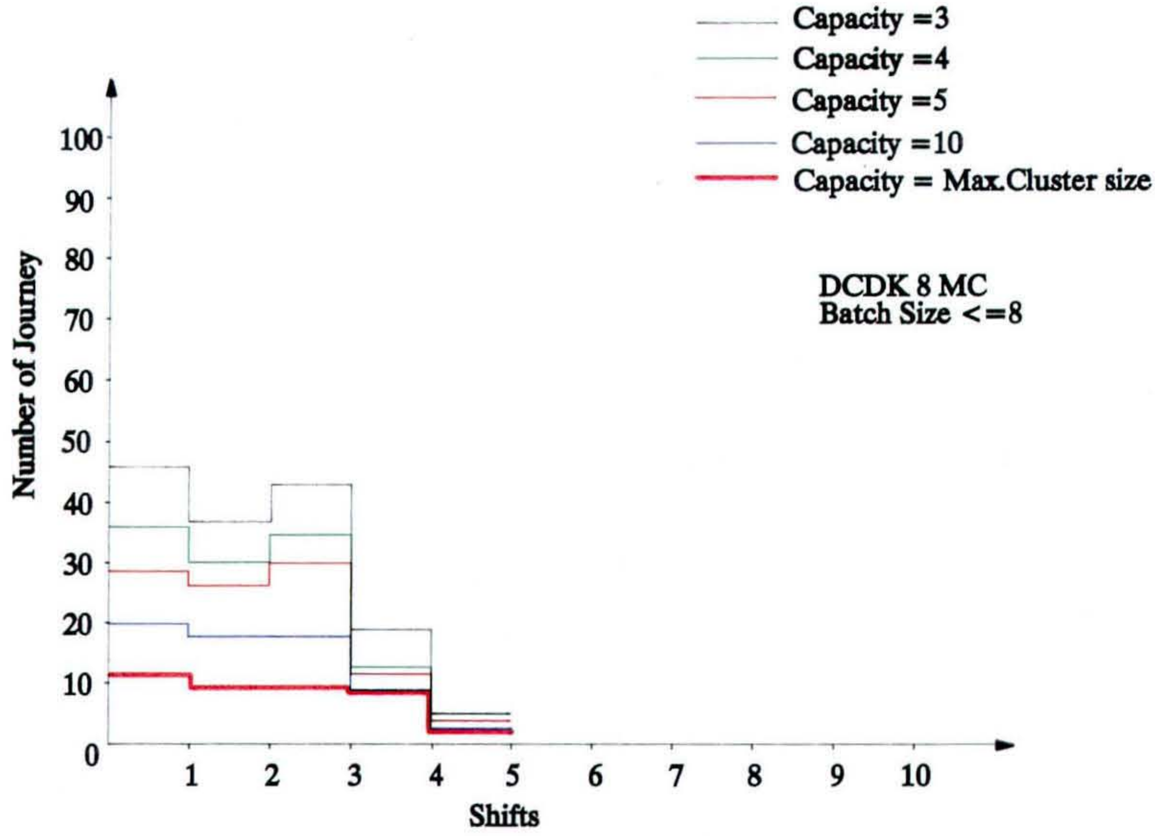
Job No	Process Time	Assigned MC	DK		HSTK		DCDK #1		DCDK #2		DCDK #3	
			Start	Δ	Start	Δ	Start	Δ	Start	Δ	Start	Δ
P6	88	2	96.7	101.75	97.15	101.75	1064.6	95.5	1282	95.5	512	95.5
P11	93.6	8	507.5	107.25	508.6	107.2	1383	101.1	1415.8	101.1	639.4	101.1
P17	60	2	707.6	73.45	707.9	73.15	999.2	67.5	1532.8	67.5	2175.9	67.5
P20	85.6	4	648.8	99.05	648.8	99.05	1361.8	93.1	1760.2	93.1	2559.8	93.1
P69	156	6	2109	168.75	2101.55	170.05	0	163.5	0	163.5	315.2	163.5

Table 18.4 Job Throughput time in main three approaches

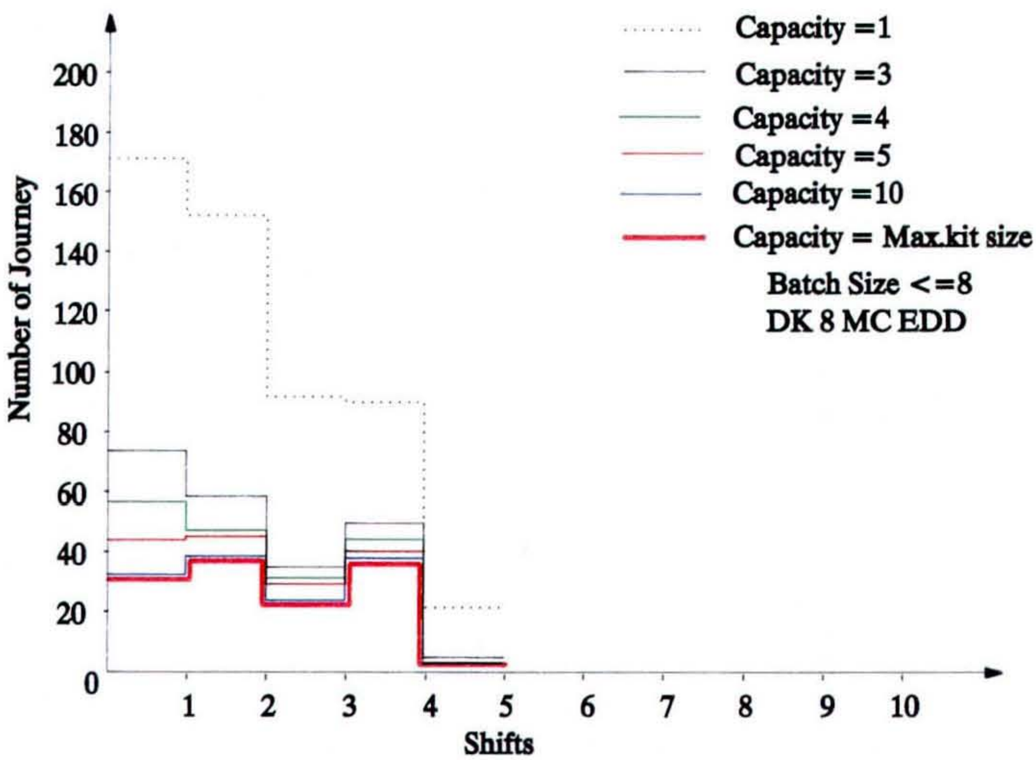
MC	Shift 1		Shift2		Shift3		Shift4		Shift5		Shift6		Shift7		Shift8		Shift9		SHift10	
	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK	DK	DCDK
1	13	15	16	6	27	18	34	21	25	17	16	–	30	–	4	–	–	14	–	–
2	25	11	13	19	25	–	27	–	9	–	18	–	23	21	27	18	22	7	–	–
3	18	12	21	21	28	–	30	17	23	10	8	15	32	14	34	12	13	4	14	–
4	14	14	13	16	20	42	27	23	22	15	13	13	34	10	22	–	17	–	6	–
STS	693	353	630	291	530	231	412	170	333	128	278	100	159	55	72	25	20	0	0	0

Table 18.5 Tool Distribution in 10-shift 4 MC examples

Strategies - DK Differential Kitting
DCDK - Dynamic Clustering Differential Kitting



Graph 18.2a Transportation Journey in DCDK Application



Graph 18.2b Transportation Journey in DK Application

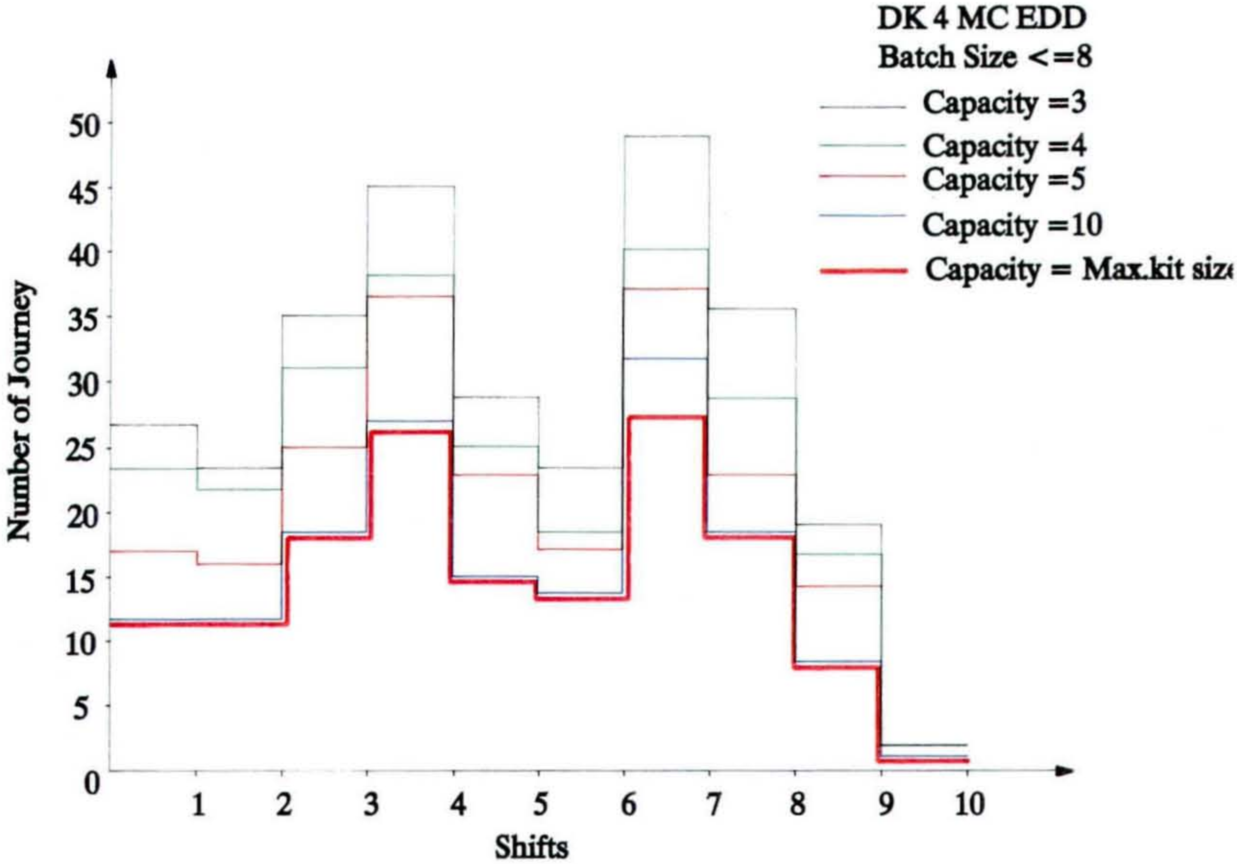


Table 18.2c Transport Journey in DK 4 MC EDD Application

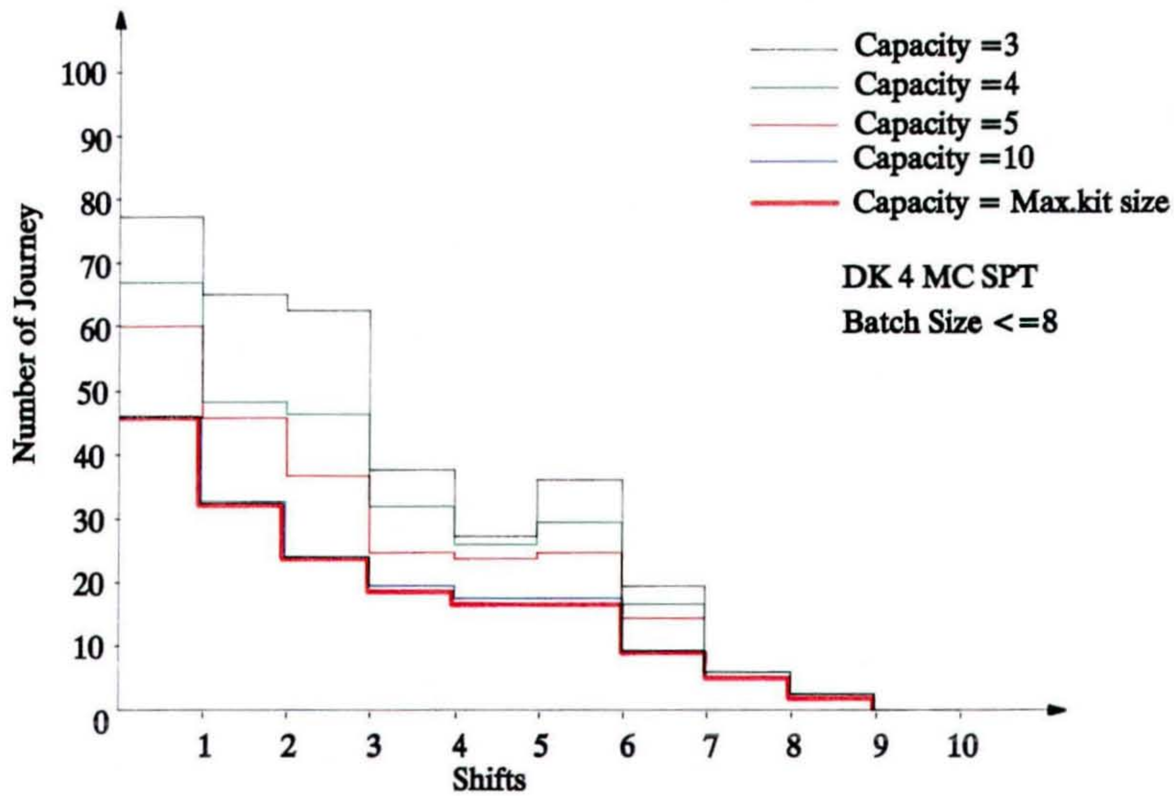
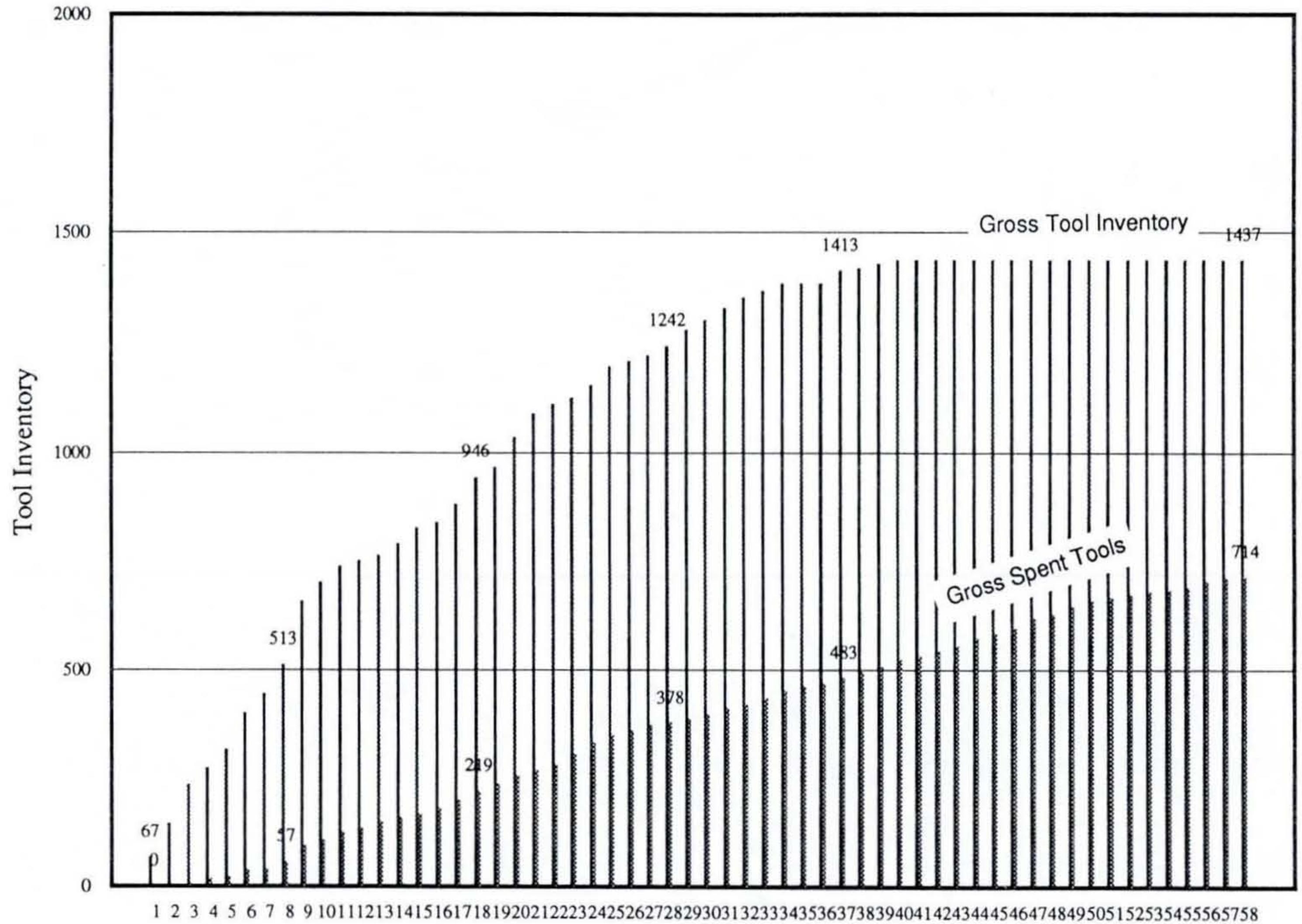
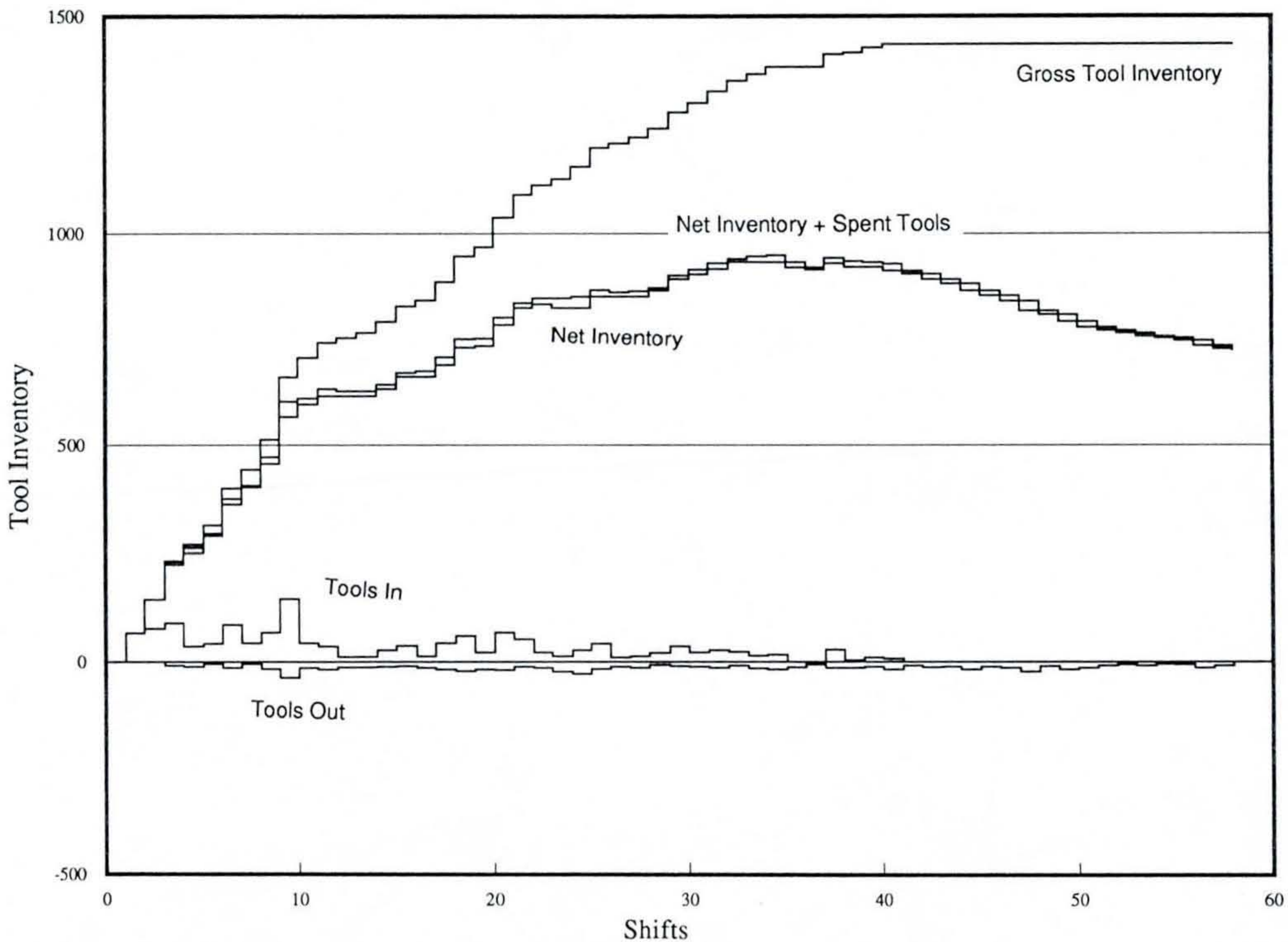


Table 18.2d Transport Journey in DK 4 MC SPT Application



Graph 18.3a The Long manufacturing period(58-Shift) Gross Tool Inventory and Spent Tools



Graph 18.3b The Long manufacturing period(58-Shift) Tool Inventory

Chapter 19
Conclusion and Further Work

19.1 Introduction

This chapter presents the conclusions drawn from research reported in this thesis and the suggestions for further work.

19.2 Conclusions

1- A comprehensive design facility, for the design of TMS up to cell level, has been implemented in software. The system consists of four modules whose performance is dominated by the use of a Lotus 123 spreadsheet. This software has proved to be very effective for carrying out research in TMS performance, however, the original software concepts that were employed at the beginning of this research have been superceded by recent developments such as new and faster computer technology and sophisticated software systems. In the future a new software platform should be produced.

2- Research into the use of tool management strategies, based on a simple set of criteria for workpiece-oriented flow and static cluster analysis, has been significantly improved as a result of the research work reported in this thesis.

Two major innovations are reported. The first concerns the use of a limited rule set to support workpiece-oriented strategies, and in particular the single tools strategy. The results of the experiments based on this approach have produced a significant step forward in the formal understanding of TMS strategies. The second major step has been the advancement of thinking on cluster analysis. The static cluster analysis technique was considered a relatively limited technique and has been overtaken by the use of what is termed dynamic clustering. This technique employs repeated cluster decisions which are supported by a rule set. It has proved to be far more effective when coupled with differential kitting than full kitting and has produced results of a very competitive quality.

3- The updated strategies commented on above have shown themselves to be the two most effective strategies employed in the experiments. In broad terms the hybrid single tools kitting strategy has proved to be a very efficient technique but it is vulnerable to significant changes in tool the list and in some cases it could be adversely influenced by tool magazine capacity.

On the other hand, dynamic cluster analysis employing differential kitting is seen to be marginally more effective than hybrid single tools kitting when dealing with discontinuities in the tool list requirements for a given manufacturing period. It has been possible to draw up a set of criteria for selecting one or other of these techniques (see Chapter 8).

4- It is considered that the results reported in chapters 14, 16 and 17 give sound guidelines for the choices of the strategies. Importantly, work reported in this thesis also emphasises strategies for cell design which are not connected with hardware choice. This point is of considerable importance to future installation design because in the past the choice of strategy has been closely linked to the mechanical decisions made in tool flow provision.

5- The study of TMS, up to cell level, is feasible and a comprehensive understanding of the system design can be achieved. It is also possible to achieve considerable economic benefits for cell operation through this work. Nevertheless, in order to gain the best results it is important that future work should be extended to include methods that consider total factory tool provision systems. Furthermore in major new installations it is recommended that a limited number of extended manufacturing period studies should be used to validate the decisions that have been made using shorter manufacturing periods.

6- It has not been found possible to use analytical tools to carry out the design process, nor has a totally generic method emerged. The need to test the conclusions reached in this thesis further, by use of a wide range of experiments, is therefore a matter of some importance. An empirical approach has been considered necessary and selecting which sets of the part/tool matrix formulation should be used has proved difficult.

7- One point that has emerged throughout this research is that whilst clear cut strategies have been defined, and it has been shown that they have produced some good results, it is expected that when strategies are employed in industrial situations they will require tailoring to the specific enterprises needs. The strategies may be amended by the addition of specific rules that apply in a particular instance. This is important both in the consideration of dynamic cluster analysis and hybrid single tools solutions.

19.3 Further Work

It is necessary to suggest future research potential if the output of this thesis is to achieve maximum effect. Some of the possibilities for future research have already been touched upon in the concluding discussion chapter.

1. The design concept should be extended to include total factory provision from warehouse through to tool room and cell. This is easily achievable.

2. It is essential that for the most effective use to be made of this work by industry then the design method reported in this thesis must be made available in a revised software environment. It is possible that a C++ solution may be the preferable. A limited utilization of the software concepts, running on a different platform, has been reported as part of the FORCAST project [79]. The research undertaken within this laboratory on the FORCAST project uses a discrete event simulation package.

3. The broad implications of TMS parameter interactions, (See Chapter 11) as reported in this thesis, would gain greater authority if further work was done in key areas using a limited number of alternative tool-part matrices.

4. Dynamic cluster analysis work necessitates human decision support, therefore, human psychology sometimes might affect the decisions made. The dynamic cluster analysis strategy should be made more automated to reduce the human interactions.

5. An extension of the dynamic clustering differential kitting strategy can be achieved by keeping the assigned cluster sets up to machine magazine capacity. Subsequently, only the tools requiring changing are removed and assigned as in hybrid single tools kitting. This could be considered a new tool issue strategy that is called a "*resident cluster set*".

6. The job scheduling in dynamic cluster analysis can be improved through sequencing already clustered jobs inside the clustered set. Currently employed FIFO may be replaced with EDD to reduce the throughput delay.

REFERENCES

1. Aanen, A., Gaalman, G.J.,
"Planning and Scheduling in an FMS", Engineering & Production Economics, Vol.17 (1989), pp.89-97

2. Abubakar, N.
"ESWELPD - An expert system for the generation of welding procedure of arc welding proceses", PhD Thesis, LUT, 1990.

3. Acaccia, G.M., Michelini, R.C., Molfino, R.M. and Raffaelli, G.,
"An Expert scheduler for tool stock management in a CIM environment", Advanced Manufacturing Engineering, Vol.1, July, 1989. pp.203-209.

4. Acaccia, G.M., Campolonghi, F., Michelini, R.C., and Molfino, R.M.,
"Expert simulation of a tool-dispatcher for factory automation" Int. Journal of Integrated Manufacturing, Vol.2, No.3 pp.131-139, 1989.

5 Accura Jigmatic AJV 80 & 120 Catologue.

6. Alberti, N., La Commare, U., La Diega, S.N. and Perrone, G.
"A tool and part flow simulator for optimal FMS management", Comp. Aided Production Engineering, 1991, Elsevier, (Eds.V.C. Venkatesh and J.A.McGeough), pp.283-292.

7. Alla, H., Ladet, P., Martinez, J., and Silva, M.,
"Modelling and Validation of complex systems by colored Petri Nets: Application to a Flexible Manufacturing System, Advances in Petri Nets", Lecture Notes in Computer Science 188, Springer Verlag, Berlin, 1985, pp.15-31

8 Amazon, Computerised Tool Management System, March 1990, Catologue

9 Andert, Ed P.
"Integrated knowledge-based system design and validation for solving problems in uncertain environments", Int. J.of Man-Machine Studies, 1992, Vol.36, pp.357-373.

10. Anon.
"Britain's Best factories", Reprinted from Management Today, 1989.

11. Anon.
"General description of makino "Max" flexible manufacturing system" Reprinted material.

12. Anon.
'"Bringing an old gap", Computerised Manufacturing, February 1989, pp.36-39

13. Anon.
"The ultimate challenge", Production Engineer, January, pp.21-24, 1989.

14. Baker K.R.
"Int. to Sequencing & Scheduling", John Wiley & Sons, New York, NY,1974

15. Balasubramanian, R., Sarin, R., and Chen, C.S.
"A model and a solution approach for the machine loading and tool allocation problem in a flexible manufacturing system", Int. J. of Prod. Research, 1990, Vol.28, No.4, pp.637-645.

16. Banerjee, S.K. and Al-Maliki, I.,
"A structured approach to FMS modelling", Int. J. Computer Integrated Manufacturing, 1988, Vol.1, No.2, pp.77-88

17. Barad, M.,
"Impact of some flexibility factors in FMSs - a performance evaluation approach", Int. J. of Prod. Research, 1992, Vol.30, No.11, pp.2587-2602.

18. Barash, M.M.,
"Computer Manufacturing Systems for discrete products", The Handbook of Industrial Engineering, John Wiley & Sons, 1982.

19. Bard, J.,
"A Heuristic for minimizing the number of tool switches on a flexible machine", IIE Transactions, Vol.20, No.4, pp.282-291, 1988.

20. Bard, Y.
"Some extentions to multiclass queueing network analysis", Performance of Computer Systems (M. Arato. Ed.,) North-Holland, Amsterdam, 1979.

21. Baskett, F., Chandy, K.M., Muntz, R.R., and Palocios, F.G.,
" Open, Closed and Mixed Networks of Queues with different Class of Customers", Journal of Association for Computing Machinery, Vol.22 No.2, 1975, pp.248-260.

22. Bauer, A., Bowden R., Browne, J., Duggan, J., and Lyons, G.,
"Shop floor control systems, from design to implementation,1991,Chapman & Hall.

23. Bell, R. and De Souza, R.B.R.,
"The management of tool flows in highly automated flexible machining installations", 2nd Int. Conference on Computer Aided Production Engineering, Edingburg, pp.233-238, 1987.

24. Bell, R., and Bilalis, G.N.
"Loading & Control Strategies for an FMS for rotational parts", 1987, pp.77-87,

25. Bestwick, P.F., & Lockyear, K.G.,
"A practical approach to production scheduling", 1979, Int.J.Prod. Research, Vol.17, No.2, pp.95-109

26. Bilalis, N.G.,
"Design of Flexible Manufacturing System for Rotational Parts", PhD Thesis, 1983, LUT.

27. Borghi, L., Briano, M., and Parmeggiani, E.
"Management of the tools resources in FMS" Proc. 5th Conf. Flexible Manufacturing Systems, November 1986, pp.477-490

28. Bowden, R., and Browne, J.,
"Approach to the production environment design task within factory coordination", Comp. Integr. Manufacturing Systems, 1991, Vol.4, No.1, pp.42-50.

29. British Aerospace , Preston, Reprinted Material.

30. Browne, J., Dubsis, D., Rathmill, K., Sethi., and Stecke, K.,
" Classification of FMS", The FMS Magazine, April, 1984, pp.114,117.

31. Browne, J., Harden, J., and Shivnan, J.,
"Production Management Systems: A CIM Perspective", Addison Wesley Publishing, 1990.

32. Brynjolfsson, S., and Arnstrom, A.,
"Error detection and recovery in flexible assembly systems", Int. J. of Advance Manufacturing Technology, 1990, Vol.5, pp.112-125.

33. Buzacott, J. A.,
"Modelling Automated Manufacturing System", Fall Industrial Eng. Conference Proceedings, pp.341-348, 1983.

34. Carrie, A.S.,
"Simulation of Manufaturing Systems", John Wiley, 1989.

35. Carrie, A.S., and Bititci, U.S.
"Tool management in FMS for integrated information and material flow", Factory 2000 Int. Conf. on Production Systems, 1988, Cambridge, pp.301-307.

36. Carrie, A.S., and Perera, T.
"Work scheduling in FMS under tool availability constraints", Int. J. Prod. Res., 1986, Vol.24, No.6, pp.1299-1308

37. Carrie, A.S. and Petsopoulos,A.C.,
"Operation Sequencing in flexible manufacturing systems", Robotica, 1985, Vol.3, pp.259-264

38. Caselli, S., Papacostatinow, C., Doty, K., and Nawathe, S.,
"A Structure-function-control paradigm for knowledge-based modelling and design of manufaturing workcells", Journal of Intelligent Manufacturing, 1992, Vol.2, pp.11-30

39. Chan, B.W.M.
"Tool management for flexible manufacturing", Int. J. of Comp. Integr. Manufacturing, 1992, Vol.5, No.4&5, pp.255-265.

40. Chan, D-Y, and Bedworth, D.D.,
"Design of a Scheduling System for Flexible Manufacturing Cells", Int.J. Prod. Research, 1990, Vol.28, No.11, pp.2037-2049

41. Chan, T.S., And Pak, H.A.,
"Modelling of a Controller for a Flexible Manufacturing Cell", Intl. Trends in Manufacturing Technology Simulation - Application in Manufacturing, 1986, pp.105-108

42. Chandra, J. & Talavage, J.,
"Intelligent dispatching for flexible manufacturing", Int.J. Prod. Research, 1991, Vol.29, No.11, pp.2259-2278

43. Chaturvedi, A.R., Hutchinson, G.K., and Nazareth, D.L.,
"A synergistic approach to manufacturing systems control using machine learning and simulation", J. of Intelligent Manufacturing, 1992, Vol.3, pp.43-57.

44. Chen, Y-J., & Askin, R.G.
"A Multiobjective Evaluation of a Flexible Manufacturing System Loading Heuristics", Int. J.Prod. Research, 1990, Vol.28, No.5, pp.895-911

45. Chung, C.-H.
"Planning tool requirements for flexible manufacturing systems", J. of Manufacturing Systems, 1990, Vol.10, No.6, pp.476-483.

46. CIMTOOL Tool Management System Catalogue.

47. Cincinnati Machine Tools Catolog.

48. Cincinnatti Milacron at Vought Aerospace, Reprineted Material.

49. Cincinnatti Milacron, Cell and Systems 1+1 = 4, Pub.No. M3276E

50. Cincinnatti Milacron, Pub.No. M-5293

51. Citroen Construction Mechaniques (CCM)

52. Clarke, B.R.
"Knowledge-based configuration of industrial automation systems", Int. J. of Computer Integrated Manufacturing, 1989, Vol.2, No.6, pp.346-355

53. Co, H.C., Biermann, J.S., and Chen, S.K.,
"A Methodical approach to the flexible manufacturing system batching, loading and tool configuration problem", Int. J. of Prod. Res., Vol.28, No.12, pp.2171-2186, 1990.

54. Co, H. Chen,S.K., and Biermann, J.
"Batching in flexible manufacturing systems", Comp.Integrated Manuf. Systems, 1989, pp.181-185.

55. Cobbin, P.
"Simple-1", '88 Simulation Winter Conference, pp. 194-198

56. Comau, Iveco-Bulzano plant, Reprinted Material.

57. Conway, R., and Maxwell, W.
"XCELL", '87 Simulation Winter Conference, pp.202-206

58 Conway, R.W., Maxwell, W.L. and Miller, L.W.,
"Theory of Scheduling", Addison Wesley, Reading Mass. 1967 ,

59. Cutkosky, M.R., Fussell, R.M., and Milligan, Jr., R.
"The design of a flexible machining cell for small batch production", J. of Manufacturing Systems, 1984, Vol.3, No.1, pp.39-59

60. Dagli, C.H.,
"Scheduling for flexible manufacturing systems", Modem Production Management Systems, A. Kusiak(Ed.), Elsevier Science Publishers B.V(North-Holland), 1987, pp.31-43

61. Daoud, Z.A. and Purcheck, G.F.K.,
"Multi-tool job scheduling for tool-change reduction", Int.J.Prod. Res., 1981, Vol.19, No.4, 425-435.

62. Das, S.K. & Sarin, S.C.,
"A 'city plan' for design and research of computer integrated production planing and control system", Int. J.Comp.Int.Manuf, 1991, Vol.2, No.1, pp.14-23

63. DECKEL DE-C Series Machine Tools Catalogue.

64. Denzler, D.R., & Boe, W.J.,
"Experimental investigation of flexible manufacturing system scheduling decision rules", Int. J. Prod. Res., 1987, Vol.25, No.7, pp.979-994.

65. Descotte, Y. and Latombe, C.H.,
"GARI: A Problem solver that plans how to machine mechanical parts", Proc. 7th. Intl. Conf. on Artificial Intelligence, 1981, pp.300-332

66. De Souza, B.R.B.
" The Management of Tool Flow in Highly Automated Manufacturing Systems", PhD Thesis, LUT, 1988

67. De Souza, R.B.R., and Bell, R.
"A tool cluster-based strategy for the management of cutting tools in flexible manufacturing system", Journal of Operation Management, Vol.10, No.1, pp.73-91, 1991.

68. Dolezalek, C.M. and Ropohl, G.,
"Flexible Fertingungsysteme, die Zukunft der Fertingungtechnik, wt-Z.ind Fertigung 60, 1970, pp.446-451"

69. Doumeingts, G. et al.
" Design of Advanced Manufacturing Systems Using AI Techniques", Proc. ICPR Cincinnatti, 1987.

70. ElMaragy, H.A.,
" Automated Tool Management in Flexible Manufacturing", Journal of Manufacturing Systems, Vol.4, No.1, pp.1-13, 1985.

71. Escudero, L.F.,
"A Mathmetical Formulation of a Hierarchical Approach for Production Planning in FMS", Modern Production Management Systems, A. Kusiak(Ed.), 1987, pp.231-245

72. Evans, G. W. and Haddock, J.,
"Modelling Tools for FMS", Production Planning and Control, 1992, Vol.3, No.2, pp.158-167

73. Eversheim, W. et al.
"Tool management: the present and the future", Annals of CIRP, 1991, Vol.40, No.2, pp.631-639.

74. Fan, I.S., and Sackett, P.J.,
"A Prolog simulator for integrative flexible manufacturing systems control", Simulation, June 1988, pp.239-247

75. Farhodi, F.,
"A knowledge-based approach to dynamic job-shop scheduling", Int. J. Computer Integrated Manufacturing, 1990, Vol.3, No.2, pp.84-95.

76. Findlay, R.C.,
"FMS Concept Realised", Proc.of the 3rd Int. Conf.on Flexible Manufacturing Systems, 11-13 Sepember 1984.(H.J. Warnecke, Ed.)

77. FMS at Remington, Cincinnatti Milacron reprinted material.

78. "FMS Handbook", Vols.I-IV, Charles Draper Laboratory, Inc. 1983

79 FORCAST Sub Project4 - Interfacing tool requirements analysis with simulation and scheduling, Dept. of Manufacturing Engineering, LUT, 1993.

80. Ford, D.R., and Schreer, B.J.
"An Expert Manufacturing System", Simulation, June 1985, pp.193-200

81. Fox, M.S., and Smith, S.F.
"ISIS- a knowledge-based system for factory scheduling", Expert Systems, 1984, Vol.1 No.1, pp.25-49.

82. Fraser Amca Int.Table type horizontal production centres, PC-40 and PC-50 catologue.

83. Fry, T.D., and Smith, A.E.,
"FMS Implementation Procedure: A Case Study", IIE Transactions, Vol.21, No.3, September, 1989, pp.228-239.

84. Ganiyusufoglu, O. S.
"Building Automated Machine Cells - A Step-by-Step Approach", Flexible Manufacturing for Small to Medium Enterprises, August, 1989, pp.43-75

85. Gershwin, S.B.,
"Hierarchical flow control: a framework for scheduling and planning discrete events in manufacturing systems", 1989, Proceeding of the IEEE, 77(1)

86. Gershwin, S. & Akella, R.,
"A hierarchical scheduling policy applied to printed circuit board assembly", Robotics & Computer-Integrated Manufacturing, 1985, 1(3/4), pp.299-305

87. Ghosh, S., Melynk, S.A., and Ragatz, G.L.
"Tooling constraints and shop floor scheduling: evaluating the impact of asequence dependency", Int. J. of Prod. Research, 1992, Vol.30, No.6, pp.1237-1253.

88. Giardini, C., Maccarini, G., and Bugini, A.
"An expert system: tool replacement in flexible manufacturing", Prod.Research, Approaching the 21st Century,1991, M.Pridman & C. O'Brien (Eds.), pp.617-624.

89. Giddings & Lewis Machine Tool Catologue

90. Gildemeister, Max Muller -MDW7 30-40, GM898Qu989 e

91. Gordon, W.J. and Newell, G.F.,
" Closed queueing networks with exponential servers, Operations Research, Vol.15, 1967, pp.254-265.

92. Grant, M. E., and Starks, D. W.,
"TESS" '88 Simulation Winter Conference, pp.136-140

93. Grant, T.,
"Categories of Contraints in Acquiring Planning and Scheduling Knowledge", Alvey Project 1986 Report.

94. Graver, T. W., and Mc Ginnis, L. F.,
"A Tool provisioning problem in FMS", 'Int. Journal of Flexible Manufacturing Systems, Vol.1, pp.239-254, 1989.

95. Groover, M.P.
"Automation, Production Systems and Computer Integrated Manufacturing", Prentice-Hall, Princeton, NJ, 1987.

96. Gupta, J.N.D.,
"Two Stage, hybrid flowshop scheduling problem", 1988, Jour. of Op. Research Society, pp,39,359-364

97. Gupta, J.N.D & Tunc, E.A.,
"Schedules for a two-stage hybrid flowshop with parallel machines at second stage", Int.J. Prod. Research, 1991, Vol.29, No.7, pp.1489-1502.

98. Gupta, Y.P., Gupta, M. C., and Bector, C.R.,
"A review of scheduling rules in flexible manufacturing systems", Int. J. Comp. Integr. Manufacturing, 1989, Vol.2, No.6, pp.356-377.

99. Gyampah, K.A., Meredith, J.R., and Raturi, A.,
"A Comparison of tool management strategies and part selection rules for a flexible manufacturing systems" Int. Journal of Production Research, Vol.30, No.4, pp.733-748

100 Hadavi, K., Shahraray, M.S., & Voigt, K.,
"ReDS-A Dynamic Planing, Scheduling and Control System for Manufacturing", J. of Manufacturing Systems, 1989, Vol.9, No.4, pp.332-344

101 Haddock, J.
"A simulation generator for flexible maufacturing systems design and control", IEE Transactions, Vol.20, No.1 March 1988, pp.22-31.

102. Haddock, J.,
"An Expert system framework based on a simulation generator", Simulation, 1988, Vol.48., pp.45-53

103. Hammer, H.
"Werner QTC System", Reprinting for Wener & Kolb, 1989.

104. Hammer, H.,
"Improving economic efficiency through flexible automation in milling and boring", Reprinted material.

105. Hammer, H. and Viehweger, B.,
"QTC, Quick Tool Change - A new method for fast and selective tool chances in machining centres", Werner and Kolb Information, Reprinted material.

106. Hankins, L.S., and Rovito, P.V.,
"The Impact of Tooling in Flexible Manufacturing Systems", National Machine Tool Builders' Assosciation 2nd Biennial Int. Machine Tool Technical Conf., September, 1984., pp.175-198.

107. Happersberg, G.
"Tool management and integrated part of an FMS", Proc. 7th Int. Conf. on Flexible Manufacturing Systems, September 1988, pp.193-199

108. Hartley, J.
"FMS at Work" IFS Publication, London, 1983.

109. Heller, BEA, Manufacturing Cell catologue.

110. Herrington G.,
"Tool Management starts in the tool stores", Reproduced from Manufacturing Technology International-Europe Yearbook, 1987.

111. Hertel -FTS Flexible Tooling System, Catologue No. 7010 - 1 D.

112. Huang, H. -P. and Chang, P.-C.,
"Specification, modelling and control of a flexible manufacturing cell", Int. J. of Prod. Research, 1992, Vol.30, No.11, pp.2515-2543.

113. Huettner, C.M. and Steudel, H.J.,
"Analysis of a manufacturing system via spreadsheet analysis, rapid modelling, and manufacturing simulation", Int. J. of Prod. Research, 1992, Vol.30, No.7, pp.1699-1714.

114. Huron Graffenstaden Horizontal machining Centres CU80 Technical Catologue.

115. Hutchison, J. et al.
"Scheduling approaches for random job shop flexible manufacturing systems", Int. J. of Production Research, Vol.29, No.5, pp.1053-1067.

116. Index GU 610, CNC Automatic Lathe Catalogue.

117. Ishii, N., And Talavage J.J,
"A Transient-based real time scheduling algorith in FMS", 1991, Int. Journal of Production Research, Vol.29, No. 12, pp.2501-2520

118. ISIS Toolware, Integrated Tool Management System, Informatics Ltd.Surrey, UK.

119. Jackson, J.R.,
"Job Shop like queueing systems", Management Science, 1962, Vol.10, pp.131-142.

120. Jacops, H. -J., Hentschel, B., and Stange, B.
"Intelligent tool monitoring for machining", Int. Journal of Prod. Res., 1988, Vol.26, No.10, pp.1579-1592

121. Johns, B.L.,
"Introduction to Computer Numerical Control", Pitman, London, 1986.

122. Johnson, L.A. & Montgomery, D.C.,
"Operation Research in Production Planning, Scheduling and Inventory Control", John Willey & Sons, 1974, New York, NY.

123. Jones, C.H.,
"An Economic Evalution of Job Shop Dispatching Rules", Management Science, Vol.21, No.3, 1973, pp.293-307

124. Jones, A.T. and McLean, C.R.,
"A Proposed hierarchical control model for automated manufacturing systems", J.of Manufacturing Systems, Vol.5, No.1, pp.15-25

125. Kalkunte, M.V., Sarin, S.C., and Wilhelm, W.E.,
" Flexible Manufacturing Systems: A Review of Modelling Approaches for Design, Justification and Operation", Flexible Manufacturing Systems: Methods and Studies, Edited by A.Kusiak, Elsevier Science Publishers B.V. (North Holland), 1986, pp.3-25

126. Kearney & Treckers Corp.
"Kearney and Treckers world od advanced manufacturing technology", KTM publications, Milwaukee, Wisconsin, USA, 1983, Revised edition.

127. Kennametal, Modular Tooling System Catolog

128. Kennametal KV Tooling System

129. King, J.R.
"Machine components grouping in production flow analysis: an approach using a rank order clustering algorithm", Int. J. of Production Research, 1980, Vol18, No.2, pp.213-232.

130. Kinoglu, F. et al.
"Expert system model of the design process", Smart Manufacturing with Artificial Intelligent, 1987.

131. Kiran, A.S., and Krason, R.J.,
"Automating Tooling in a Flexible Manufacturing System", Industrial Engineering, April 1988, pp.52-57

132. Kobayaski, S., and Nakamura. K.
"Knowledge Compilation and refinement for fault diagnosis",IEEE Expert Systems, October 1991, pp.39-46.

133. Kochan, A., "BAe ambitions are about to be realised", The FMS Magazine, 5(2), pp.63-67, 1987.

134. Kolb, Flexible Manufacturing Cells and Systems Reference Book.

135. Kolb, Flexible Manufacturing Cell, CUBIMAT HC 1500 Catologue.

136. Koulamas, C. P.,
"Total tool requirements in multi-level machining systems", Int.Journal of Production Research, Vol.29, No.2, pp.417-437, 1991.

137. Kouvelis, P.
"Design and planning problems in flexible manufacturing systems: a critical review", J. of Intelligent Manufacturing, 1992, Vol.3, no.75-99.

138. KTM Fleximatic V Series Machine tool catologue.

139. Kurimoto, A. " Tool management system for advanced manufacturing", Reprinted from Manufacturing Technology International, Europe 1989.

140 Kurimoto, A., So, K., and Hill, D.
"Fully integrated tool management system", reprint, Proc. of the 7th Int. Conf. on Flexible Manufacturing Systems, September, 1988, pp.22-28.

141. Kusiak, A.,
" Design of Flexible Manufacturing System", CASA/SME FMS '86 Conference, March 1986.

142. Kusiak, A. and Ahn, J.,
"Intelligent scheduling of automated machining systems", 1992, Computer Integrated Manufacturing Systems, Vol.5, No.1, pp.3-14

143. Kusiak, A & Jaekyoung, A.
"Intelligent scheduling of automated machining systems", Comp.Integrated Manuf. Sytems, Vol.5, No.1, 1992, pp. 3-14

144. Kusiak, A.,
"Loading models in FMS", In. Rouf A. & Ahmed, S.(Eds.), 1986,Flexible Manufacturing, Elsevier Science Publ. Amsterdam

145.Kwok, M.C.K., and Carrie, A.S.,
"An Expert system approach to the design of flexible manufacturing systems", 1991, Production Research - Approaching the 21 st Century, Eds. M. Pridham, C. O'Brien, pp.625-632

146. La Diega, S.N., Passannati, A., and Passannati, G.
"Optimum tool replacement policies in integrated manufacturing systems", Comp. Aided Production Engineering, 1991, Elsevier, (Eds.V.C. Venkatesh and J.A.McGeough), pp. 315-332.

147. Law, A.
"Simulation of Manufacturing Systems", Proc. of the 1988 Winter Simulation Conference, pp.40-51 (M. Abrams, P. Haingh and J. Comfort Eds.)

148. Lenz, J.E.,
"An Expert System for manufacturing simulation", Modern Production Management Systems, A.Kusiak (Ed.) 1987, pp.639-648

149. Lenz, J.E., Gross, J.R.,
"MAST", '88 Simulation Winter Conference, pp.194-198

150. Lenz, J.E.,
"MAST: A Simulation tools as advanced as the FMS it studies", Proc. 1st Int. Conference on Simulation in Manufacturing, 1985.

151. Leung, L.C., Maheshwari, S.K., and Miller, W.A.
"Concurrent part assignment and tool allocation in FMS with material handling considerations", Int. J. of Prod. Research, 1993, Vol.31, No.1, pp.117-138.

152. Leyland Bus trunkey installation, Farrington, Reprinted material.

153. Lucas Diesel Systems at Sudbury, Reprinted material.

154. Luggen, W.W.,
"Flexible Manufacturing Cells and Systems", Prentice-Hall, Princeton, N.J. 1991

155. Luger, G.F., and Stubblefield, W. A.,
"AI and Design of Expert Systems", Benjamin/Cummings Publication Company, California, 1989.

156. Lynee, C.S.,
"A Proven Tooling System for Flexible Turning Machines", National Machine Tool Builders' Assosciation 2nd Biennial Int. Machine Tool Technical Conf., September, 1984., pp.157-174.

157. The Management of Tool Flow in Highly Automated Manufacturing Systems, ACME Sponsored Project Proposal Report, GR/F 42706, Dept. of Manufacturing Engineering, LUT, 1989.

158. McQueen, L.,
"Dual Flow of Parts and Tools in FMS", 1993, PhD Thesis, LUT

159. Media Scara, Highly Automated Horizontal Working Unit, MCM, Machining Centres Manufacturing Spa.

160. Mellichamp, J.M., and Wahap, A.F.A.,
"An Expert System for FMS Design", Simulation, May 1987, pp.201-208

161. Mellichamp, J.M., Kwon, O. -J., and Wahab, A.F.A.,
"FMS Designer: an expert system for flexible manufacturing system design", Int. J. of Prod. Research, 1990, Vol.28, No.11, pp.2013-2024.

162. Melnyk, S.A., Ghosh, S., and Ragatz, G.L.
Tooling constrains and shop floor scheduling: a simulation study", J. of Oper. Management, 1989, Vol.8, No.2, pp.69-89.

163. Merchant, M.E.,
"Current Status of Potential for Automation in the Metalworking Manufacturing Industry", Annals of the CIRP, Vol.32, No.2, 1983, pp.519-523.

164. Miles, T., Sadowski, R.P., and Wermer, B.M.
"Animation with Cinema", Simulation Winter Conference 1988, pp.180-187.

165. Modern Machine Shop, CIM Special Issue, December, 1987.

166. Moore, T.N.,Jeswiet, J. and Lipsett, M.G.
"Machinery fault diagnosis for automated machining systems", Computer-Aided Production Engineering, Edited by V.C. Van Katesh and J.A. McGeough, Elsevier, 1991.

167. Montezari, M. And Van Wassenhove, L.N.,
" Analysis of Scheduling Rules for an FMS" 1990, Int. Journal of Production Research, Vol.28, No. 4, pp.785-802

168. Mori-Seiki, DAECL9111 E05 Machine tool catologue.

169. Mori-Seiki MV Series, Machine tool catologue.

170. Mukhopadhiyay, S.K., et al.
"Heuristic to the scheduling problems in flexible manufacturing system", 1991, Int. J.Prod. Research, Vol.29, No.10, pp. 2003-2024

171. Mukhopadhyay, S. K., Sanjay, M., and Krishna, V.M.,
"A heuristic procedure for loading problems in flexible manufacturing systems", Int. J. of Production Research, 1992, Vol.30, No.9, pp.2213-2228

172 Narou, N., Letho, M and Salvendy, G.
"Development of a knowledge-based decision support system for diagnosing multifunctions of advanced production equipment", Int. J. Production Research, 1990, Vol.28, No.12, pp.2259-2276.

173. Nee, A.Y.C., Shan, X.H., and Poo, A.N.
"An AI/neural network based solution for cutting tool selection", Comp. Aided Production Engineering, 1991, Elsevier, (Eds.V.C. Venkatesh and J.A.McGeough), pp.251-260.

174. Newell, A. and Simon, H.,
"GPS, A Program that simulate human thought", Computer and Thought, E.A. Feingbaum and J. Felman(Eds.), McGraw-Hill, N.Y., 1963

175. Newman, P.
"Scheduling in CIM systems", Artificial Intelligence: Computer Integrated Manufacturing, A. Kusiak (Ed.) IFS Publication, 1987.

176. Newman, S.T.,
"An Integrated approach to the Design and evaluation of Flexible Machining Cells", PhD Thesis, LUT, 1990.

177. Nippon Kokan Technical, Presswork, NKK, FMC, Catalogue.

178. Nof, S.Y., Whinston, A.B, and Bullers, W.I.,
" Control and Decision Support in Automatic Manufacturing Systems", AIIE Transactions, Vol.12, No.2(1980), pp.156-169]

179. Norrie et al.
"Object Oriented management planning for advanced manufacturing", Int. Journal of Comp. Integrated Manufacturing, 1990, Vol.3, No.6, pp.373-378

180. Numas, M., & Morishita, S.
"A scheduling environment for steel making processes", 1989, IEEE.

181. O'Grady, P.J., & Menon, U.,
"Loading a flexible manufacturing systems", Int.J.Prod. Research, 1987, Vol.25, No.7, pp.1053-1068.

182. O'Grady, P.J.,
"Controlling Automated Manufacturing Systems", Kogan Page, 1986

183. O'Grady, P. & Seshadri, R.,
"Operating of X-Cell- an Intelligent Cell Control System", CIMS, Vol.5, No.1, February 1992, pp.21-30

184. O'Keefe, R.,
"Simulation and Expert Systems-Taxonomy and Some Examples", Simulation, January 1986, pp.10-16

185. Okuma Oguchi plant in Japan, Reprinted Material.

186. O'Reilly, J. J., and Lilegdon, W. R.,
"SLAM", '88 Simulation Winter Conf. pp.85-90 1988.

187. Oren, T.I., and Zeigher, B.H.,
"Artificial Intelligence in Modelling and Simulation:Directors to explore", Simulation, April 1987, pp.131-134

188. Osabe, S.,
"FMS Age and Cutting Tool Technologies ", Metalworking Engineering and Marketing, March 1984, pp.40-44.

189. Pan, J. Y.-C., Tenenbaum, J. M., and Glicksman, J.,
"A Framework for Knowledge-Based Computer Intergrated Manufacturing", IEEE Transactions on Semiconductor Manufacturing, 1989, Vol.2, No.2, pp.33-46

190. Padalkar. S., Karsari, G., Bigol, C., and Sztipanavits, J.
"Real-Time fault diagnosis", IEEE Expert Systems, 1991, June, pp.75-85.

191. Parrish, D.J.
"Flexible Manufacturing", Butterworth-Heinemann, London, 1990.

192. Pedgen, C.D., Shannon, R. E., and Sadowski, R. P.,
" Introduction to Simulation using SIMAN", McGraw-Hill, 1990

193. Pourbabai, B.,
"A short term production planning and scheduling model", Eng. Costs & Production Economies, 18, (1989), pp.159-167.

194. Quinlan, J.C., "Talking with Tools" April, 1988, Tooling & Production pp.50-56

195. Rajgopal, J. and Bidanda, B.
"On scheduling parallel machines with two setup classes", Int.J. Production Research, 1991, Vol.29, No.12, pp.2443-2458.

196. Ranjit, R.
"A premier on Taguchi method", van Nostrand Reinhold, New York, 1990.

197. Ranky, P.G.,
" Design and Operations of Flexible Manufacturing Systems", IFS Publications, 1983.

198. Reddy, C.E., Chetty, O.V.K., and Chaudhuri, D.,
"A Petri nets approach for analysing tool management issues in FMS", Int. J. of Prod. Research, 1992, Vol.30, No.6, pp.1427-1446.

199. Reiser, M. and Lavenberg, S.S,
"Mean-value analysis of closed multi-chain queueing networks", J. ACM, Vol.27, No.2, 1980, pp.313-323

200. Rhodes, J. S.,
"FMS Tool Management Systems", CASA/SME Flexible Manufacturing Systems '86 Conference, March 1986, pp.269-286

201. Rockwell International Printing Machine Plant, Peterborough.

202. Rogers, P., & Williams, D,J.,
"Knowledge-based control in manufacturing automation", Int. J. Comp.Int. Manuf., Vol.1, No.1, pp.21-30, 1988

203. Rolston, L. J., and Miner, R. J.,
"MAP/1" Pristker and Associates, Inc. West Lafeyette, Indiana, 1988

204. Ryzin, G.J.V. et al.
"Scheduling job shops with delay", Int.J. of Prod. Research, 1991, Vol.29, No.7, 1407-1422.

205. Sandvik, Block Tooling System Catolog

206. Sandvik Coromant, Metalworking Products, Compact Reference catologue.

207. Sandvik Coromant, CoroTas Tool Management System Printed material.

208. Sandvik Coromant, Tool Identification System Catologue.

209. Sarin, S.C., and Chen, C.S.,
"The machine loading and tool allocation problem in a flexible manufacturing system", Int. J. of Prod. Research, 1987, Vol.25, No.7, pp.1081-1094.

210. Sarin, S.C. and Salgame, R.R.,
"Development of a knowledge-based system for dynamic scheduling", IJPR, 1990, Vol.28, No.8, pp.1499-1512

211. Schorer, B.J., and Tseng, F.T.,
"Modelling Complex Manufacturing Systems using Simulation", Proc. of the 1987 Winter Simulation Conf. A.Thesen, H.Grant, W. D. Kelton, (eds), pp.677-682, 1987.

212. Schriber, T.J.,
"Perspectives on Simulation Using GPSS", Proce. of the 1989 Winter Simulation Conference, E.A. MacNair, K.J. Musselman, P. Heidelberger (eds), 115-128, 1989.

213. Schweitzer, P.J.,
"Maximum throughput in finite capacity open queueing networks with product form solutions", Management Science, Vol.24, pp.217-224.

214. Shanker, K. and Tzen,J.,
"A loading and dispatching problem in a random FMS", Int.J.Prod.Research, Vol.25 No.3, 1985, pp.579-595

215. Shannon, R.E., Mayer, R., and Adelsberger, H.H.,
"Expert Systems and Simulation", Simulation, June 1985, pp.275-284

216. Shape, Sigma Index CNC Punch Presses catologue.

217. Sharit, J. and Elhence, S.
"Computerization of tool-replacement decision making in flexible manufacturing systems: a human-systems perspective", Int. J. of Prod. Research, 1989, Vol.27, No.12, pp.2027-2039.

218. Shaw, M.J.P., and Whinston, A.B.,
"Applications of artificial intelligence to planning and scheduling in flexible manufacturing", Flexible Manufacturing Systems: A Review of Modelling Approaches for Design, Justification and Operation", Edited by A.Kusiak, Elsevier Science Publishers B.V. (North Holland), 1986, pp.223-242

219. SHW Machine Tools catologue.

220. Silva, C.
"An Investigation into Tooling Requirements and Strategies for FMS Operation", PhD Thesis, LUT, 1988.

221. Simmons,
"Sequencing & Scheduling", John Wiley & Sons, 1982

222. Smith, M.L., Ramesh, R., Dudek,R. and Blair, E.,
"Characteristics of US Flexible Manufacturing Systems Survey", Proc. 2nd ORSA/TIMS Conf. FMS, 1986, pp.477-486

223. SMT CPC Machine Tools Catologue.

224. Solberg, J.J.
"Computer Models for Design and Control of Flexible Manufacturing Systems", 16th NCS, pp.111-117, 1979.

225. Solberg, J.J.,
"Optimal Design and Control of Computerized Manufacturing Systems", Proc. AIIE Systems Engineering Conference, 1976.

226. Solberg, J.J.
"Quantitative design tools for computerized manufacturing systems", Proc. 6th North American Metalworking research committee, Florida, 1978.

227. Solberg, J.J.,
" Mathematical Design tools for integrated production systems", Production 23rd MTDR Conference, 1982.

228. Solot, P. and Bastos, J.M.
"Choosing a queueing model for an FMS", March 1987, Brown Boveri CRB 87-40-C.

229. Spur, G., Seliger, G and Viehweger, B.
"Cell Concepts for flexible automated manufacturing", J. of Manufacturing Systems, 1986, Vol.5, No.3, pp.171-179

230. Stecke, K.E.,
"Design, planning, scheduling and control problems of flexible manufacturing systems", Intelligent Manufacturing, M.Oliff (Ed.), 1988, pp.189-198

231. Stecke, K.E.,
"Formulation and solution of nonlineer Integer Production Planning for Flexible Manufacturing Systems", Management Science, Vol.29, No.3, 1983, pp.273-288.

232. Stecke, K. E., and Kim, I.,
"A fexible approach to implementing the short-term FMS planning function", Proc. 2nd. ORSA/TIMS Conf. on FMS: OR Models and App. Eds. K.E. Stecke & R. Suri, 1986, Michigan, pp.283-295

233. Stratton, T.
Private Communication, Rockwell International, Peterborough.

234. Suri, R.
" An Overview of Evaluative Models for FMS", Annuals of OR, Vol.3, pp.13-21, 1985.

235. Suri, R., and Withney,
"DSS Requirements in FMS", J. of Manufaturing Systems, 1984, Vol3, No1, pp.61-69

236. Suri, R. and Hildebrant, R.R.,
"Modelling flexible manufacturing systems using mean-value analysis", Journal of Manufacturing Systems, Vol.3, No.1, 1984, pp.61-69

237. Syan, C.S.
"A computer-based system for automatic cutting tool selection", Prod.Research, Approaching the 21st Century,1991, M.Pridman & C. O'Brien (Eds.), pp.551-558.

238. Sycara, K.P., et al.
"Reseorce allocation in distributed factory scheduling", IEEE Expert, Feb. 1991, pp. 29-40

239. Synder, J., and Mackulak, G.T.,
Winter Simulation Conference, 1988, pp.357-363

240. Taguchi, G.,
"System of experimental design", New York, UNIPUB, Kraus International Publication, 1987.

241. Talavage, J.J. and Shodhan, R.,
"Automated development of design and control strategy for FMS", Int. J. Comp. Integr. Manuf. Systems, 1992, Vol.5, No.6, pp.335-348.

242. Tang, C.S., and Denardo, E.V.,
"Models arising from a flexible manufacturing machine, Part 1: Minimization of the number of tool switches", Operation Researchs, Vol.36, No.5, pp.767-777, 1988.

243. Tang, C.S., and Denardo, E.V.,
"Models arising from a flexible manufacturing machine, Part 2: Minimization of the number of tool switches", Opeartion Researchs, Vol.36, No.5, pp.778-784, 1988.

244. Toczylowski, E.,
"Optimization of Simultaneous Loading and lot size Scheduling in a Functional Manufacturing Cell", Modern Production Management Systems, Kusiak (Ed.) 1987, pp.107-120]

245. Tomek, P.
"Tooling Concepts for FMS", Proc. 5th Int. Conf. on FMS, November, 1986, pp.315-326

246. Toon, L.K., and Jin, C.T.
"Integration of MRP II, CAPP with an integrated tool management system (ITMS)", Comp. Aided Production Engineering, 1991, Elsevier, (Eds.V.C. Venkatesh and J.A.McGeough), pp.293-303.

247. Torvinen, S.J., Salminen, K., and Vasek, L.
"Integration of a CIM tool management system to an intelligent feature-based process planning system", Computers in Industry, 1991, Vol.17, pp.207-216.

248. Toshiba Machine, Shibaura, BMC-50B, SM87092

249. TOS Olomuc Plant, Reprinted material.

250. Traub Press Information, PI 16/91 e, Traub-TNS 65D.

251. Unal, A.T. And Kiran, A.S.
"Batch Sequencing", 1992, IIE Transactions, Vol.24, No.4, pp.73-83

252. Ventura, J.A., Chen, F.F.,
"Grouping parts and tools in flexible manufacturing systems production planning", Int.J. of Prod. Research, 1990, Vol.28, No.6, pp.1039-1056.

253. Wang, W., and Bell, R.,
"A knowledge based multi-level modelling system for the design of flexible machining facilities", Int. J. Prod. Res., 1992, Vol.30, No.1, pp.13-34.

254. Wang, W.
"A Knowledge based modelling system for the design and evaluation of flexible manufacturing facilities", PhD Thesis, LUT, 1989.

255. Warnecke, H.J., and Dangelmaier, W.,
"Functions and interfaces in a flexible production planning and control system", Comp. Int. Manufacturing Systems, Vol.4, No.1, February 1991, pp.31-41

256. Werner Horizontal Machining Centre Series - TC1, Catalogue.

257. Werner, Horizontal Machining Centre, Series - TC2 Catalogue.

258. Wener-Kolb Machine Tools Catalogue.

259. Werner Kolb, Tool Cassette System Catologue.

260. Wilhelm, W.E. and sarin, S.C.,
"Models for the Design of Flexible Manufacturing Systems", Proc. of Annual Industrial Eng. Conference, 1983.

261. Williamson D.T.N.
"Mollins System 24- A New Concept of Manufacture", Machinery and Production Engineering, October 25, 1967, pp.852-863.

262. Yamashina, H., Okumura, S., and Kumamato, H.,
"Automatic detection of wear and chipping of cutting tools by image processing techniques", Int. J. Prod. Res., 1990, Vol.28, No.4, pp.647-660

263. Yamazaki Mazak Computer Integrated Manufacturing System Catalogue

264. Yamazaki, Mazak H-1000 Machine Tool Catalogue.

265. Yamazaki Mazak, Machine Tools Catalogue.

266. Yamazaki, Mazak Multiplex 620 Machine Tool Catalogue.

267. Yamazaki Mazak Slant Turn 60 & 80 Machine Tool Catalogue.

268. Yamazaki Mazak Tool Hive System Catalogue.

269. Yamazaki Minokamo plant, Reprinted material.

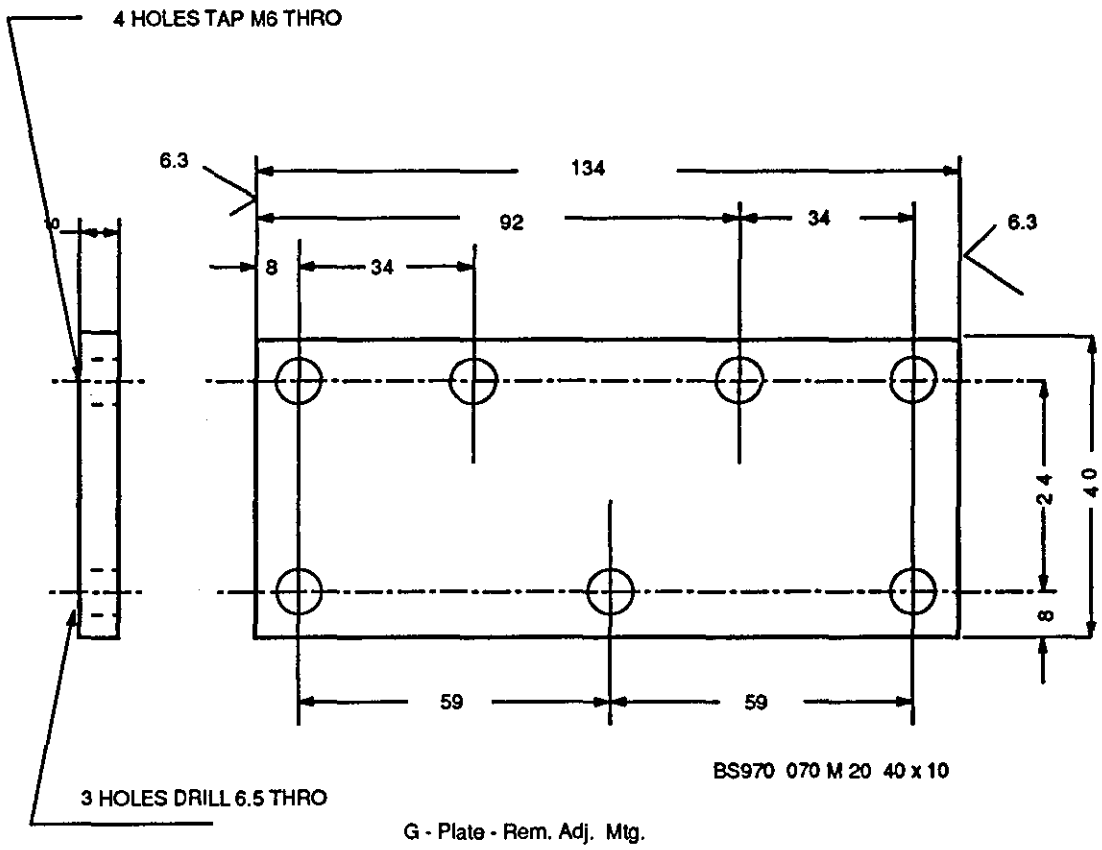
270. Zavenalla, L., and Buguni, A.,
"Planning tool requirements for flexible manufacturing:an analytical approach", Int. J. of Prod. Research, 1992, Vol.30, No.6, pp.1401-1414.

271. Zeleny, Y.,
"FMS with Automated Transport of Tools", Annals of CIRP, 1981, Vol.30, No.1, pp.349-352.

272. Zhang, P.
"The Management of Tool Flows in Flexible manufacturing Systems for Cylindrical Parts ", PhD Thesis, LUT, 1989.

273. Zhou, C., and Whsk, R. A.
"Tool management for computer integrated manufacturing", Int. Industrial Eng. Conference and Societies' Manufacturing and Productivity Symposium Proceedings, 1989, pp.603-607.

Appendix I
Part-Tool Data

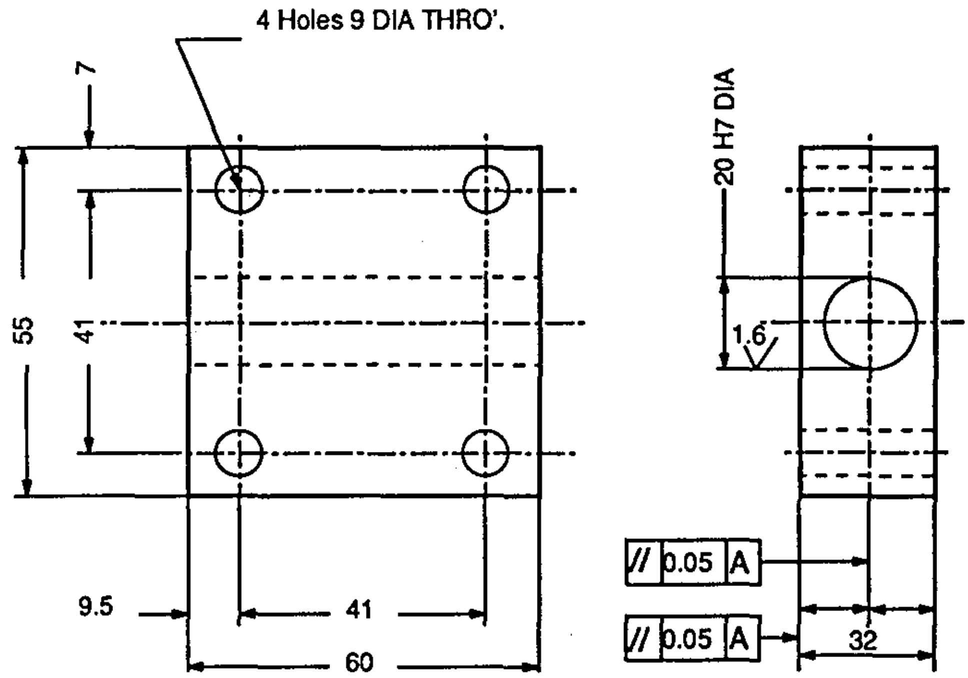


Part I.D: 6604053D **Description:**

Material:

Op. No.	M/C	Operation Description	Set-Up Time	Cutt. Time	Tool Type
1		Milling	0.31	1	T5320
2		Milling		0.9	T5321
3		Drilling		1.6	T1050
4		Drilling		1.3	T1066
5		Tapping		1.7	T2060

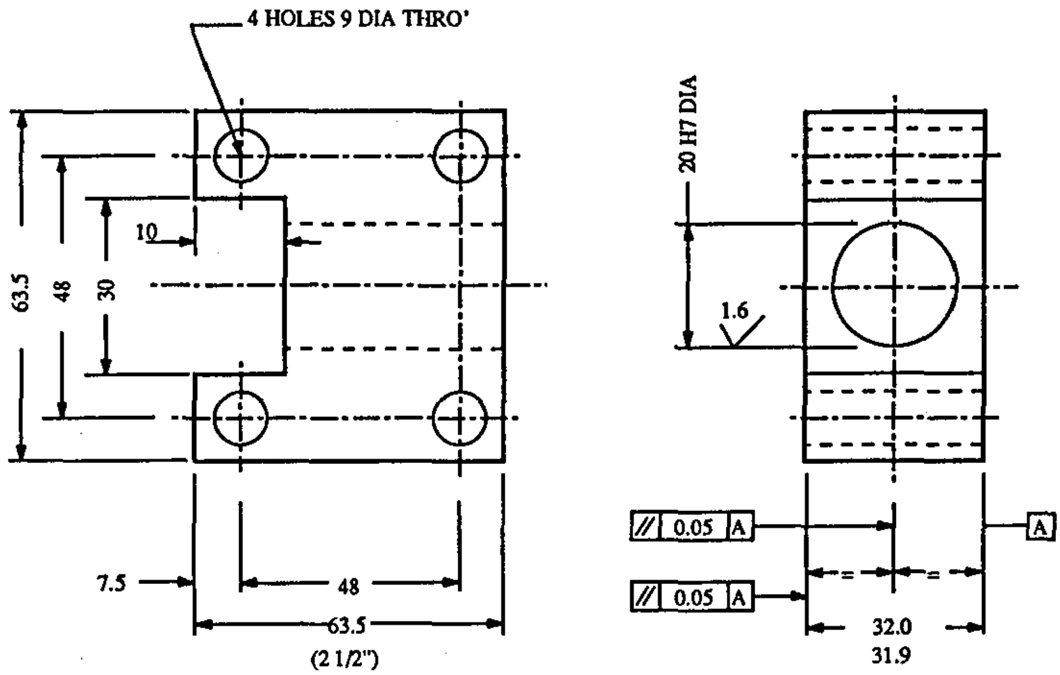
Figure I-1	Workpiece Information - Part No. 6604053D	LUT-FMS Research Gr.



1. ALL MACHINING 3.2 ✓ UNLESS OTHERWISE STATED
2. BLAKODISE
3. REMOVE ALL SHARP CORNERS

Part I.D: 6603985D		Material:	Description		
Oper. No.	**M/C**	**Operation Description**	**Set-Up Time**	**Cutt. Time**	**Tool Type**
1		Milling	0.17	1.6	T5625
2		Milling		5.5	T5200
3		Milling		2.3	T5626
4		Drilling		2.1	T1197
5		Reaming		8.3	T3200

Figure I-2	Part No. 6603986B	LUT-FMS Research Gr.



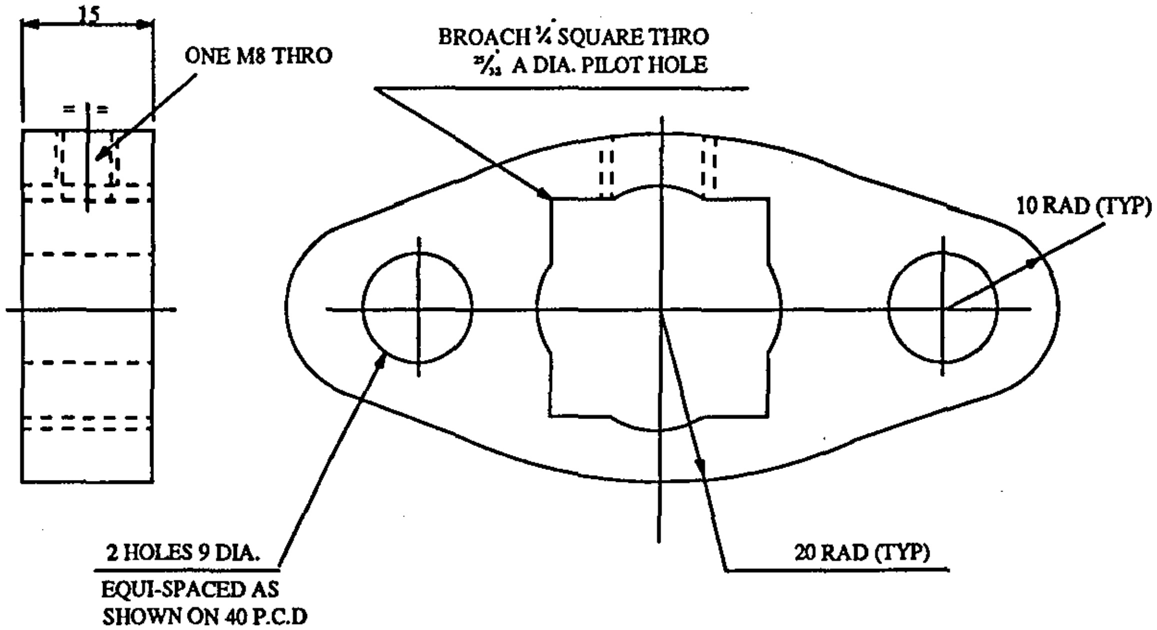
1. All Machining 3.2 Unless Otherwise Stated
2. Blackodise
3. Remove All Sharp Corners

Part I.D: 6603985D Description:

Material:

Ope. No.	M/C	Operation Description	Set-Up Time	Cutt. Time	Tool Type
1		Milling	0.17	1.6	T5625
2		Milling		5.5	T5200
3		Milling		2.3	T5626
4		Drilling		2.1	T1197
5		Reaming		8.3	T3200

Figure I-3 | Workpiece Information - Part No. 6603985D | LUT-FMS Research Group

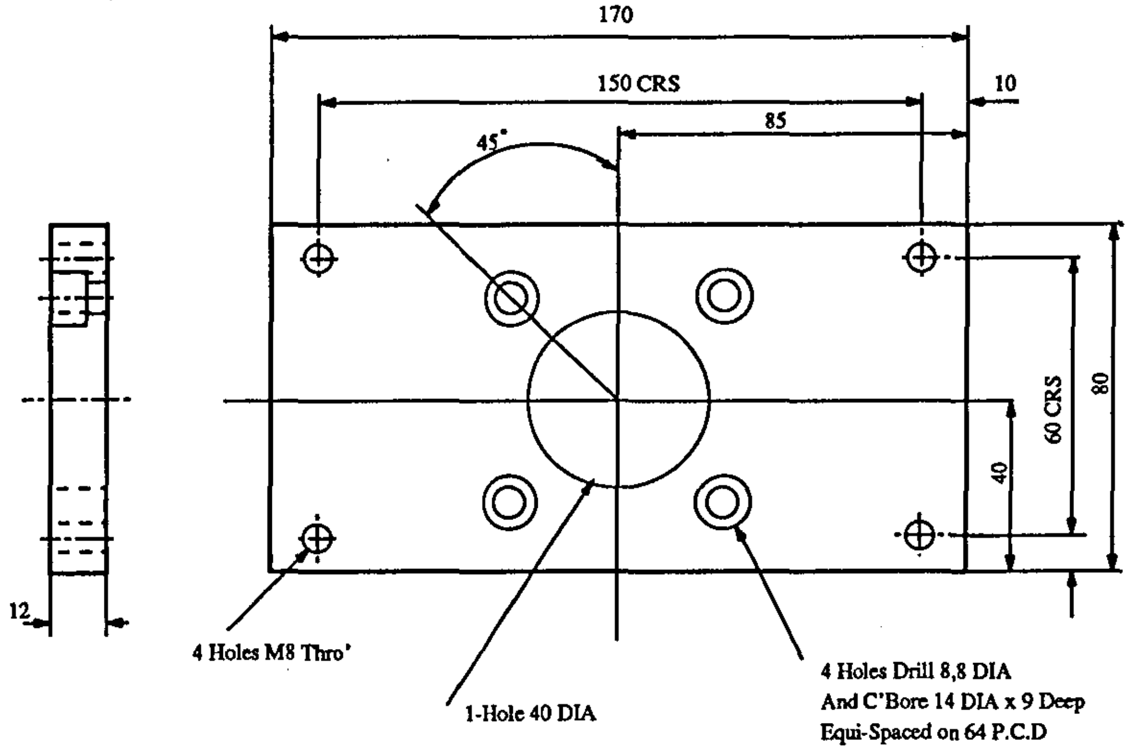


Part I.D: 6600921A **Description:**

Material:

Ope. No.	M/C	Operation Description	Set-Up Time	Cutt. Time	Tool Type
1		Drilling	0.2	0.9	T1197
2		Reaming		1.9	T3200
3		Drilling		1.4	T1001
4		Drilling		0.8	T1068
5		Tapping		0.7	T2080
6		Drilling		2	T1090

Figure I-4	Workpiece Information - Part No. 6600921A	LUT-FMS Research Group



Part I.D: 6406623D

Description:

Material:

Op. No.	M/C	Operation Description	Set-Up Time	Cutt. Time	Tool Type
1		Drilling	1.42	1.7	T1068
2		Drilling		1.6	T1137
3		Drilling		1.2	T1088
4		Milling		3.2	T5140
5		Drilling		0.7	T1390
6		Boring		1	T4040
7		Chamfering		1.4	T7012
8		Tapping		1.5	T2080

Figure I-5	Workpiece Information - Part No.6406623D	LUT - FMS Research Group

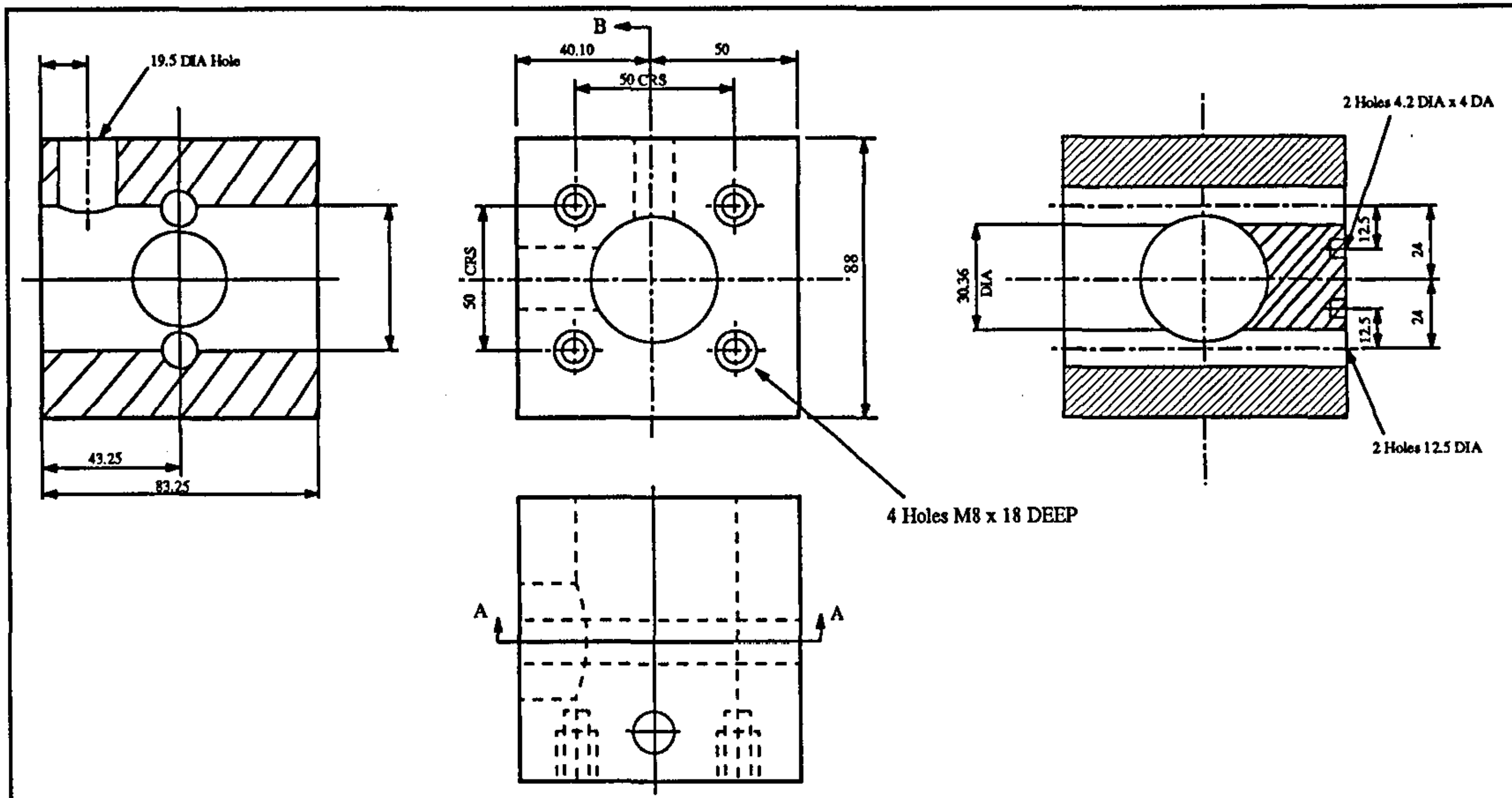
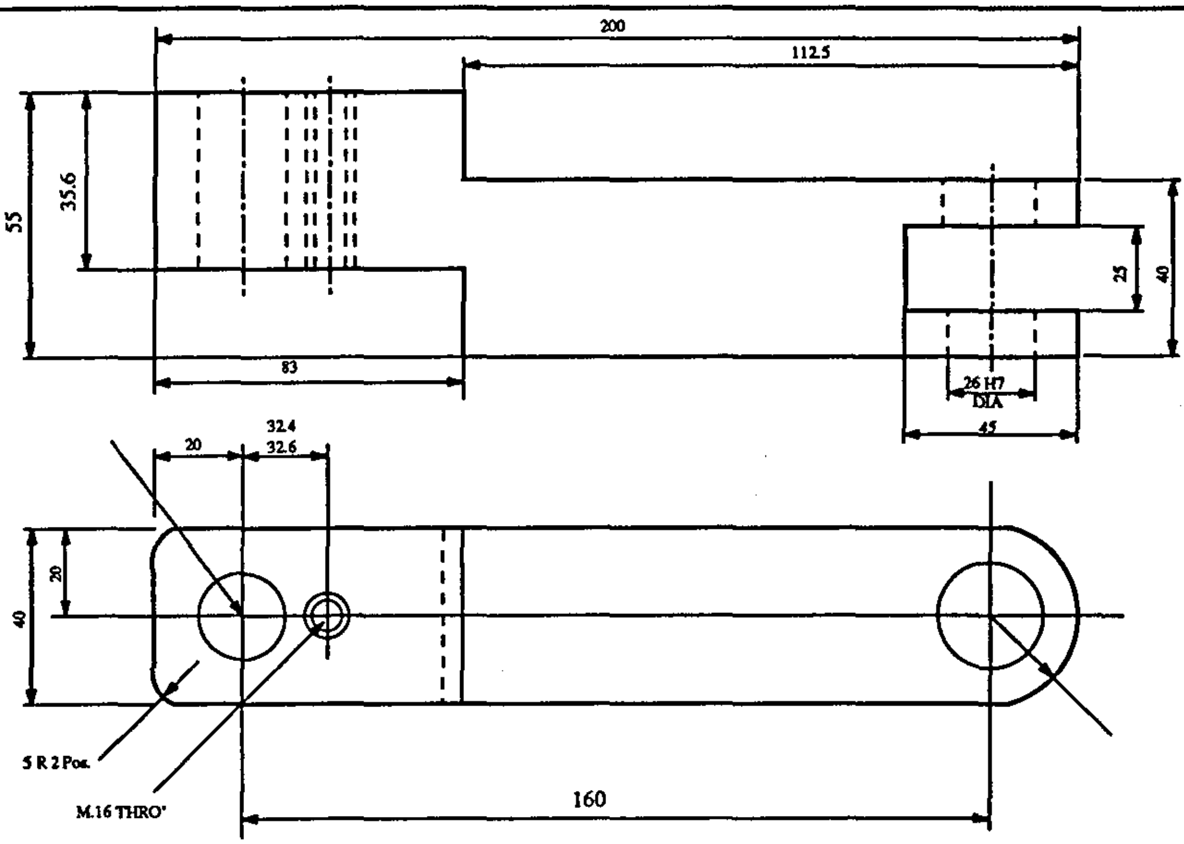


Figure I-6	Workpiece Information - 6414204F	LUT-FMS Research Group



Part I.D: 6488280E Material: Description:

Ope. No.	M/C	Operation Description	Set-Up Time	Cutt. Time	Tool Type
1		Milling	0.38	4.9	T5625
2		Milling		4.3	T5630
3		Drilling		1.1	T1257
4		Drilling		1.3	T1197
5		Drilling		1.3	T1140
6		Reaming		3.1	T3200
7		Reaming		3.6	T3260
8		Tapping		0.9	T2160
9		Chamfering		1.2	T7012

Figure I-7 Workpiece Information - Part No.6488280E LUT-FMS Research Group

Tool No	Tool Type	Tool Life	Tool Cost(£)	Total in STS	Refurb/ Dispo.	Refurb. Cost	Max. No.of Ref.
1	T1001	360	75		R	4.25	10
2	T1025	60	2		R	4.25	10
3	T1033	60	4		R	4.25	10
4	T1042	120	4		R	4.25	10
5	T1050	90	4		R	4.25	10
6	T1052	60	4		R	4.25	10
7	T1057	60	4		R	4.25	10
8	T1066	150	4		R	4.25	10
9	T1068	120	4		R	4.25	10
10	T1077	120	4		R	4.25	10
11	T1082	60	4		R	4.25	10
12	T1085	60	4		R	4.25	10
13	T1088	60	4		R	4.25	10
14	T1090	120	4		R	4.25	10
15	T1097	90	4		R	4.25	10
16	T1102	90	4		R	4.25	10
17	T1110	120	4		R	4.25	10
18	T1117	60	4		R	4.25	10
19	T1120	25	8.20		R	4.25	10
20	T1137	120	30		D	0	0

Figure I-8	Tool Data	LUT - FMS Research Gr.

Tool No	Tool Type	Tool Life	Tool Cost(£)	Total in STS	Refurb/ Dispo.	Refurb. Cost	Max. No.of Ref.
21	T1140	125	30		D	0	0
22	T1157	60	30		D	0	0
23	T1182	45	30		R	4.25	10
24	T1190	45	30		R	4.25	10
25	T1197	60	30		R	4.25	10
26	T1217	100	30		R	4.25	10
27	T1247	80	30		D	0	0
28	T1257	45	30		D	0	0
29	T1297	60	30		D	0	0
30	T1310	25	3.70		D	0	0
31	T1340	40	3.70		D	0	0
32	T1390	20	3.70		R	4.25	10
33	T1440	25	3.70		R	4.25	10
34	T1490	30	3.70		R	4.25	10
35	T1650	25	3.70		R	4.25	10
36	T2040	60	9.75		R	4.25	10
37	T2050	60	10.15		D	0	0
38	T2060	60	10.15		R	4.25	10
39	T2080	120	12.20		R	4.25	10
40	T2081	60	13.15		R	4.25	10

Figure I-10	Tool Data	LUT - FMS Research Gr.

Tool No	Tool Type	Tool Life	Tool Cost(£)	Total in STS	Refurb/ Dispo.	Refurb. Cost	Max. No.of Ref.
41	T2100	60	13.6		R	4.25	10
42	T2120	50	17.45		R	4.25	10
43	T2160	60	24.35		R	4.25	10
44	T3080	100	96.8		D	0	0
45	T3100	120	96.15		D	0	0
46	T3120	110	99		D	0	0
47	T3140	120	104		D	0	0
48	T3160	120	109		D	0	0
49	T3200	100	106.55		D	0	0
50	T3220	100	123.57		R	4.25	10
51	T3260	100	124.1		D	0	0
52	T3300	100	142.25		D	0	0
53	T4032	135	2.45		D	0	0
54	T4035	135	2.45		D	0	0
55	T4040	135	2.45		D	0	0
56	T4045	135	2.45		D	0	0
57	T4050	25	2.45		D	0	0
58	T5050	30	3.82		R	5	3
59	T5080	300	4.32		R	5	3
60	T5100	80	7.23		R	5	3

Figure I-11	Tool Data	LUT - FMS Research Gr.

Tool No	Tool Type	Tool Life	Tool Cost(£)	Total in STS	Refurb/ Dispo.	Refurb. Cost	Max. No.of Ref.
61	T5120	180	5.87		R	5	3
62	T5140	240	5.87		R	5	3
63	T5180	300	10.78		R	5	3
64	T5182	200	16.25		R	5	3
65	T5200	200	12		R	5	3
66	T7012	120	4		R	5	3
67	T7016	60	4		R	5	3
68	T5251	90	10.20		R	5	3
69	T5320	50	5.63		R	5	3
70	T5321	120	350		R	45	10
71	T5500	60	6.5		R	5	10
72	T5625	65	9.2		R	5	10
73	T5626	360	4.72		R	5	10
74	T5630	65	4		R	5	10
75	T6125	300	4		R	5	10
76	T6160	300	4		R	5	10
77	T6180	90	5		R	5	10
78	T6200	270	4		R	5	10
79	T7001	45	2.5		R	5	10
80							

Figure I-12	Tool Data	LUT - FMS Research Gr.

Appendix II

Computer Modelling and Tool Management Prototype Software

Appendix II

Computer Modelling and Tool Management Prototype Software

II.1 Introduction

In this appendix, the software design is presented and the user is introduced to the modules which form the prototype tool management design facility. The functions and structure of each model is presented to understand the tool management design facility's capability. Explanations are presented for each stage of the prototype software with menu screens for the purpose of guiding users to use of the software.

II.2 Model Overview

The tool management system (TMS) design facility consists of following modules:

1. Relational Database Management System (RDBMS),
2. Expert Scheduling,
3. Tool Requirements Planning,
4. Expert Tool Management Strategy Selection, and
5. Expert Tool Management Interrogation system.

Three main commercial software packages have been used as platforms within the TMS design facility. Firstly, the Knowledge Engineering System (KES) has been used for the design of the scheduling, strategy selection and interrogation system. Secondly Lotus 123 has been used for the design of the tool requirements planning and finally the ORACLE relational database has been used for the design of the tool management and manufacturing system database. Each module has own its menu system and can be used either as part of the integrated design tool or as a standalone design facility. The relational database is in the centre point and supports all other modules and stores the semi-processed and processed output to transfer from one module to another.

II.3. Database Management System

Databases are defined as the collection of information that can be accessed by both end-users and application programs. A large amount of data for parts, tools, machines, operations, cells and other ancillary functions has to be manipulated among several computer programs in TMS design process. The data set has to have a certain format and a logical relation with other parts of the data set. It has to be easily updated, deleted, changed, stored, transferred and reached. Therefore a relational database management system (RDBMS) is a major part of the tool management design facility.

A commercial relational database management system, ORACLE, has been used to store the TMS data set and to support the other design models. The database serves as a store for all those parameters common to all the modelling tools. The shared information essentially includes jobs, workstations, tools, tool stores and cell data organised in a relational hierarchy such that for example, tools are related to jobs and jobs may be related to workstations.

The database management system has been built in 10 blocks. These are; cell block, part block, tool block, workstation block, jobs block, operation block, pallet block, primary tool store block, secondary tool store block, batch block. Each block is connected with the others by one or more reference data.

All the blocks can be run in any sequence and for any number of times, so that each block can be processed individually without touching the rest. Once the data has been input, it is possible to edit any individual data entry without requiring the need to edit the whole data record again.

Each block has its own menu system and access to the data is done by querying the data. Also, the next and previous records can be easily reached. The data handling, querying and accessing related data in another block is made much easier because of the software used.

System Block: The system block stores the general system data such as tool inventory, performance measurements and time related data. Figure II.1 The system block is linked to cell block.

Workstation Block: This block stores the machine data such as PTS capacity, number of spindles, set-up time etc. Fig.II.2. Workstation data is linked to cell block.

Cell Block : The cell block stores the general data which should be known in any manufacturing cell. Figure II.3. Several blocks are linked to the cell block. These are: the part block, system block, STS block, generic manufacturing workstation block and pallet block.

Part Block : The part block stores all the part data as well as keeps the data related to batch, pallet and cell visited. It is easily found which part belongs to which cell and which pallets are used and to which batch they belong. Figure II.4. The part block is linked to cell, pallet and process batch blocks.

Pallet Block : The pallet block stores all pallet related data. Figure II.5. Pallet block is linked to the cell, part and process batch blocks.

Kit Block: The kit block stores all the tool sets data and is linked to cell, tool and job blocks. Figure II.6.

STS Block: STS block stores the local tool store data as well as time related data. Figure II.7. and is linked to the cell block.

Tool Block: This block stores all tool related data. Figure II.8 and is linked to cell, STS and job blocks.

Process Batch Block: This block stores the process batch data, Figure II.9 and is linked to cell, part, job and pallet blocks.

Job Block : Job block stores all the jobs data Figure II.10 and is linked to cell, part, process batch and kit blocks.

II.4. Expert Production Scheduling

Expert production scheduling is the first module in the expert tool management design facility. Select 1 in the main menu, Figure II.11, to enter the production scheduling module. Now, the production scheduler module is ready to run. There are four options in this module. Figure II.12. The part scheduling to a manufacturing cell option releases the parts to the related cell which has been chosen either randomly or technologically but in both cases in capable of processing the jobs. The scheduler considers part batching, part kitting, prioritised release or other user defined rules and enables user interaction to represent the user knowledge and also the facility to introduce "new" jobs or delete "previous" jobs.

The second option is to part schedule to the individual workstations. This option allows users to see which job goes to which station and list jobs for related machines. Four scheduling rules have been practiced in the expert scheduler. These are, earliest due date assignment (EDD), shortest processing time (SPT), longest processing time (LPT) and grouped parts in terms of used tools (GRP). Due to data transfer difficulties between the expert system and the database, four expert systems have been produced separately and each one runs one specific part scheduling rule.

If there are identical machines which can perform the same operations, the expert system first prefers the idle one and if both of them are idle, this time prefers the one on which workload rate is less in order to balance the machine workload and utilisation.

The third option is to view the job release to the manufacturing workstation. This is functionally not an active option but it gives a better view to user in order to get clear understanding. This option includes tool data which is received from tool requirements planning and visualises the accompanied tool kit, tool list, sister tools and the kit cost for that particular operation as well as job start and finish times, selected station and the release value as a statistic.

The last option is to exit to the main menu back.

This module is interactive with tool requirements planning and partly feeds TRP by giving the machining list and what the batch size should be and receives some of the processed data (output) to visualise to the user. (Option 2 and 3)

II.5 Expert Tool Management Strategy Selection

Strategy selection is the second module in expert design facility. Select 2 from the main menu to introduce the strategy selection module. When you introduce the TMSS module, a new menu which belongs to TMSS appears. Figure II.13. This menu is basically in three groups which views of the issue strategies' results, strategy selection which has one sub-menu for different configurations. Figure II.14. and justification of the selected strategy.

The first four operations of the TMSS menu give the global results to the users which were gathered from tool requirements planning for kitting strategy, differential kitting strategy, single tools strategy and cluster analysis respectively. The captive tool size, cost, machine utilisation, transportation utilisation, throughput and lead time output are demonstrated here globally which tool strategy selection is basically based on these outputs.

The next two options (6 and 7 in menu) are the global view of the job and machine data which are used as input in the entire expert system. The option to diagnose the system orientation (8 in the menu) selects the suitable tool management strategy, i.e. workpiece-oriented or tool-oriented. When this option is selected, the expert system asks a range of questions to figure out what type of hardware configurations and what type of soft automation is in use. Then, this interactive option suggests one strategy which could be applied to that particular configuration. Every single question should be answered clearly so as not to confuse the expert system and in order to reach a clear suggestion. Optionally, if it is desired, default values can be put in the program to prevent so many questions each time, but this is only valid if the hardware configuration and the software automation in use are fixed and not to be changed for a certain period. Default values force the expert system to choose the most suitable strategy and this will remain the same unless the defaults are changed.

The 10th option is tool issue strategy selection and this option triggers another sub-menu, Figure II.14, which gives several options to choose. These are the best strategy for the overall system or cell or workstations and the justification of these results. If the system is a multi-cell, multi-machine environment, more than one strategy may be applied at the same time for different parts of the system. For example, depending on the configuration, one strategy may be suitable for one machine but some other strategies could be more suitable for the other machines. But one strategy will give a better performance for the overall system. The first option makes this suggestion by assessing the entire system based on pre-determined one or more user selected criteria. These criteria are :

- captive tool size,
- tool inventory,
- machine utilisation,
- throughput time,
- minimum tool flow.

The expert system first asks which of the criteria is/are of primary importance for the user and then decides the best strategy which is convenient for that particular configuration and criteria.

For the second and third options, basically the same process will be repeated but this time for the manufacturing cell and workstations respectively.

The expert system makes a decision for both cases and suggests the best strategy based on the user selected criteria and hardware configuration.

Finally, the expert system in the main and sub-menu of the TMSS justifies the decision made. At this point a range of rules that force the expert system to the make decision will appear on the screen Figure II.16. These rules may not be meaningful for the end user because of the programmer writing style.

The final options in TMSS are exit which returns to previous menus.

II.6 Expert Tool Management Output Analysis

The tool management interrogation system is the final option in the expert design facility. This option calls the interrogation menu (Figure II.17), which basically contains two main options. These are system performance analysis and system operation problems and fault detection. These two basic options each has their own menu, Figure II.22. and Figure II.23. respectively.

The interrogation system is uses all the other modules' output as input to make decisions or assess the output from the other modules.

Performance analysis assesses workstation, central tool store, secondary tool store, primary tool stores, tool and transportation utilisation respectively and explains the tool movement in the FMC, the tools used, the cost for a particular joblist and the FMC hardware configuration. A final report is produced for the throughput and lead time.

The second part of the interrogation system is a fault diagnosing system which has been designed to solve major and widely met manufacturing problems within the tool management context. First, problems has been classified as manufacturing, cell, machine and tooling problems. Then a set of possible solutions have been provided for each problem likely to be met. However problem discovery mostly relies on interactive communication of man and machine. The TMIS asks a range of questions in order to describe the facility configuration and asks for the acceptable user tolerances in order to assess the output which has been produced by tool requirements planning and strategy selection. In addition to the current situation, the program structure lets the user define their own possible problems and solution rules.

The system, then, provides solutions to the problems faced (option 9) and justifies the problems (options 5 to 8) and the solutions (option 10). The final options in both menus return the user to the main menu.

II.7 Tool Requirements Planning

Tool requirements planning (TRP) is the core of the tool management system design facility Figure II.20, and calculates the requested tool number by the job, job list and entire system applying the several part and tool issue strategies. The module is supported by the knowledge-based batching and scheduling system and the database. The module has been implemented in a Lotus 123 spreadsheet. Unfortunately, due to the nature of the software, there is no front-end user interface to make it easier to use.

Although TRP is supported by the relational database, at the same time, TRP has its own database Figure II.21.

Three workpiece-oriented tool issue strategies; namely, kitting, differential kitting, and single tools and one tool oriented tool issue strategy, dynamic cluster analysis, have been implemented to calculate the tool requirements. Jobs are sequenced by the knowledge-based scheduling system and transferred to TRP (See Section II.4.1.).

The module specifies tool requirements, kit size for each related batch, tool configuration, tool inventory, number of sister tools, worn tools, primary and secondary tool store configurations, actual tool usage, tool monitoring and production throughput time. Mainly, the module gives the answers to the questions of what type of tools, how many tools, where, how and when tools are going to be used for several sized batches when the specified tool issue strategy is used.

The spreadsheet has been divided into three main parts, input, output, and macros. Inputs include tool data, part data, pallet data, machine data, and cell data. Outputs, as stated above include tooling, tool store and system output. Macros are the Lotus 123 programming code which are written for six different issue strategies.

To move from one place to another arrows keys or page down, page up or Lotus 123's own facility function key, F5, specifying the destination address can be used. The spreadsheet is used both horizontally and vertically. The output is given under the specified title. To see the related data, the cursor could be moved horizontally. Each line shows specific output.

- **Dynamic Cluster Analysis :** Although it is part of TRP, this strategy has been implemented in a separate spreadsheet. It contains two variants dynamic clustering full kitting and DCDK. The analysis, Figure II.22 commences with the building up of a two dimensional array for parts and tools. The cluster analysis then, may, in its simplest form, be expressed as that of determining by a process of row and column exchanges of the array, a conversion from a haphazard pattern of data into an arrangement whereby the data is contained in mutually exclusive groups.

After the first clustering iteration, the identified clustered jobs are removed from the initial part-tool matrix and will be assigned to nearest idle workstation. The rest of the jobs are then re-organized and re-clustered to determine new tool cluster sets. This process could be repeated up to the last group of job clustered. This dynamic approach uses the same clustering algorithm , ROC, applied by De Souza [3] and it is based on the static clustering developed by De Souza and Bell [4], but it is more efficient. This new form of cluster analysis gives better clusters and the chance to cluster more times as well as a more realistic tool requirement.

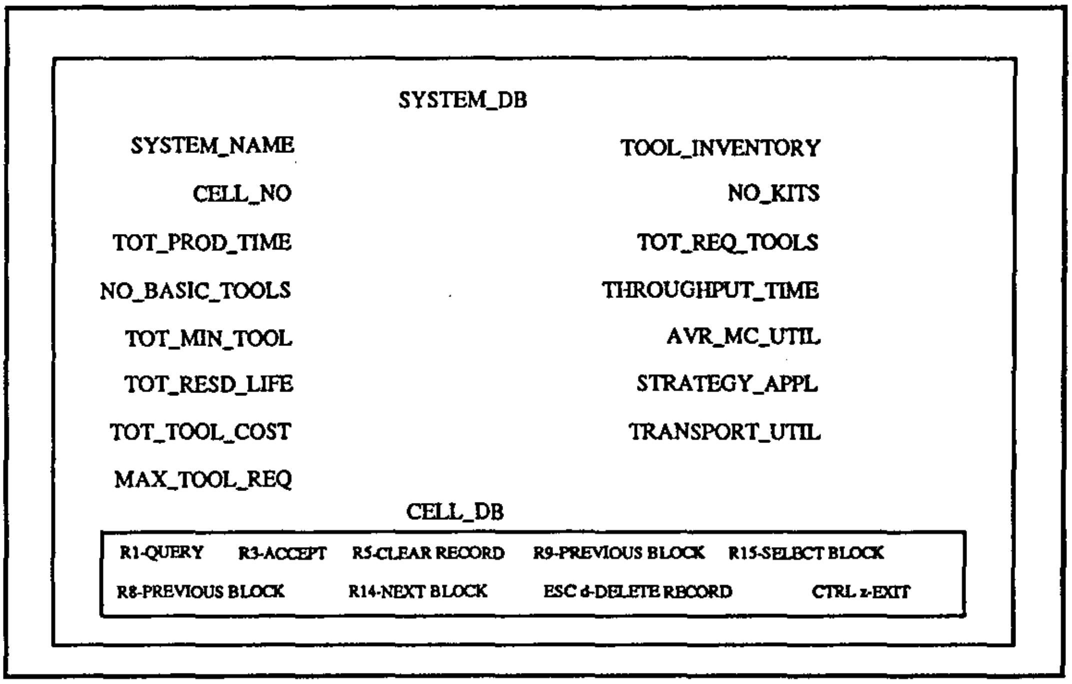


Figure II.1	TMS - Database System Block Screen	LUT-FMS Research Group

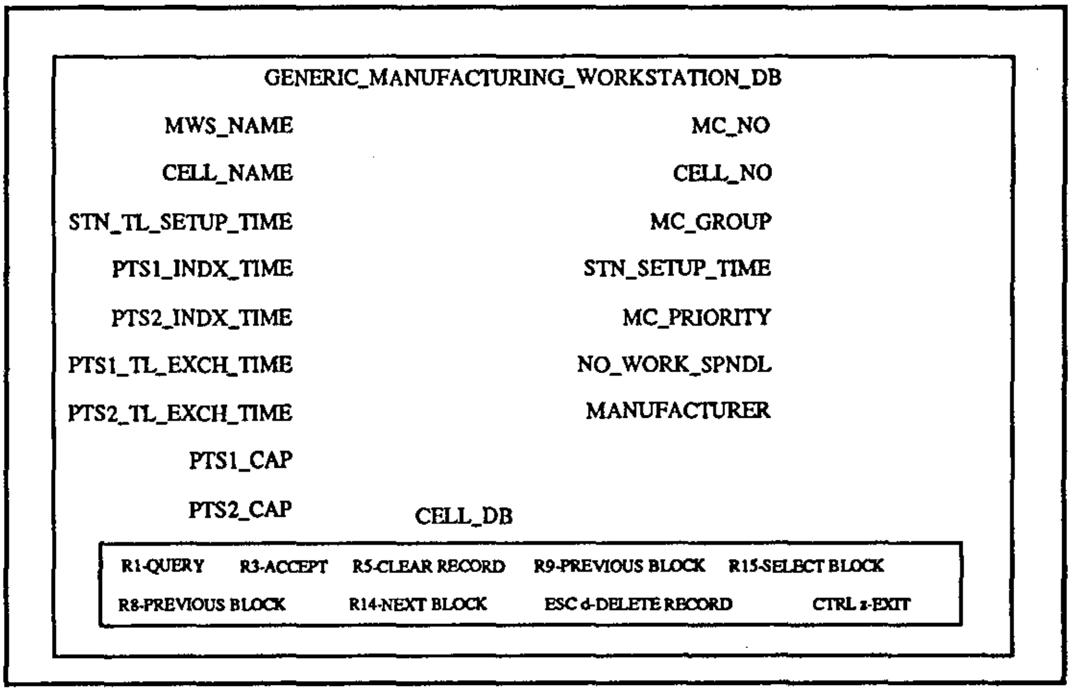


Figure II.2	TMS Database - Workstation Block Screen	LUT-FMS Research Group

CELL_DB

CELL_NAME NO_PALLETS
CELL_NO STS_NAME
NO_MACHINE TOOL_INVENTORY
NO_PARTS
STS_CAPACITY

CELL_DB PART_DB STS_DB GMWS_DB PALLET_DB SYSTEM_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK
R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II.3	TMS - Database Cell Block Screen	LUT-FMS Research Group

PART_DB

CELL_NAME CELL_NO
PART_NO PART_NAME
NO_SUBOPS SCHEDULED(Y/N)

CELL_DB PALL_DB OP_PRO_BAT_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK
R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II.4	TMS Database - Part Block Screen	LUT-FMS Research Group

PALL_DB

CELL_NAME	SCHEDUL_PALL(Y/N)
CELL_NO	PALL_TYPE
PALLET_NAME	PALL_CAPA
NO_PALL_AVAIL	PALL_TIME
PALL_PRIORITY	PART_NAME
FIXT_TYPE	PART_NO

CELL_DB PART_DB OP_PRO_BAT_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK
R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II.5	TMS - Database Cell Block Screen	LUT-FMS Research Group

KIT_DB

CELL_NAME	CELL_NO
KIT_TYPE	JOB_NO
KIT_SIZE	TOOL_USED
BAS_KIT_SIZE	WORN_TOOLS
OP_PRO_BAT_NO	SISTER_TOOLS
TOOL_OP_TIME	CRITICAL_TOOLS
	SCHEDULED(Y/N)

CELL_DB TOOL_DB JOB_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK
R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II.6	TMS Database - Tool Kit Block Screen	LUT-FMS Research Group

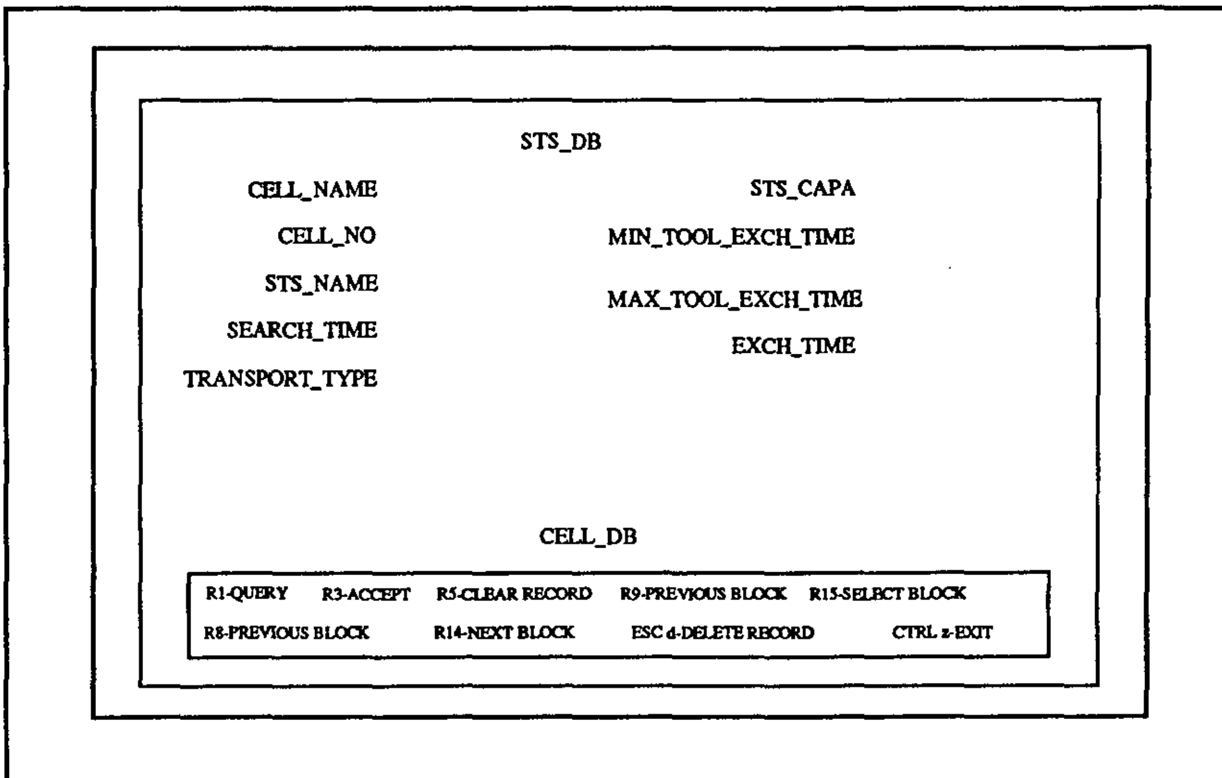


Figure II-7 | TMS - Database STS Block Screen | LUT-FMS Research Group

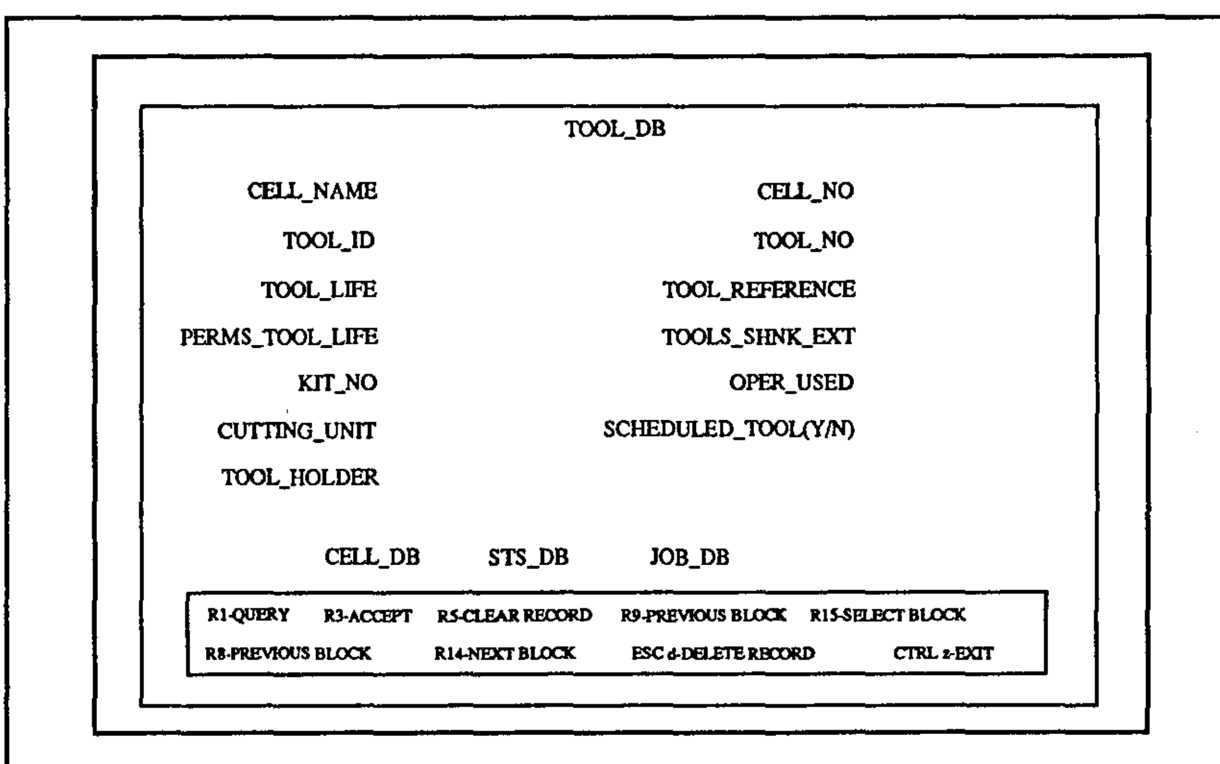


Figure II-8 | TMS Database - Tool Block Screen | LUT-FMS Research Group

OPERATION_PROCESS_BATCH_DB

CELL_NAME PART_NO

CELL_NO PALLET_TYPE

NO_OPER TOOL_LIST

PROC_BATCH_SIZE TOT_OP_TIME

NO_TRANS_BATCH NO_PALL_AVAIL

TRANS_BATCH_SIZE SCHEDULED_PR_BATCH(Y/N)

REM_BATCH_SIZE

CELL_DB JOB_DB KIT_DB PALL_DB PART_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK

R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II-9	TMS - Database Process Batch Block Screen	LUT-FMS Research Group

JOB_DB

CELL_NAME CELL_NO

TOOL_ID JOB_NO

BASIC_KIT_SIZE

JOB_PRIORITY

PALL_QUANT

PROC_BATCH_NO

MC_NAME

PRC_BATCH_QUANT

MC_GROUP

MACHINING_TIME

KIT_NAME

PALL_TIME

DEPALL_TIME

KIT_SIZE

JOB_OPER_PREDESSOR

KIT_NO KIT_NAME

CELL_DB PART_DB OP_PROC_BAT_DB KIT_DB

R1-QUERY R3-ACCEPT R5-CLEAR RECORD R9-PREVIOUS BLOCK R15-SELECT BLOCK

R8-PREVIOUS BLOCK R14-NEXT BLOCK ESC d-DELETE RECORD CTRL z-EXIT

Figure II-10	TMS Database - Job Block Screen	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. JOB SCHEDULING SYSTEM
2. TOOL MANAGEMENT DECISION SUPPORT SYSTEM
3. TOOL MANAGEMENT INTERROGATION SYSTEM
4. QUIT

=? 1

Figure II.11	DSS Main Menu	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. VIEW JOB RELEASE TO MANUFACTURING CELL
2. SCHEDULE JOBS TO MANUFACTURING WORKSTATIONS
3. VIEW JOB RELEASE TO MANUFACTURING WORKSTATIONS
4. QUIT

=? 1

Figure II.12	Scheduling Menu	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. View global system results for the kitting strategy
2. View global system results for the differential kitting strategy
3. View global system results for the single tools strategy
4. View global system results for the dynamic cluster analysis strategy
5. View global system results for the hybrid single tools strategy
6. View job data
7. View station data
8. Diagnose the system orientation
9. Justify the system orientation
10. Tool Issue Strategy Selection
11. Leave this menu

=? 1

Figure II.13	Strategy Selection Menu	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. BEST STRATEGY FOR OVERALL SYSTEM
2. BEST STRATEGY FOR THE MANUFACTURING CELL
3. BEST STRATEGY FOR THE MANUFACTURING WORKSTATION
4. JUSTIFY THE SELECTED STRATEGY
5. EXIT

=? 1

Figure II.14	Strategy Selection Alt Menu	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. TOOL INVENTORY
2. MACHINE UTILIZATION
3. THROUGHPUT TIME
4. TOOL MOVEMENT
5. CAPTIVE TOOL SIZE

= ? 1

Figure II.15	Priority List	LUT-FMS Research Group

4. JUSTIFY THE SELECTED STRATEGY

****

For the selected strategy hybrid kitting the justification is :

****

The value of the best strategy = "hybrid kitting"

This is due to the following knowledge sources:

Rule : Strategy_rule2 selects the best strategy for overall system

Would you like to see the supporting knowledge sources and demons? (y/n)

Name : Strategy_rule2 selects the best strategy for overall system

Kind of entity : Production Rule

....

Figure II.16	Expert System Justification	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. SYSTEM PERFORMANCE ANALYSIS
2. SYSTEM OPERATION PROBLEMS AND FAULT DETECTION
3. EXIT

= ? 1

Figure II.17	Interrogation Menu	LUT-FMS Research Group

WHAT WOULD YOU LIKE TO DO?

1. MANUFACTURING WORKSTATION UTILIZATION
2. CTS UTILIZATION
3. STS UTILIZATION
4. PTS UTILIZATION
5. TOOL UTILIZATION
6. TRANSPORTER UTILIZATION
7. THROUGHPUT AND LEAD TIME REPORT
8. EXIT

= ? 1

Figure II.18	Performance Analysis Menu	LUT-FMS Research Group

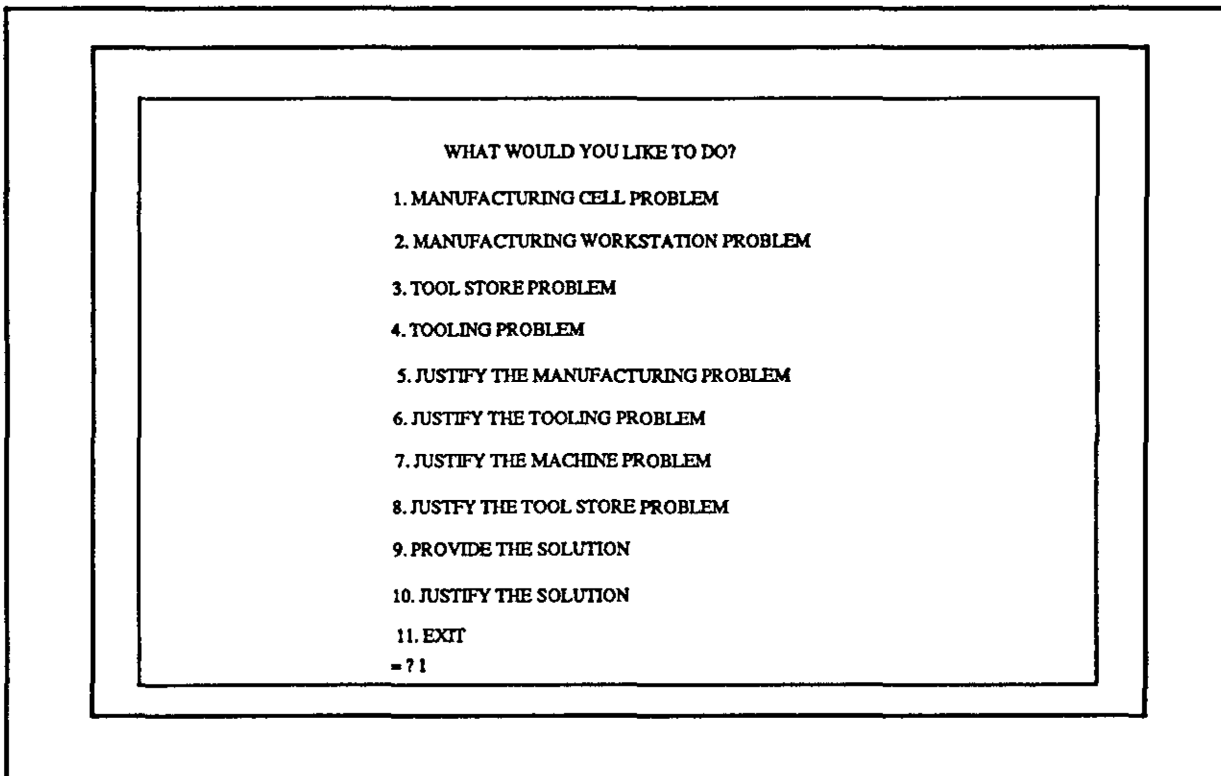


Figure II.19	Fault Detection Menu	LUT-FMS Research Group

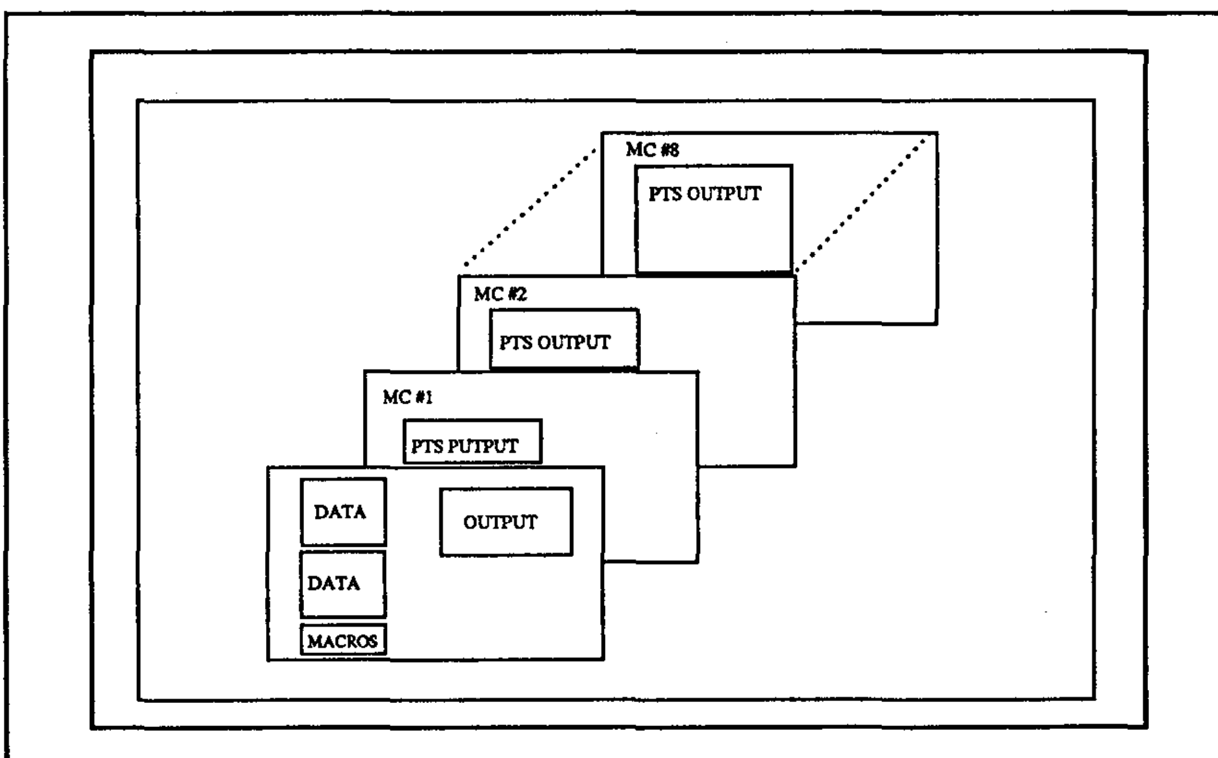


Figure II.20	TRP Layout	LUT-FMS Research Group

PARTS / TOOLS	PART1	PART2	....	PART 70	TOOL LIFE	PERMISSIBLE TOOL LIFE
T1001	0	0		0	360	0.90
T1025	5.7	3		0	60	0.90
T1033	0	4		0	120	0.90
T1042	0	0		1	90	0.90
T1050	0	5		1.2	60	0.90
BATCH SIZE	8	8	....	8	8	

Figure II.21	TRP Database Structure	LUT-FMS Research Group

Parts

A	Tools	7	15	43	12	65	2	23	29	36
3	5	1	1	1	1	1	1			
4	13	1	1	1	1	1	1			
5	9	1	1	1	1	1	1			
6	2	1	1	1	1	1	1			
7	55	1	1	1	1	1	1			
8	43	1	1	1	1	1	1			
9	22	1	1	1	1	1	1			
10	28							1	1	1
11	19							1	1	1
12	14							1	1	1
13	11							1	1	1
14	20							1	1	1
15	31							1	1	1
16	24							1	1	1
17	15									
18	6									
19	17									
20	8									
21	29									
22	3									
23	71									
24	42									

Frequent Clustering Screen

Parts

A	Tools	41	57	14	21	65	55	75	15	32
3	5	1	1	1	1	1	1			
4	33	1	1	1	1	1	1	1	1	1
5	3							1	1	1
6	41	1	1					1	1	1
7	27	1	1	1	1	1	1			
8	16			1	1	1	1			
9	17	1	1	1	1	1	1	1	1	
10	8									1
11	9				1	1	1			
12	11				1	1	1	1	1	
13	44							1	1	
14	58									1
15	14				1	1	1			
16	26				1	1	1			
17	35	1	1							
18	73	1	1							
19	71							1	1	
20	18									
21	19									
22	20									
23	21									1
24	22									1

Infrequent Clustering Screen

Figure II.22	Cluster Analysis Screen	LUT-FMS Research Group

Appendix III

Mathematical Representation of Scheduling Model
and
Scheduling Output

(Complementary to Chapter 6)

Appendix III
Mathematical Representation of Scheduling Model
and
Scheduling Output

III.1 Introduction

This appendix presents the mathematical representation of the scheduling model presented a in rule-based and algorithmic format in Chapter 6. The Appendix further gives the scheduling output generated by the rule-base model.

III.2 Nomenclature and Mathematical Representation of Model

The nomenclature and terminology used throughout the batching and scheduling problem in Chapter 6 is set out as below:

$I:\{i \mid i = 1,2,\ldots,N\}$ *the index set of jobs*

$M:\{m \mid m = 1,2,\ldots,U\}$ *the index set of machines*

$J:\{j \mid j = 1,2,\ldots,V\}$ *the index set of operations of part i*

$T:\{t \mid t = 1,2,\ldots,L\}$ *the index set of tools*

$S:\{s \mid s = 1,2,\ldots,F\}$ *the index set of components that form the batch(job)*

$V:\{v \mid v = 1,2,\ldots,D\}$ *process batch (order quantity) for a given period*

$P:\{p \mid p = 1,2,\ldots,E\}$ *the index set of pallets*

$C:\{c \mid c = 1,2,\ldots,H\}$ *the index set of parts*

B_{ij} = *size of batch (job), i=1,2,...,n produced by operation j*

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

M_{iju} = *process j of i is carried out on machine M using tool set u (kit)*

U_{ijt} = *process j of job i uses tool set t which forms kit U*

Z_m = *magazine capacity of machine m*

P_{iju} *size of pallets which contain job i, its operation use kit u*

The rule based logic presented in Chapter 6 may be expressed in the mathematical modelling form as follows :

$\text{Max}\sum B_{ij}$

$U_{ijt} \leq Z_m \; \textit{for all } m$

$B_{iju} \leq P_{iju}$

$\textit{all variables} \geq 0$

III.3 Production Scheduling

The nomenclature and terminology defined in the previous section is used to express scheduling in a mathematical modelling form which was already defined in the rule-based form in Chapter 6, Sec.3.2.

$$\textit{Process Batch},\; V = \sum_{c \in C} s$$

$\textit{job} = \textit{number of pallets x components}$

$i = \sum_{p \in E} \sum_{s \in F} p \times s \quad \textit{number of operation in a job(batch)}$

$= i \times u = \sum_{p \in E} \sum_{m \in U} s \times u$

$X_{ijpm} = 1$ *if operation j of pallet p of job i is assigned machine m*

$= 0$ *otherwise*

$Z_{ijp} = 1$ *if operation j of pallet p of job i is assigned*

$= 0$ *otherwise*

W_{ijp} *the processing time of operation j of all components of pallet p, job i*

The total processing time of operations j of job i which contains number of components s, performed on machine m

$$\sum W_{ijm}, W'_{ijm} = \sum_{p=1}^{E_i} W_{ijm} \times X_{ijpm}$$

Total processing time of job i (transfer batch)

$$W_i = \sum_{j \in M} W_{ij} = \sum_{j=1}^{S_i} W_{ij} = \sum_{m \in U} \sum_{j \in M} W_{ijm} = \sum_{p=1}^{E_i} \sum_{j \in M} W'_{ijpm}$$

Pallet processing time, P_{ip} the time required to complete pallet p of job i $P_{ip} = (\Sigma P_{ij}) \times P_i$

Total waiting time that the pallet p of job i should wait before the commence of operation j

Total waiting time of job i $B_i = \sum_{p=1}^{E_i} \sum_{j \in M} b_{ipj}$

Makespan (Throughput time) K is the sum of the processing times of all jobs

$$K = \sum_{v=1}^{D} \sum_{p=1}^{E} \sum_{j=1}^{M} W'_{ijpu} \times V_i$$

Completion time (H_i): The time point at which all the operations of the job i have been completed,

$H_i = e_i + P_i + B_i$

e_i: set up time

Due Date (d_i) is the date line for the jobs completion

Lateness of job i $L_i = H_i - d_i$

Tardiness of job i $T_i = \max\{L_i, 0)$

Earliness of job i $E_i = \max\{0, -L_i\}$

III.4 Rule-Base Scheduling Output

```
{Mustafa:45} kesr tmsdss.pkb

Knowledge Engineering System (KES), Release 3.0.
Copyright 1990, Software Architecture & Engineering, Inc.
Loading the knowledge base 'tmsdss.pkb'.

 *****************************************************
  *          KNOWLEDGE BASED                              *
  *        JOB RELEASE MECHANISM                          *
  *  TOOL MANAGEMENT DECISION SUPPORT SYSTEM              *
  *            &                                          *
  *   TOOL MANAGEMENT INTERROGATION SYSTEM                *
  *           by  M. Ozbayrak                             *
  *  Loughborough University of Technology                *
  *   Dept. of Manufacturing Engineering.                 *
 *****************************************************

 This knowledge base selects a job from a job list
   to be released into a flexible machining cell
 using production rules based on priority release
  for Work [and Tool] Assignments to Workstations
 and makes a decision to find the best tool issue
 starategy for a selected cell configuration based
 on the issue of: tool kits, differential tool kit
  dynamic tool cluster sets, single tools kits,
        Hybrid Single Tools Strategy.
  Finally Expert System analyses the both job
  release and DSS  output and gives cell as well
      as plant level report for the TMS.
 TMS Output Interrogation System analyses the
  outputs and gives several suggestions for the
   faced tooling problems in cell environment.
           KBfile:TMSDSS.KB
    datafiles:JOBS.DAT,PALL.DAT,STAT.DAT,
           CLUS.DAT,STRAT.DAT

Type 'c' to continue

Ready for command: c

There are: 17 jobs to be scheduled
to 4 available manufacturing workstations.

What is the scheduling period ?

(Enter a number)
=? 1440

What would you like to do ?

  1. Job Scheduling System
  2. Tool Management Decision Support System
  3. Tool Management Interrogation System
  4. Quit
=? 1

What would you like to do ?
```

1. Schedule jobs to manufacturing workstations
2. View job release to manufacturing cell
3. View job release to manufacturing workstations
4. quit

=? 1

job: none is not feasible
job: job1 is feasible
job: job2 is feasible
job: job3 is feasible
job: job4 is feasible
job: job5A is feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job1
the station selected for its manufacture is : stations1
this job had its preceeding operation in job: none

job1 has now been completed on stations1

jobs released to cell: 1

job: none is not feasible
job: job1 is not feasible
job: job2 is feasible
job: job3 is feasible
job: job4 is feasible
job: job5A is feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job2
the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job1

job2 has now been completed on stations2 jobs released to cell: 2

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is feasible
job: job4 is feasible
job: job5A is feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job3
the station selected for its manufacture is : stations3
this job had its preceeding operation in job: job2

job3 has now been completed on stations3

jobs released to cell: 3
job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is feasible
job: job5A is feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job4
the station selected for its manufacture is : stations4
this job had its preceeding operation in job: job3

job4 has now been completed on stations4

jobs released to cell: 4

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible

job: job3 is not feasible
job: job4 is not feasible
job: job5A is feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job5A
the station selected for its manufacture is : stations4
this job had its preceeding operation in job: job4

job5A has now been completed on stations4

jobs released to cell: 5

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is feasible
job: job5C is feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job5B
the station selected for its manufacture is : stations3
this job had its preceeding operation in job: job5A
job5B has now been completed on stations3

jobs released to cell: 6

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is feasible

job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job5C
the station selected for its manufacture is : stations1
this job had its preceeding operation in job: job5B

job5C has now been completed on stations1

jobs released to cell: 7

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job6
the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job5C

job6 has now been completed on stations2

jobs released to cell: 8

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is feasible
job: job8 is feasible
job: job9 is feasible

job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job7
the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job6

job7 has now been completed on stations2

jobs released to cell: 9

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is feasible

job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job8
the station selected for its manufacture is : stations3
this job had its preceeding operation in job: job7

job8 has now been completed on stations3

jobs released to cell: 10

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible

job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job9
the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job8
job9 has now been completed on stations2

jobs released to cell: 11

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job10
the station selected for its manufacture is : stations4
this job had its preceeding operation in job: job9

job10 has now been completed on stations4

jobs released to cell: 12

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is not feasible
job: job11 is feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job11

the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job10

job11 has now been completed on stations2

jobs released to cell: 13

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is not feasible
job: job11 is not feasible
job: job12 is feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job12
the station selected for its manufacture is : stations3
this job had its preceeding operation in job: job11

job12 has now been completed on stations3

jobs released to cell: 14

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is not feasible
job: job11 is not feasible
job: job12 is not feasible
job: job13 is feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job13
the station selected for its manufacture is : stations4
this job had its preceeding operation in job: job12

job13 has now been completed on stations4 jobs released to cell: 15

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is not feasible
job: job11 is not feasible
job: job12 is not feasible
job: job13 is not feasible
job: job14 is feasible
job: job15 is feasible

the feasible job released into the cell is : job14
the station selected for its manufacture is : stations1
this job had its preceeding operation in job: job13

job14 has now been completed on stations1

jobs released to cell: 16

job: none is not feasible
job: job1 is not feasible
job: job2 is not feasible
job: job3 is not feasible
job: job4 is not feasible
job: job5A is not feasible
job: job5B is not feasible
job: job5C is not feasible
job: job6 is not feasible
job: job7 is not feasible
job: job8 is not feasible
job: job9 is not feasible
job: job10 is not feasible
job: job11 is not feasible
job: job12 is not feasible
job: job13 is not feasible
job: job14 is not feasible
job: job15 is feasible

the feasible job released into the cell is : job15
the station selected for its manufacture is : stations2
this job had its preceeding operation in job: job14

job15 has now been completed on stations2

jobs released to cell: 17

Type 'c' to continue or 's' to stop.

What would you like to do ?

1. Schedule jobs to manufacturing workstations
2. View job release to manufacturing cell
3. View job release to manufacturing workstations
4. quit

=? 2

*********************** CELL JOB RELEASE TABLE ************************

Job	: job1
Release Value	: 1
Start Time	: 2
Finish Time	: 527.35999
Kit Size	: 11
Diff. Kit Size	: 11
Single Kit Size	: 11
Hybrid S.T.Kit Size	: 11
Tool List	: T5625,T5626,T1197,T1390,T4040,T3200,T7012,T5500,T6200
Sister Tools	: 1390,T6200
NoOf Sister Tools	: 1,1
No of Basic Tools	: 9
Kit Cost	: 0
Kit	: Kit1

Job	: job2
Release Value	: 2
Start Time	: 2
Finish Time	: 269.67999
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T1068,T1137,T1088,T5140,T1390,T4040,T7012,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 8
Kit Cost	: 0
Kit	: Kit2

Job	: job3
Release Value	: 3
Start Time	: 15
Finish Time	: 250.44
Kit Size	: 9
Diff. Kit Size	: 9
Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T1068,T1137,T1088,T5140,T1390,T4040,T7012,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 67.5
Kit	: Kit3

Job	: job4
Release Value	: 4
Start Time	: 2
Finish Time	: 112.64
Kit Size	: 9
Diff. Kit Size	: 9
Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T5320,T5120,T1247,T5200,T3260,T1110,T5100,T7012,T7001
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 0
Kit	: Kit4

Job	: job5A
Release Value	: 5
Start Time	: 112.64
Finish Time	: 684.32001
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: T1066,T3140
NoOf Sister Tools	: 1,1
No of Basic Tools	: 6
Kit Cost	: 0
Kit	: Kit5

Job	: job5B
Release Value	: 6
Start Time	: 250.44
Finish Time	: 823.62
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: T1066,T3140
NoOf Sister Tools	: 1,1
No of Basic Tools	: 6
Kit Cost	: 0
Kit	: Kit6

Job	: job5C
Release Value	: 7
Start Time	: 527.35999
Finish Time	: 811.12
Kit Size	: 6
Diff. Kit Size	: 5
Single Kit Size	: 5
Hybrid S.T.Kit Size	: 5
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 6

Kit Cost	: 0
Kit	: Kit7

Job	: job6
Release Value	: 8
Start Time	: 269.67999
Finish Time	: 671.35999
Kit Size	: 13
Diff. Kit Size	: 13
Single Kit Size	: 13
Hybrid S.T.Kit Size	: 13
Tool List	: T5320,T5050,T1090,T5080
Sister Tools	: T5050
NoOf Sister Tools	: 9
No of Basic Tools	: 4
Kit Cost	: 0
Kit	: Kit8

Job	: job7
Release Value	: 9
Start Time	: 671.35999
Finish Time	: 836.07996
Kit Size	: 12
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 8
Tool List:	T5625,T1137,T1490,T5626,T4050,T7012,T1068,T2080,T1247,T1297,T3300,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 11
Kit Cost	: 0
Kit	: Kit9

Job	: job8
Release Value	: 10
Start Time	: 823.62
Finish Time	: 858.21997
Kit Size	: 5
Diff. Kit Size	: 5
Single Kit Size	: 5
Hybrid S.T.Kit Size	: 5
Tool List	: T1140,T4045,T1001,T1090,T1042
Sister Tools	: NONE
NoOf Sister Tools	: 0
No of Basic Tools	: 5
Kit Cost	: 0
Kit	: Kit10

Job	: job9
Release Value	: 11
Start Time	: 836.07996
Finish Time	: 1248.48
Kit Size	: 10
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 10
Tool List	: T5230,T5321,T1001,T1117,T3120,T1050,T2060
Sister Tools	: T1050,T1117,T2060

NoOf Sister Tools	: 1,1,1
No of Basic Tools	: 7
Kit Cost	: 0
Kit	: Kit11

Job	: job10
Release Value	: 12
Start Time	: 684.32001
Finish Time	: 730.76001
Kit Size	: 4
Diff. Kit Size	: 4
Single Kit Size	: 4
Hybrid S.T.Kit Size	: 3
Tool List	: T1247,T1157,T3160,T5050
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 4
Kit Cost	: 0
Kit	: Kit12

Job	: job11
Release Value	: 13
Start Time	: 730.76001
Finish Time	: 872.14001
Kit Size	: 8
Diff. Kit Size	: 7
Single Kit Size	: 7
Hybrid S.T.Kit Size	: 2
Tool List	: T5320,T1247,T5200,T3260,T1110,T5100,T7012,T7001
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 8
Kit Cost	: 0
Kit	: Kit13

Job	: job12
Release Value	: 14
Start Time	: 858.21997
Finish Time	: 1352.1599
Kit Size	: 9
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1001,T1042,T1102,T1050,T2120
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 7
Kit Cost	: 0
Kit	: Kit14

Job	: job13
Release Value	: 15
Start Time	: 730.76001
Finish Time	: 1014.82
Kit Size	: 11
Diff. Kit Size	: 9

Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T5625,T5626,T1190,T1090,T1077,T3080,T5180,T5181,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 11
Kit Cost	: 0
Kit	: Kit15

Job	: job14
Release Value	: 16
Start Time	: 811.12
Finish Time	: 1056.86
Kit Size	: 9
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 6
Tool List	: T5625,T5626,T1190,T1090,T1077,T3080,T5180,T5181,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 0
Kit	: Kit16

Job	: job15
Release Value	: 17
Start Time	: 872.14001
Finish Time	: 1109.36
Kit Size	: 12
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 5
Tool List	T5320,T5180,T5200,T5321,T1050,T1068,T1097,T1137,T3100,T3140,T2060,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 12
Kit Cost	: 0
Kit	: Kit17

Type 'c' to continue or 's' to stop.

What would you like to do ?

1. Schedule jobs to manufacturing workstations
2. View job release to manufacturing cell
3. View job release to manufacturing workstations
4. quit

=? 3

******************** STATION JOB RELEASE TABLE ********************

Station	: stations1
Group	: 1
Release Value	: 1
Job	: job1
Start Time	: 2
Finish Time	: 527.35999
Kit	: Kit1
Kit Size	: 11
Diff. Kit Size	: 11
Single Kit Size	: 11
Hybrid S.T.Kit Size	: 11
Tool List	: T5625,T5626,T1197,T1390,T4040,T3200,T7012,T5500,T6200
Sister Tools	: 1390,T6200
NoOf Sister Tools	: 1,1
No of Basic Tools	: 9
Kit Cost	: 0

Station	: stations1
Group	: 1
Release Value	: 2
Job	: job5C
Start Time	527.35999
Finish Time	: 811.12
Kit	: Kit7
Kit Size	: 6
Diff. Kit Size	: 5
Single Kit Size	: 5
Hybrid S.T.Kit Size	: 5
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 6
Kit Cost	: 0

Station	: stations1
Group	: 1
Release Value	: 3
Job	: job14
Start Time	: 811.12
Finish Time	: 1056.86
Kit	: Kit16
Kit Size	: 9
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 6
Tool List	: T5625,T5626,T1190,T1090,T1077,T3080,T5180,T5181,T7012

Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 1
Job	: job2
Start Time	: 2
Finish Time	: 269.67999
Kit	: Kit2
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T1068,T1137,T1088,T5140,T1390,T4040,T7012,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 8
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 2
Job	: job6
Start Time	: 269.67999
Finish Time	: 671.35999
Kit	: Kit8
Kit Size	: 13
Diff. Kit Size	: 13
Single Kit Size	: 13
Hybrid S.T.Kit Size	: 13
Tool List	: T5320,T5050,T1090,T5080
Sister Tools	: T5050
NoOf Sister Tools	: 9
No of Basic Tools	: 4
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 3
Job	: job7
Start Time	: 671.35999
Finish Time	: 836.07996
Kit	: Kit9
Kit Size	: 12
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 8
Tool List	T5625,T1137,T1490,T5626,T4050,T7012,T1068,T2080,T1247,T1297,T3300,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 11
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 4
Job	: job9
Start Time	: 836.07996
Finish Time	: 1248.48
Kit	: Kit11
Kit Size	: 10
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 10
Tool List	: T5230,T5321,T1001,T1117,T3120,T1050,T2060
Sister Tools	: T1050,T1117,T2060
NoOf Sister Tools	: 1,1,1
No of Basic Tools	: 7
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 5
Job	: job11
Start Time	: 730.76001
Finish Time	: 872.14001
Kit	: Kit13
Kit Size	: 8
Diff. Kit Size	: 7
Single Kit Size	: 7
Hybrid S.T.Kit Size	: 2
Tool List	: T5320,T1247,T5200,T3260,T1110,T5100,T7012,T7001
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 8
Kit Cost	: 0

Station	: stations2
Group	: 1
Release Value	: 6
Job	: job15
Start Time	: 872.14001
Finish Time	: 1109.36
Kit	: Kit17
Kit Size	: 12
Diff. Kit Size	: 10
Single Kit Size	: 10
Hybrid S.T.Kit Size	: 5
Tool List	T5320,T5180,T5200,T5321,T1050,T1068,T1097,T1137,T3100,T3140,T2060,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools: 12	
Kit Cost	: 0

Station	: stations3
Group	: 1
Release Value	: 1
Job	: job3
Start Time	: 15
Finish Time	: 250.44
Kit	: Kit3

Kit Size	: 9
Diff. Kit Size	: 9
Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T1068,T1137,T1088,T5140,T1390,T4040,T7012,T2080
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 67.5

Station	: stations3
Group	: 1
Release Value	: 2
Job	: job5B
Start Time	: 250.44
Finish Time	: 823.62
Kit	: Kit6
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: T1066,T3140
NoOf Sister Tools	: 1,1
No of Basic Tools	: 6
Kit Cost	: 0

Station	: stations3
Group	: 1
Release Value	: 3
Job	: job8
Start Time	: 823.62
Finish Time	: 858.21997
Kit	: Kit10
Kit Size	: 5
Diff. Kit Size	: 5
Single Kit Size	: 5
Hybrid S.T.Kit Size	: 5
Tool List	: T1140,T4045,T1001,T1090,T1042
Sister Tools	: NONE
NoOf Sister Tools	: 0
No of Basic Tools	: 5
Kit Cost	: 0

Station	: stations3
Group	: 1
Release Value	: 4
Job	: job12
Start Time	: 858.21997
Finish Time	: 1352.1599
Kit	: Kit14
Kit Size	: 9
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1001,T1042,T1102,T1050,T2120
Sister Tools	: None
NoOf Sister Tools	: 0

No of Basic Tools	: 7
Kit Cost	: 0

Station	: stations4
Group	: 1
Release Value	: 1
Job	: job4
Start Time	: 2
Finish Time	: 112.64
Kit	: Kit4
Kit Size	: 9
Diff. Kit Size	: 9
Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T5320,T5120,T1247,T5200,T3260,T1110,T5100,T7012,T7001
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 9
Kit Cost	: 0

Station	: stations4
Group	: 1
Release Value	: 2
Job	: job5A
Start Time	: 112.64
Finish Time	: 684.32001
Kit	: Kit5
Kit Size	: 8
Diff. Kit Size	: 8
Single Kit Size	: 8
Hybrid S.T.Kit Size	: 8
Tool List	: T5320,T5321,T1066,T1137,T3140,T7012
Sister Tools	: T1066,T3140
NoOf Sister Tools	: 1,1
No of Basic Tools	: 6
Kit Cost	: 0

Station	: stations4
Group	: 1
Release Value	: 3
Job	: job10
Start Time	: 684.32001
Finish Time	: 730.76001
Kit	: Kit12
Kit Size	: 4
Diff. Kit Size	: 4
Single Kit Size	: 4
Hybrid S.T.Kit Size	: 3
Tool List	: T1247,T1157,T3160,T5050
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 4
Kit Cost	: 0

Station	: stations4
Group	: 1
Release Value	: 4

Job	: job13
Start Time:	730.76001
Finish Time	: 1014.82
Kit	: Kit15
Kit Size	: 11
Diff. Kit Size	: 9
Single Kit Size	: 9
Hybrid S.T.Kit Size	: 9
Tool List	: T5625,T5626,T1190,T1090,T1077,T3080,T5180,T5181,T7012
Sister Tools	: None
NoOf Sister Tools	: 0
No of Basic Tools	: 11
Kit Cost	: 0

Type 'c' to continue or 's' to stop.

Appendix IV
TRP Output
(Complementary to Chapter 7)

Workpiece-Oriented Experiments Output

Tables & Graphs

The Supplementary Experiment No. 17

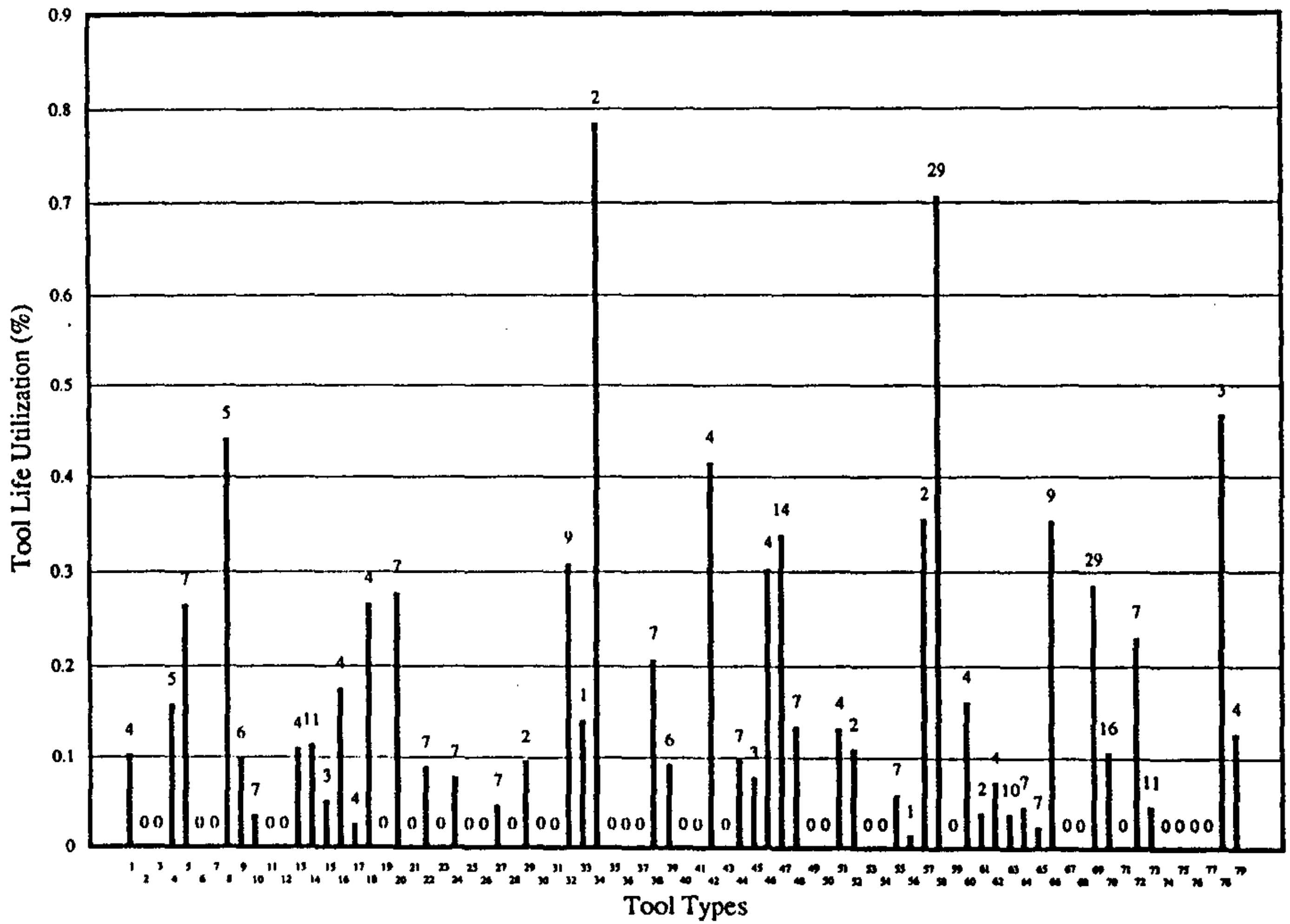
Throughput Time : 1520.65 Avr. Transport Util.(%): 11.022

Avr. MC Util.(%): 95.452

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	Tool Usage
4	0.41	3.59	0	1	24	4	0.10
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
5	0.80	4.20	0	1	12	5	0.16
7	1.85	5.15	0	2	27	7	0.26
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
5	2.20	2.80	0	3	31	5	0.44
6	0.60	5.40	0	1	11	6	0.10
7	0.26	6.74	0	1	8	7	0.04
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	0.44	3.56	0	1	5	4	0.11
11	1.27	9.73	0	2	16	11	0.12
3	0.16	2.84	0	1	4	3	0.05
4	0.71	3.29	0	1	11	4	0.18
4	0.11	3.89	0	1	4	4	0.03
4	1.07	2.93	0	2	12	4	0.27
0	0.00	0.00	0	0	0	0	0.00
7	1.95	5.05	0	2	42	7	0.28
0	0.00	0.00	0	0	0	0	0.00
7	0.63	6.37	0	1	7	7	0.09
0	0.00	0.00	0	0	0	0	0.00
7	0.55	6.45	0	1	8	7	0.08
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
7	0.34	6.66	0	1	7	7	0.05
0	0.00	0.00	0	0	0	0	0.00
2	0.19	1.81	0	1	2	2	0.10
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
9	2.78	6.22	0	3	11	9	0.31
1	0.14	0.86	0	1	1	1	0.14
2	1.57	0.43	0	2	2	2	0.79
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
7	1.45	5.55	0	2	16	7	0.21
6	0.56	5.44	0	1	11	6	0.09
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	1.66	2.34	0	2	11	4	0.42
0	0.00	0.00	0	0	0	0	0.00
7	0.68	6.32	0	1	8	7	0.10
3	0.24	2.76	0	1	4	3	0.08
4	1.21	2.79	0	2	12	4	0.30
12	4.06	7.94	2	5	35	14	0.34
7	0.95	6.05	0	1	7	7	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	0.53	3.47	0	1	4	4	0.13
2	0.22	1.78	0	1	2	2	0.11
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
7	0.42	6.58	0	1	11	7	0.06
1	0.01	0.99	0	1	1	1	0.01
2	0.71	1.29	0	1	2	2	0.36
15	10.61	4.39	9	11	15	24	0.71
0	0.00	0.00	0	0	0	0	0.00
4	0.65	3.35	0	1	4	4	0.16
2	0.08	1.92	0	1	2	2	0.04
4	0.30	3.70	0	1	5	4	0.07
10	0.40	9.60	0	1	19	10	0.04
7	0.33	6.67	0	1	8	7	0.05
7	0.18	6.82	0	1	8	7	0.03
9	3.18	5.82	0	4	56	9	0.35
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
25	7.15	17.85	4	8	79	29	0.29
16	1.72	14.28	0	2	51	16	0.11
0	0.00	0.00	0	0	0	0	0.00
7	1.61	5.39	0	2	16	7	0.23
11	0.52	10.48	0	1	27	11	0.05
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.40	1.60	0	2	6	3	0.47
4	0.51	3.49	0	1	4	4	0.13
296	59	237	15	86	669	311	

The Supplementary Experiment No. 17 - Tool Life Utilization



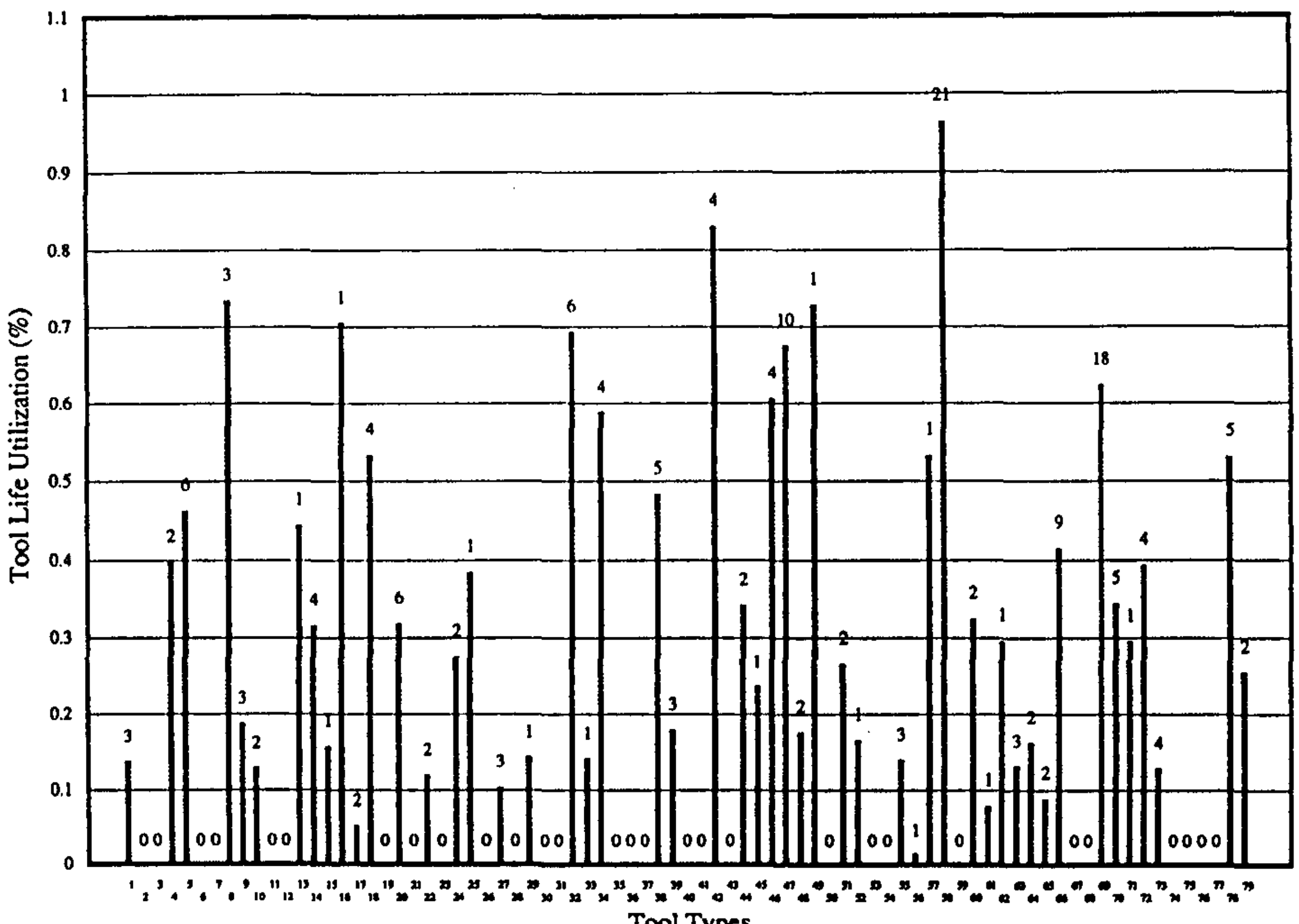
Part Type =15, # MC =4, Batch Size <=4, Manufacturing Period =3-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No. 22

Throughput Time :	1237.8	Avr.Transport.Util.(%):	3.191
Avr. MC Util.(%):	87.106		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
3	0.41	2.59	0	1	3	3	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.80	1.20	0	1	2	2	0.40
4	1.85	2.15	1	2	4	5	0.46
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	2.20	0.80	0	3	3	3	0.73
3	0.56	2.44	0	1	3	3	0.19
2	0.26	1.74	0	1	2	2	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.44	0.56	0	1	1	1	0.44
4	1.27	2.73	0	2	4	4	0.32
1	0.16	0.84	0	1	1	1	0.16
1	0.71	0.29	0	1	1	1	0.71
2	0.11	1.89	0	1	2	2	0.05
2	1.07	0.93	1	2	2	3	0.53
0	0.00	0.00	0	0	0	0	0.00
6	1.91	4.09	0	2	6	6	0.32
0	0.00	0.00	0	0	0	0	0.00
2	0.24	1.76	0	1	2	2	0.12
0	0.00	0.00	0	0	0	0	0.00
2	0.55	1.45	0	1	2	2	0.28
1	0.39	0.61	0	1	1	1	0.39
0	0.00	0.00	0	0	0	0	0.00
3	0.31	2.69	0	1	4	3	0.10
0	0.00	0.00	0	0	0	0	0.00
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	2.78	1.22	2	3	4	6	0.69
1	0.14	0.86	0	1	1	1	0.14
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.45	1.55	1	2	3	4	0.48
3	0.54	2.46	0	1	3	3	0.18
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	1.66	0.34	1	2	2	3	0.83
0	0.00	0.00	0	0	0	0	0.00
2	0.68	1.32	0	1	2	2	0.34
1	0.24	0.76	0	1	1	1	0.24
2	1.21	0.79	1	2	2	3	0.61
6	4.06	1.94	3	5	6	9	0.68
2	0.35	1.65	0	1	2	2	0.18
1	0.73	0.27	0	1	1	1	0.73
0	0.00	0.00	0	0	0	0	0.00
2	0.53	1.47	0	1	2	2	0.27
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.42	2.58	0	1	3	3	0.14
1	0.01	0.99	0	1	1	1	0.01
1	0.53	0.47	0	1	1	1	0.53
11	10.61	0.39	10	11	11	21	0.96
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.33
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
3	0.40	2.60	0	1	4	3	0.13
2	0.33	1.67	0	1	2	2	0.16
2	0.18	1.82	0	1	3	2	0.09
8	3.32	4.68	1	4	11	9	0.42
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
11	6.87	4.13	5	7	13	16	0.62
5	1.72	3.28	0	2	6	5	0.34
1	0.30	0.70	0	1	1	1	0.30
4	1.58	2.42	0	2	5	4	0.39
4	0.52	3.48	0	1	6	4	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.59	1.41	1	2	3	4	0.53
2	0.51	1.49	0	1	2	2	0.26
140	59	81	28	88	152	168	



Part Types = 15, # MC = 4, Batch Size <= 50, Manufacturing Period = 3-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No. 65

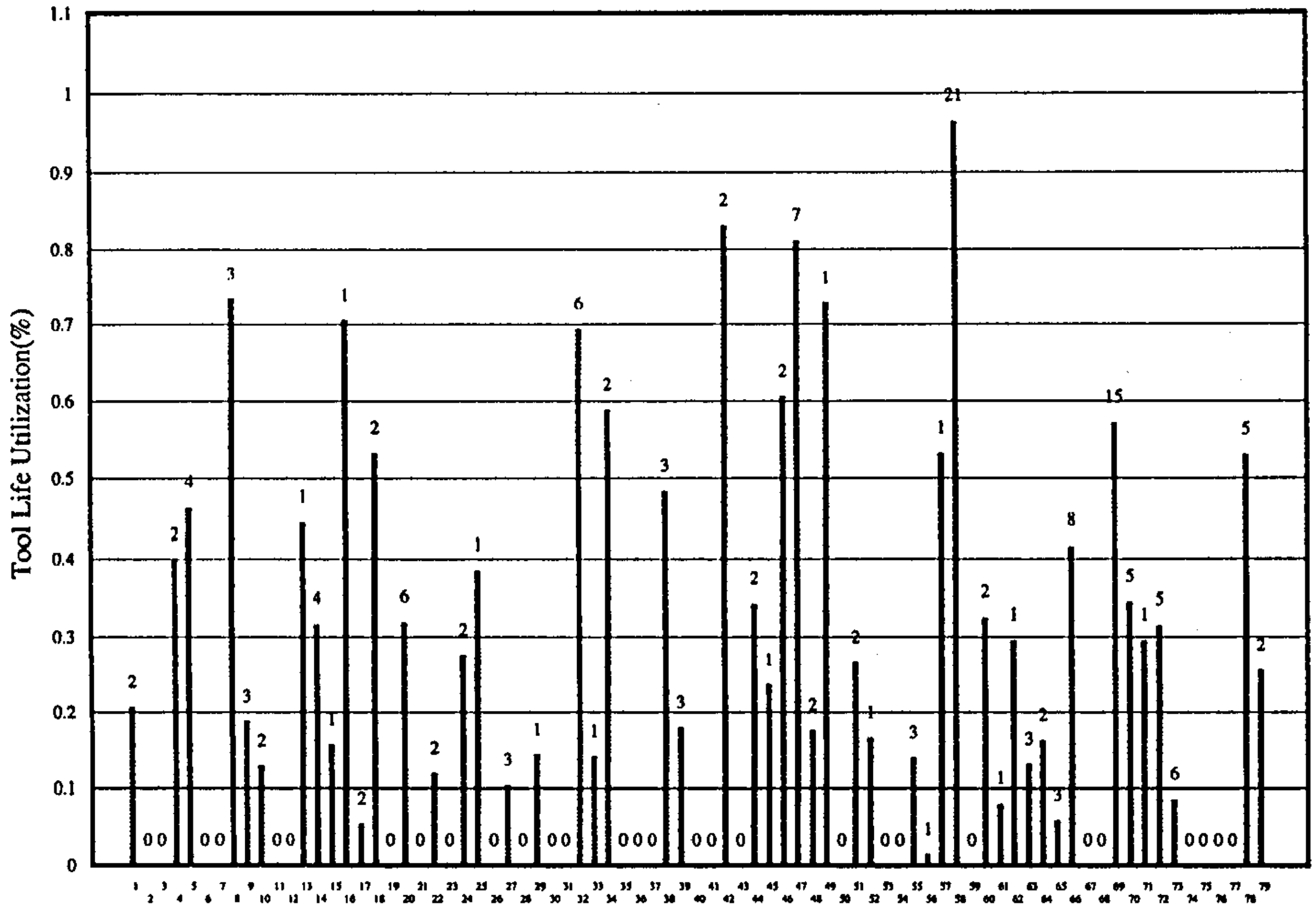
Throughput Time : 742.8 Avr.Transport Util.(%): 5.358

Avr. MC Util.(%): 72.572

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
2	0.41	1.59	0	1	3	2	0.21
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.80	1.20	0	1	2	2	0.40
4	1.85	2.15	0	2	4	4	0.46
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	2.20	0.80	0	3	3	3	0.73
3	0.56	2.44	0	1	3	3	0.19
2	0.26	1.74	0	1	2	2	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.44	0.56	0	1	1	1	0.44
4	1.27	2.73	0	2	4	4	0.32
1	0.16	0.84	0	1	1	1	0.16
1	0.71	0.29	0	1	1	1	0.71
2	0.11	1.89	0	1	2	2	0.05
2	1.07	0.93	0	2	2	2	0.53
0	0.00	0.00	0	0	0	0	0.00
6	1.91	4.09	0	2	6	6	0.32
0	0.00	0.00	0	0	0	0	0.00
2	0.24	1.76	0	1	2	2	0.12
0	0.00	0.00	0	0	0	0	0.00
2	0.55	1.45	0	1	2	2	0.28
1	0.39	0.61	0	1	1	1	0.39
0	0.00	0.00	0	0	0	0	0.00
3	0.31	2.69	0	1	4	3	0.10
0	0.00	0.00	0	0	0	0	0.00
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	2.78	1.22	2	3	4	6	0.69
1	0.14	0.86	0	1	1	1	0.14
2	1.18	0.82	0	2	2	2	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.45	1.55	0	2	3	3	0.48
3	0.54	2.46	0	1	3	3	0.18
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	1.66	0.34	0	2	2	2	0.83
0	0.00	0.00	0	0	0	0	0.00
2	0.68	1.32	0	1	2	2	0.34
1	0.24	0.76	0	1	1	1	0.24
2	1.21	0.79	0	2	2	2	0.61
5	4.06	0.94	2	5	6	7	0.81
2	0.35	1.65	0	1	2	2	0.18
1	0.73	0.27	0	1	1	1	0.73
0	0.00	0.00	0	0	0	0	0.00
2	0.53	1.47	0	1	2	2	0.27
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.42	2.58	0	1	3	3	0.14
1	0.01	0.99	0	1	1	1	0.01
1	0.53	0.47	0	1	1	1	0.53
11	10.61	0.39	10	11	11	21	0.96
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.33
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
3	0.40	2.60	0	1	4	3	0.13
2	0.33	1.67	0	1	2	2	0.16
3	0.18	2.82	0	1	3	3	0.06
8	3.32	4.68	0	4	11	8	0.42
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
12	6.87	5.13	3	7	13	15	0.57
5	1.72	3.28	0	2	6	5	0.34
1	0.30	0.70	0	1	1	1	0.30
5	1.58	3.42	0	2	5	5	0.32
6	0.52	5.48	0	1	6	6	0.09
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.59	1.41	1	2	3	5	0.53
2	0.51	1.49	0	1	2	2	0.26
143	59	84	18	88	152	162	

The Supplementary Experiment No. 65 - Tool Life Utilization



Part Type = 15, Batch Size <= 50, # MC =8, Manufacturing Period = 3-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

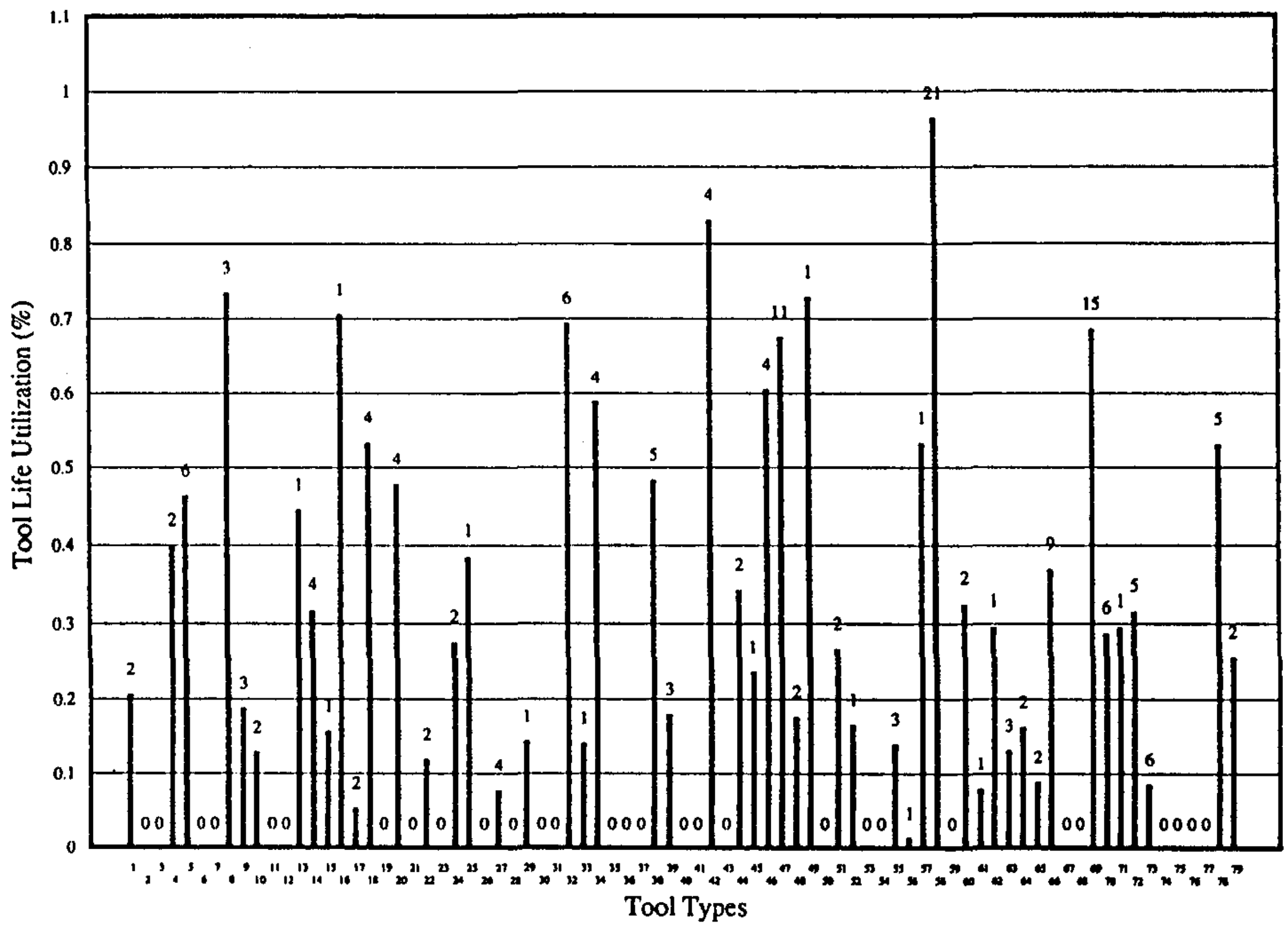
The Supplementary Experiment No. 66

Throughput Time : 1214.4   Avr.Transport Util.(%): 3.269

Avr. MC Util.(%): 88.778

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
2	0.41	1.59	0	1	3	2	0.21
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.80	1.20	0	1	2	2	0.40
4	1.85	2.15	1	2	4	5	0.46
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	2.20	0.80	0	3	3	3	0.73
3	0.56	2.44	0	1	3	3	0.19
2	0.26	1.74	0	1	2	2	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.44	0.56	0	1	1	1	0.44
4	1.27	2.73	0	2	4	4	0.32
1	0.16	0.84	0	1	1	1	0.16
1	0.71	0.29	0	1	1	1	0.71
2	0.11	1.89	0	1	2	2	0.05
2	1.07	0.93	1	2	2	3	0.53
0	0.00	0.00	0	0	0	0	0.00
4	1.91	2.09	0	2	6	4	0.48
0	0.00	0.00	0	0	0	0	0.00
2	0.24	1.76	0	1	2	2	0.12
0	0.00	0.00	0	0	0	0	0.00
2	0.55	1.45	0	1	2	2	0.28
1	0.39	0.61	0	1	1	1	0.39
0	0.00	0.00	0	0	0	0	0.00
4	0.31	3.69	0	1	4	4	0.08
0	0.00	0.00	0	0	0	0	0.00
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	2.78	1.22	2	3	4	6	0.69
1	0.14	0.86	0	1	1	1	0.14
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.45	1.55	1	2	3	4	0.48
3	0.54	2.46	0	1	3	3	0.18
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	1.66	0.34	1	2	2	3	0.83
0	0.00	0.00	0	0	0	0	0.00
2	0.68	1.32	0	1	2	2	0.34
1	0.24	0.76	0	1	1	1	0.24
2	1.21	0.79	1	2	2	3	0.61
6	4.06	1.94	3	5	6	9	0.68
2	0.35	1.65	0	1	2	2	0.18
1	0.73	0.27	0	1	1	1	0.73
0	0.00	0.00	0	0	0	0	0.00
2	0.53	1.47	0	1	2	2	0.27
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.42	2.58	0	1	3	3	0.14
1	0.01	0.99	0	1	1	1	0.01
1	0.53	0.47	0	1	1	1	0.53
11	10.61	0.39	10	11	11	21	0.96
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.33
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
3	0.40	2.60	0	1	4	3	0.13
2	0.33	1.67	0	1	2	2	0.16
2	0.18	1.82	0	1	3	2	0.09
9	3.32	5.68	0	4	11	9	0.37
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
10	6.87	3.13	3	7	13	13	0.69
6	1.72	4.28	0	2	6	6	0.29
1	0.30	0.70	0	1	1	1	0.30
5	1.58	3.42	0	2	5	5	0.32
6	0.52	5.48	0	1	6	6	0.09
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.59	1.41	1	2	3	4	0.53
2	0.51	1.49	0	1	2	2	0.26
142	59	83	25	88	152	167	



Part Type = 15, # MC =4, Batch Size <=50, Manufacturing Period = 3-Shift, Permissible Tool Life =90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

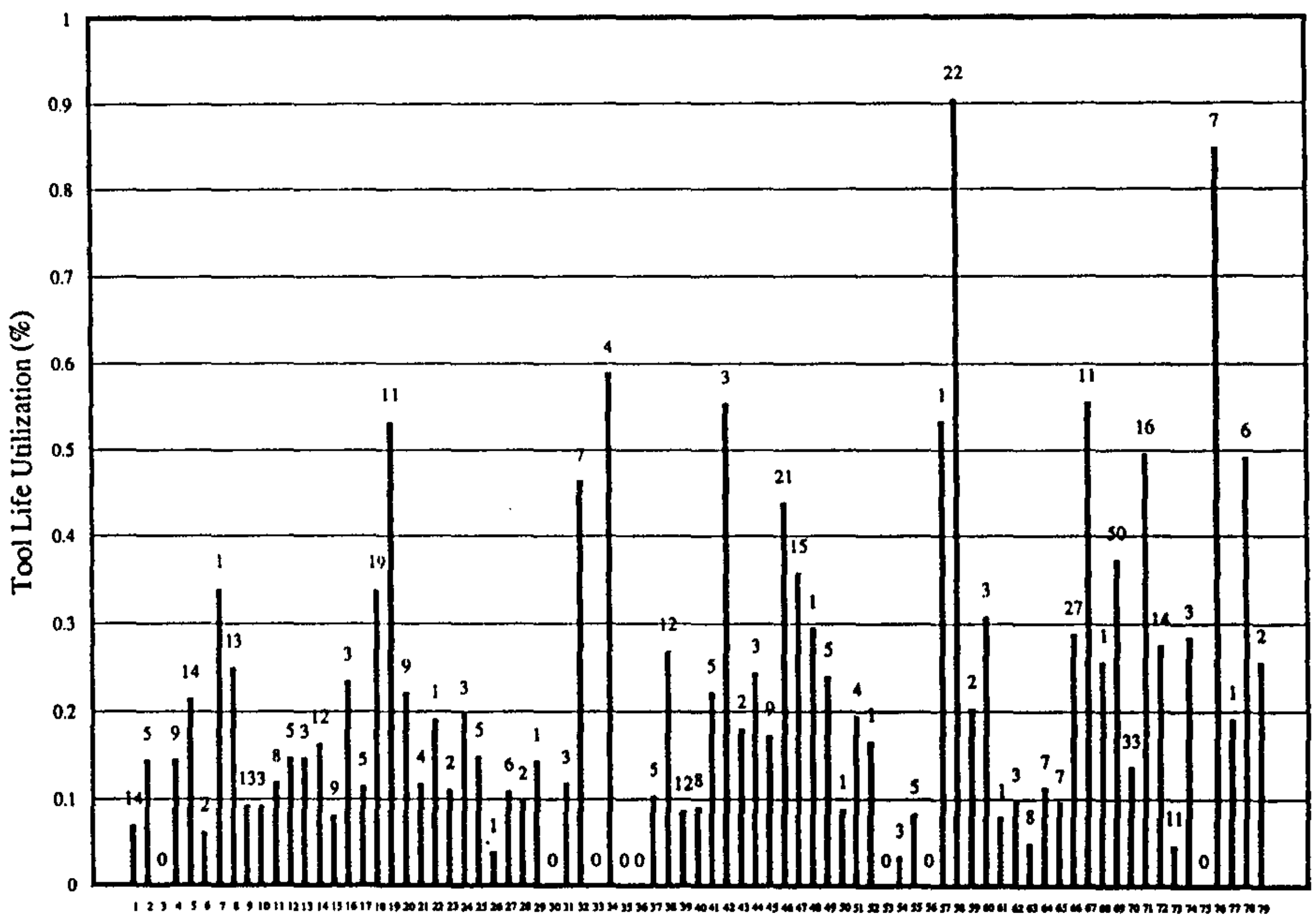
The Supplementary Experiment No. 18

Throughput Time :	3192.4	Avr. Transport.Util.(%):	6.353
Avr. MC Util.(%):	95.71		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
14	0.98	13.02	0	1	32	14	0.07
5	0.73	4.27	0	1	5	5	0.15
0	0.00	0.00	0	0	0	0	0.00
9	1.31	7.69	0	2	14	9	0.15
13	2.80	10.20	1	3	20	14	0.22
2	0.13	1.87	0	1	2	2	0.06
1	0.34	0.66	0	1	1	1	0.34
12	3.00	9.00	1	4	24	13	0.25
13	1.21	11.79	0	2	15	13	0.09
3	0.28	2.72	0	1	4	3	0.09
8	0.96	7.04	0	1	8	8	0.12
5	0.74	4.26	0	1	5	5	0.15
3	0.44	2.56	0	1	3	3	0.15
12	1.97	10.03	0	2	13	12	0.16
9	0.74	8.26	0	1	10	9	0.08
3	0.71	2.29	0	1	6	3	0.24
5	0.58	4.43	0	1	5	5	0.12
15	5.09	9.91	3	6	18	18	0.34
8	4.27	3.73	2	5	8	10	0.53
9	2.00	7.00	0	3	23	9	0.22
4	0.47	3.53	0	1	6	4	0.12
1	0.19	0.81	0	1	1	1	0.19
2	0.22	1.78	0	1	2	2	0.11
3	0.59	2.41	0	1	4	3	0.20
5	0.75	4.25	0	1	5	5	0.15
1	0.04	0.96	0	1	1	1	0.04
6	0.66	5.34	0	1	7	6	0.11
2	0.20	1.80	0	1	2	2	0.10
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
3	0.36	2.64	0	1	3	3	0.12
6	2.78	3.22	1	3	6	7	0.46
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
5	0.52	4.48	0	1	5	5	0.10
11	2.96	8.04	1	3	14	12	0.27
12	1.04	10.96	0	2	14	12	0.09
8	0.73	7.27	0	1	8	8	0.09
5	1.11	3.89	0	2	5	5	0.22
3	1.66	1.34	0	2	6	3	0.55
2	0.36	1.64	0	1	3	2	0.18
3	0.73	2.27	0	1	4	3	0.24
9	1.56	7.44	0	2	10	9	0.17
16	7.01	8.99	3	8	18	19	0.44
12	4.30	7.70	2	5	19	14	0.36
1	0.30	0.70	0	1	1	1	0.30
5	1.20	3.80	0	2	5	5	0.24
1	0.09	0.91	0	1	1	1	0.09
4	0.78	3.22	0	1	4	4	0.20
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
3	0.11	2.89	0	1	3	3	0.04
5	0.42	4.58	0	1	6	5	0.08
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
11	9.96	1.04	9	10	11	20	0.91
2	0.41	1.59	0	1	2	2	0.20
3	0.93	2.07	0	1	3	3	0.31
1	0.08	0.92	0	1	1	1	0.08
3	0.30	2.70	0	1	3	3	0.10
8	0.40	7.60	0	1	10	8	0.05
7	0.80	6.21	0	1	8	7	0.11
7	0.67	6.33	0	1	8	7	0.10
23	6.64	16.36	3	7	43	26	0.29
8	4.44	3.56	3	5	8	11	0.56
1	0.26	0.74	0	1	1	1	0.26
38	14.17	23.83	9	15	69	47	0.37
30	4.13	25.87	2	5	57	32	0.14
10	4.96	5.04	2	5	10	12	0.50
12	3.31	8.69	1	4	13	13	0.28
11	0.53	10.47	0	1	12	11	0.05
3	0.85	2.15	0	1	3	3	0.28
0	0.00	0.00	0	0	0	0	0.00
5	4.24	0.76	2	5	5	7	0.85
1	0.19	0.81	0	1	1	1	0.19
5	2.46	2.54	1	3	5	6	0.49
2	0.51	1.49	0	1	2	2	0.26
483	122	361	47	161	659	530	

The Supplementary Experiment No. 18 - Tool Life Utilization



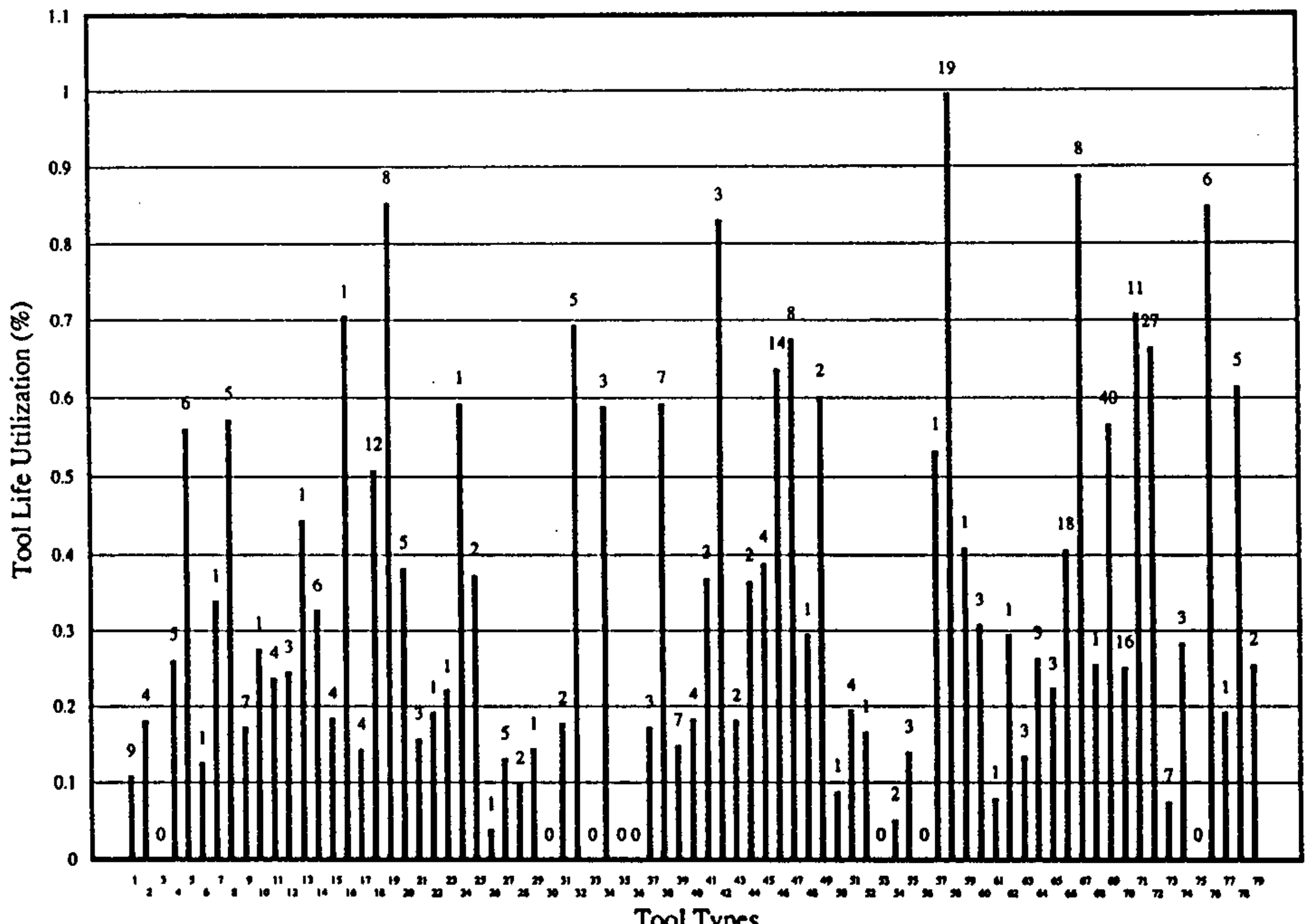
Part Type = 40, # MC = 4, Batch Size <=8, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No. 21

Throughput Time :	2810.95	Avr.Transport. Util.(%):	3.401
Avr. MC Util.(%):	94.389		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
9	0.98	8.02	0	1	13	9	0.11
4	0.73	3.27	0	1	4	4	0.18
0	0.00	0.00	0	0	0	0	0.00
5	1.31	3.69	0	2	6	5	0.26
5	2.80	2.20	1	3	5	6	0.56
1	0.13	0.87	0	1	2	1	0.13
1	0.34	0.66	0	1	1	1	0.34
5	2.86	2.14	0	3	5	5	0.57
7	1.21	5.79	0	2	9	7	0.17
1	0.28	0.72	0	1	2	1	0.28
4	0.96	3.04	0	1	4	4	0.24
3	0.74	2.26	0	1	3	3	0.25
1	0.44	0.56	0	1	1	1	0.44
6	1.97	4.03	0	2	6	6	0.33
4	0.74	3.26	0	1	5	4	0.18
1	0.71	0.29	0	1	1	1	0.71
4	0.58	3.43	0	1	4	4	0.14
10	5.09	4.91	2	6	10	12	0.51
5	4.27	0.73	3	5	5	8	0.85
5	1.91	3.09	0	2	6	5	0.38
3	0.47	2.53	0	1	4	3	0.16
1	0.19	0.81	0	1	1	1	0.19
1	0.22	0.78	0	1	1	1	0.22
1	0.59	0.41	0	1	2	1	0.59
2	0.75	1.25	0	1	3	2	0.37
1	0.04	0.96	0	1	1	1	0.04
5	0.66	4.34	0	1	5	5	0.13
2	0.20	1.80	0	1	2	2	0.10
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
2	0.36	1.64	0	1	2	2	0.18
4	2.78	1.22	1	3	4	5	0.69
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.52	2.48	0	1	3	3	0.17
5	2.96	2.04	2	3	5	7	0.59
7	1.04	5.96	0	2	8	7	0.15
4	0.73	3.27	0	1	4	4	0.18
3	1.11	1.89	0	2	3	3	0.37
2	1.66	0.34	1	2	2	3	0.83
2	0.36	1.64	0	1	2	2	0.18
2	0.73	1.27	0	1	2	2	0.37
4	1.56	2.44	0	2	5	4	0.39
11	7.01	3.99	3	8	11	14	0.64
6	4.06	1.94	2	5	6	8	0.68
1	0.30	0.70	0	1	1	1	0.30
2	1.20	0.80	0	2	3	2	0.60
1	0.09	0.91	0	1	1	1	0.09
4	0.78	3.22	0	1	4	4	0.20
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
2	0.11	1.89	0	1	2	2	0.05
3	0.42	2.58	0	1	3	3	0.14
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
10	9.96	0.04	9	10	10	19	1.00
1	0.41	0.59	0	1	1	1	0.41
3	0.93	2.07	0	1	3	3	0.31
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
3	0.40	2.60	0	1	4	3	0.13
3	0.80	2.21	0	1	4	3	0.27
3	0.67	2.33	0	1	5	3	0.22
16	6.51	9.49	2	7	19	18	0.41
5	4.44	0.56	3	5	5	8	0.89
1	0.26	0.74	0	1	1	1	0.26
31	17.56	13.44	9	18	35	40	0.57
16	4.05	11.95	0	5	19	16	0.25
7	4.96	2.04	4	5	8	11	0.71
18	11.98	6.02	9	12	18	27	0.67
7	0.53	6.47	0	1	8	7	0.08
3	0.85	2.15	0	1	3	3	0.28
0	0.00	0.00	0	0	0	0	0.00
5	4.24	0.76	1	5	5	6	0.85
1	0.19	0.81	0	1	1	1	0.19
4	2.46	1.54	1	3	4	5	0.62
2	0.51	1.49	0	1	2	2	0.26
311	133	178	54	170	344	365	



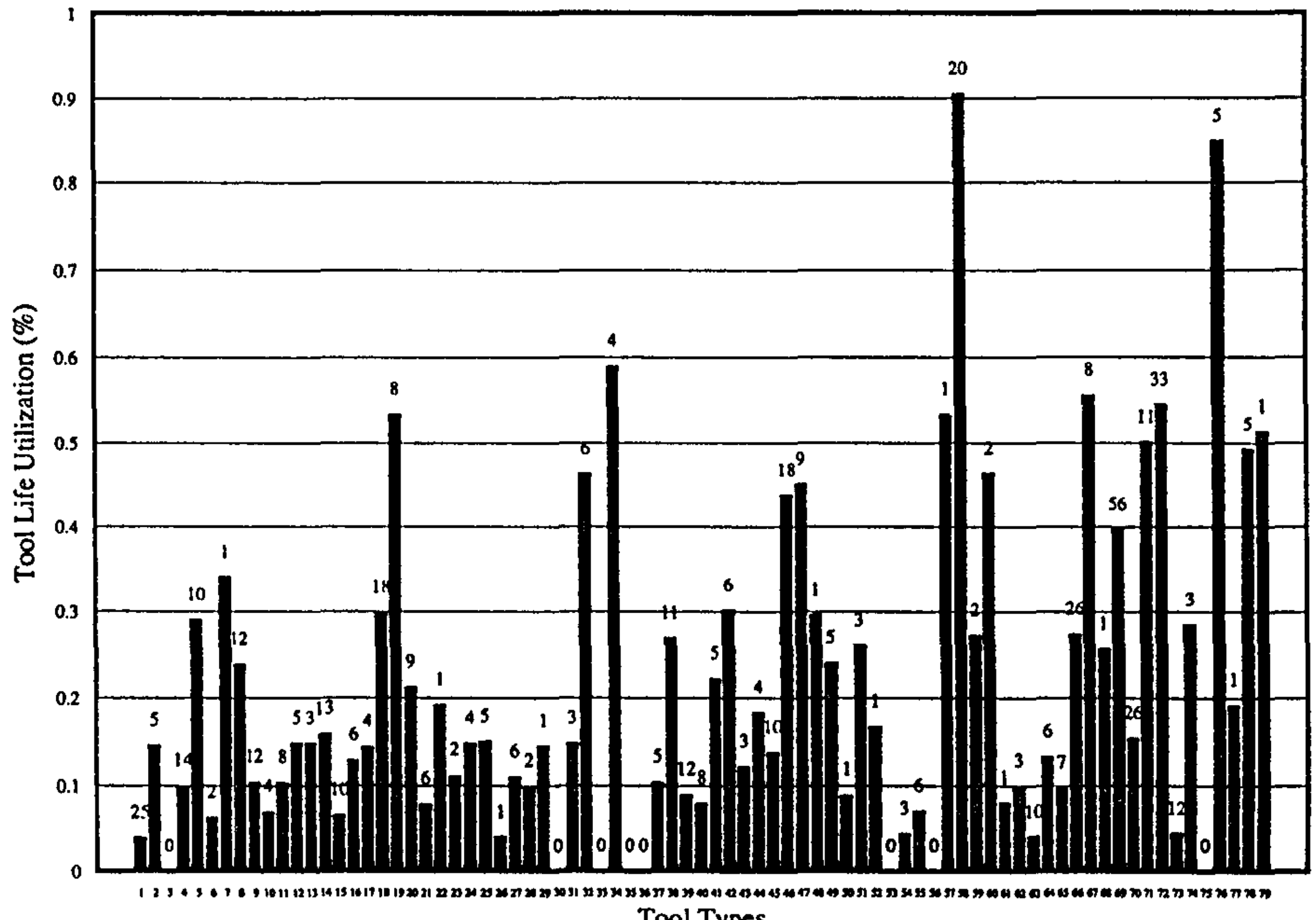
Part Type = 40, Batch Size <=50, # MC =4, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No.75

Throughput Time :	1676.9	Avr.Transport.Util.(%) :	11.414
Avr. MC Utils.(%):	90.246		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	Tool Usage
25	0.99	24.01	0	1	32	25	0.04
5	0.73	4.27	0	1	5	5	0.15
0	0.00	0.00	0	0	0	0	0.00
14	1.38	12.62	0	2	14	14	0.10
10	2.90	7.10	0	3	20	10	0.29
2	0.13	1.87	0	1	2	2	0.06
1	0.34	0.66	0	1	1	1	0.34
12	2.86	9.14	0	3	23	12	0.24
12	1.24	10.76	0	2	15	12	0.10
4	0.28	3.72	0	1	4	4	0.07
8	0.82	7.18	0	1	8	8	0.10
5	0.74	4.26	0	1	5	5	0.15
3	0.44	2.56	0	1	3	3	0.15
13	2.06	10.94	0	3	13	13	0.16
10	0.66	9.34	0	1	10	10	0.07
6	0.77	5.23	0	1	6	6	0.13
4	0.58	3.43	0	1	5	4	0.14
17	5.09	11.91	1	6	18	18	0.30
8	4.27	3.73	0	5	8	8	0.53
9	1.91	7.09	0	2	22	9	0.21
6	0.47	5.53	0	1	6	6	0.08
1	0.19	0.81	0	1	1	1	0.19
2	0.22	1.78	0	1	2	2	0.11
4	0.59	3.41	0	1	4	4	0.15
5	0.75	4.25	0	1	5	5	0.15
1	0.04	0.96	0	1	1	1	0.04
6	0.66	5.34	0	1	7	6	0.11
2	0.20	1.80	0	1	2	2	0.10
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
3	0.44	2.56	0	1	3	3	0.15
6	2.78	3.22	0	3	6	6	0.46
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	2	2	2	4	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
5	0.52	4.48	0	1	5	5	0.10
11	2.96	8.04	0	3	14	11	0.27
12	1.07	10.93	0	2	14	12	0.09
8	0.63	7.37	0	1	8	8	0.08
5	1.11	3.89	0	2	5	5	0.22
6	1.81	4.19	0	2	6	6	0.30
3	0.36	2.64	0	1	3	3	0.12
4	0.73	3.27	0	1	4	4	0.18
10	1.38	8.62	0	2	10	10	0.14
16	7.01	8.99	2	8	18	18	0.44
9	4.06	4.94	0	5	18	9	0.45
1	0.30	0.70	0	1	1	1	0.30
5	1.20	3.80	0	2	5	5	0.24
1	0.09	0.91	0	1	1	1	0.09
3	0.78	2.22	0	1	4	3	0.26
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
3	0.13	2.87	0	1	3	3	0.04
6	0.42	5.58	0	1	6	6	0.07
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
11	9.96	1.04	9	10	11	20	0.91
2	0.55	1.45	0	1	2	2	0.27
2	0.93	1.07	0	1	3	2	0.46
1	0.08	0.92	0	1	1	1	0.08
3	0.30	2.70	0	1	3	3	0.10
10	0.40	9.60	0	1	10	10	0.04
6	0.80	5.21	0	1	8	6	0.13
7	0.67	6.33	0	1	8	7	0.10
24	6.57	17.43	2	7	42	26	0.27
8	4.44	3.56	0	5	8	8	0.56
1	0.26	0.74	0	1	1	1	0.26
44	17.48	26.52	12	18	72	56	0.40
26	4.01	21.99	0	5	56	26	0.15
8	4.01	3.99	3	5	9	11	0.50
22	11.98	10.02	11	12	22	33	0.54
12	0.53	11.47	0	1	12	12	0.04
3	0.85	2.15	0	1	3	3	0.28
0	0.00	0.00	0	0	0	0	0.00
5	4.24	0.76	0	5	5	5	0.85
1	0.19	0.81	0	1	1	1	0.19
5	2.46	2.54	0	3	5	5	0.49
1	0.51	0.49	0	1	2	1	0.51
519	132	387	42	171	665	561	



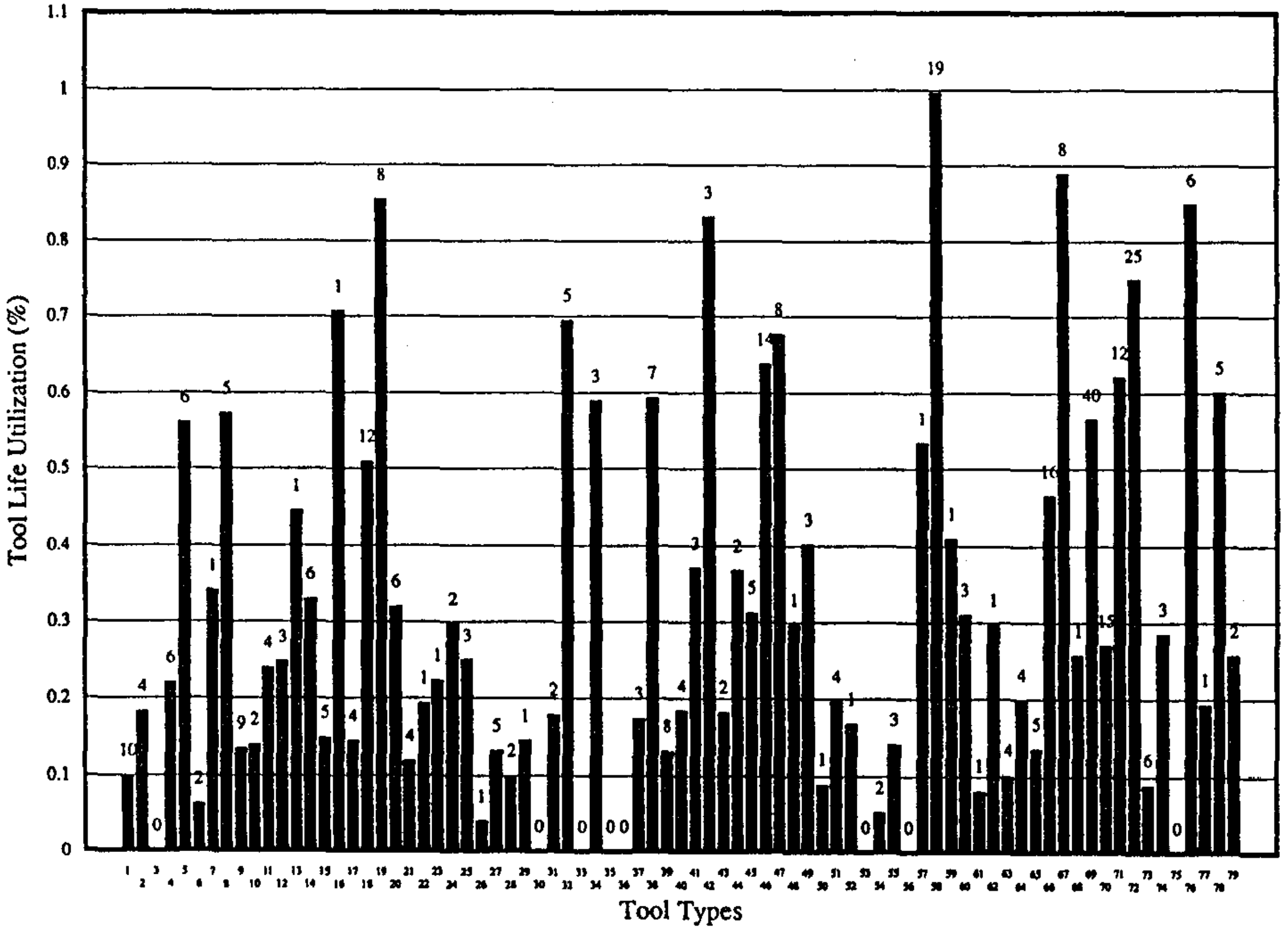
Part Type = 40, Batch Size <=8, # MC =8, Manufacturing Period =10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No: 77

Throughput Time :	1878.3	Avr.Transport.Util.(%):	4.137
Avr. MC Util.(%):	72.369		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
10	0.98	9.02	0	1	13	10	0.10
4	0.73	3.27	0	1	4	4	0.18
0	0.00	0.00	0	0	0	0	0.00
6	1.31	4.69	0	2	6	6	0.22
5	2.80	2.20	1	3	5	6	0.56
2	0.13	1.87	0	1	2	2	0.06
1	0.34	0.66	0	1	1	1	0.34
5	2.86	2.14	0	3	5	5	0.57
9	1.21	7.79	0	2	9	9	0.13
2	0.28	1.72	0	1	2	2	0.14
4	0.96	3.04	0	1	4	4	0.24
3	0.74	2.26	0	1	3	3	0.25
1	0.44	0.56	0	1	1	1	0.44
6	1.97	4.03	0	2	6	6	0.33
5	0.74	4.26	0	1	5	5	0.15
1	0.71	0.29	0	1	1	1	0.71
4	0.58	3.43	0	1	4	4	0.14
10	5.09	4.91	2	6	10	12	0.51
5	4.27	0.73	3	5	5	8	0.85
6	1.91	4.09	0	2	6	6	0.32
4	0.47	3.53	0	1	4	4	0.12
1	0.19	0.81	0	1	1	1	0.19
1	0.22	0.78	0	1	1	1	0.22
2	0.59	1.41	0	1	2	2	0.30
3	0.75	2.25	0	1	3	3	0.25
1	0.04	0.96	0	1	1	1	0.04
5	0.66	4.34	0	1	5	5	0.13
2	0.20	1.80	0	1	2	2	0.10
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
2	0.36	1.64	0	1	2	2	0.18
4	2.78	1.22	1	3	4	5	0.69
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.52	2.48	0	1	3	3	0.17
5	2.96	2.04	2	3	5	7	0.59
8	1.04	6.96	0	2	8	8	0.13
4	0.73	3.27	0	1	4	4	0.18
3	1.11	1.89	0	2	3	3	0.37
2	1.66	0.34	1	2	2	3	0.83
2	0.36	1.64	0	1	2	2	0.18
2	0.73	1.27	0	1	2	2	0.37
5	1.56	3.44	0	2	5	5	0.31
11	7.01	3.99	3	8	11	14	0.64
6	4.06	1.94	2	5	6	8	0.68
1	0.30	0.70	0	1	1	1	0.30
3	1.20	1.80	0	2	3	3	0.40
1	0.09	0.91	0	1	1	1	0.09
4	0.78	3.22	0	1	4	4	0.20
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
2	0.11	1.89	0	1	2	2	0.05
3	0.42	2.58	0	1	3	3	0.14
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
10	9.96	0.04	9	10	10	19	1.00
1	0.41	0.59	0	1	1	1	0.41
3	0.93	2.07	0	1	3	3	0.31
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
4	0.40	3.60	0	1	4	4	0.10
4	0.80	3.21	0	1	4	4	0.20
5	0.67	4.33	0	1	5	5	0.13
14	6.51	7.49	2	7	19	16	0.46
5	4.44	0.56	3	5	5	8	0.89
1	0.26	0.74	0	1	1	1	0.26
31	17.50	13.50	9	18	35	40	0.56
15	4.05	10.95	0	5	19	15	0.27
8	4.96	3.04	4	5	8	12	0.62
16	11.98	4.02	9	12	18	25	0.75
6	0.53	5.47	0	1	8	6	0.09
3	0.85	2.15	0	1	3	3	0.28
0	0.00	0.00	0	0	0	0	0.00
5	4.24	0.76	1	5	5	6	0.85
1	0.19	0.81	0	1	1	1	0.19
4	2.40	1.60	1	3	4	5	0.60
2	0.51	1.49	0	1	2	2	0.26
314	132	182	54	169	331	368	



Part Type =40, # MC = 8, Batch Size <=50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization indicate the tool inventory level of that particular tool type.

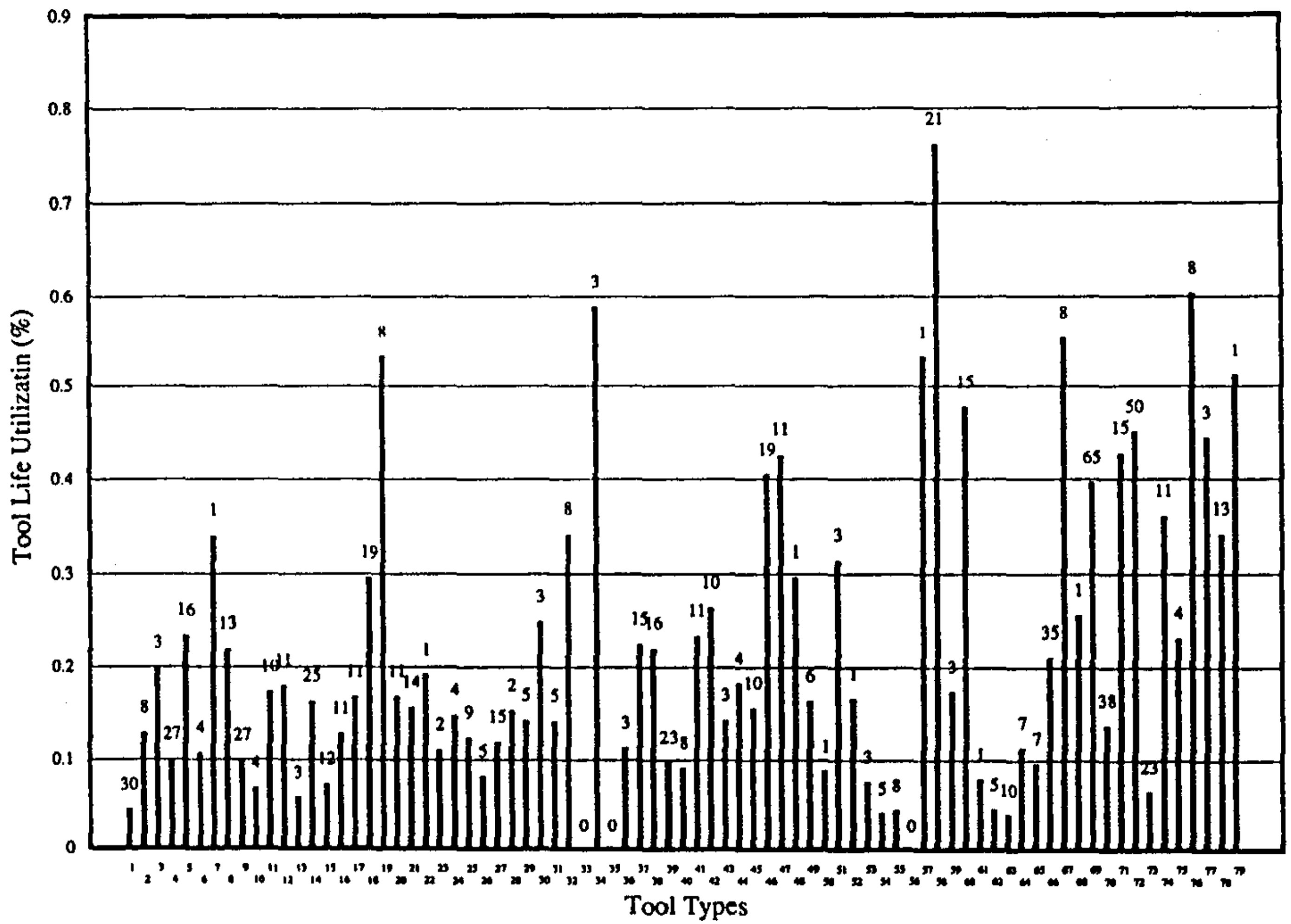
The Supplementary Experiment No.25

Throughput Time :	2474.75	Avr. Transport.Util.(%):	13.945
Avr. MC Util.(%):	91.610		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
30	1.36	28.64	0	2	48	30	0.05
8	1.04	6.96	0	2	8	8	0.13
3	0.60	2.40	0	1	3	3	0.20
27	2.71	24.29	0	3	31	27	0.10
16	3.75	12.25	0	4	28	16	0.23
4	0.43	3.57	0	1	4	4	0.11
1	0.34	0.66	0	1	1	1	0.34
13	2.86	10.14	0	3	23	13	0.22
27	2.68	24.32	0	3	36	27	0.10
4	0.28	3.72	0	1	4	4	0.07
10	1.73	8.27	0	2	12	10	0.17
11	1.99	9.01	0	2	13	11	0.18
3	0.18	2.82	0	1	3	3	0.06
25	4.07	20.93	0	5	26	25	0.16
12	0.89	11.11	0	1	12	12	0.07
11	1.41	9.59	0	2	12	11	0.13
11	1.85	9.15	0	2	14	11	0.17
19	5.63	13.37	0	6	20	19	0.30
8	4.27	3.73	0	5	8	8	0.53
11	1.85	9.15	0	2	24	11	0.17
14	2.19	11.81	0	3	16	14	0.16
1	0.19	0.81	0	1	1	1	0.19
2	0.22	1.78	0	1	2	2	0.11
4	0.59	3.41	0	1	4	4	0.15
9	1.12	7.88	0	2	9	9	0.12
5	0.41	4.59	0	1	5	5	0.08
15	1.80	13.20	0	2	17	15	0.12
2	0.31	1.69	0	1	2	2	0.15
5	0.71	4.29	0	1	5	5	0.14
3	0.75	2.25	0	1	3	3	0.25
5	0.71	4.29	0	1	5	5	0.14
8	2.73	5.27	0	3	8	8	0.34
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
3	0.34	2.66	0	1	3	3	0.11
15	3.38	11.62	0	4	20	15	0.23
16	3.53	12.47	0	4	20	16	0.22
23	2.24	20.76	0	3	31	23	0.10
8	0.73	7.27	0	1	8	8	0.09
11	2.57	8.43	0	3	13	11	0.23
10	2.64	7.36	0	3	10	10	0.26
3	0.43	2.57	0	1	3	3	0.14
4	0.73	3.27	0	1	4	4	0.18
10	1.56	8.44	0	2	10	10	0.16
19	7.71	11.29	0	8	20	19	0.41
11	4.69	6.31	0	5	20	11	0.43
1	0.30	0.70	0	1	1	1	0.30
6	0.98	5.02	0	1.	6	6	0.16
1	0.09	0.91	0	1	1	1	0.09
3	0.94	2.06	0	1	4	3	0.31
1	0.17	0.83	0	1	1	1	0.17
3	0.23	2.77	0	1	3	3	0.08
5	0.21	4.79	0	1	5	5	0.04
8	0.37	7.63	0	1	8	8	0.05
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
14	10.67	3.33	7	11	14	21	0.76
3	0.52	2.48	0	1	3	3	0.17
12	5.73	6.27	3	6	13	15	0.48
1	0.08	0.92	0	1	1	1	0.08
5	0.24	4.76	0	1	5	5	0.05
10	0.40	9.60	0	1	10	10	0.04
7	0.80	6.21	0	1	8	7	0.11
7	0.67	6.33	0	1	8	7	0.10
35	7.41	27.59	0	8	54	35	0.21
8	4.44	3.56	0	5	8	8	0.56
1	0.26	0.74	0	1	1	1	0.26
62	24.23	36.77	3	25	105	65	0.40
38	5.23	32.77	0	6	72	38	0.14
13	5.57	7.43	2	6	14	15	0.43
41	17.60	21.40	9	18	44	50	0.45
23	1.52	21.48	0	2	34	23	0.07
11	3.97	7.03	0	4	13	11	0.36
4	0.93	3.07	0	1	4	4	0.23
8	4.83	3.17	0	5	8	8	0.60
3	1.33	1.67	0	2	3	3	0.44
13	4.44	8.56	0	5	13	13	0.34
1	0.51	0.49	0	1	2	1	0.51
811	189	619	25	226	1038	836	

The Supplementary Experiment No.25 - Tool Life Utilization



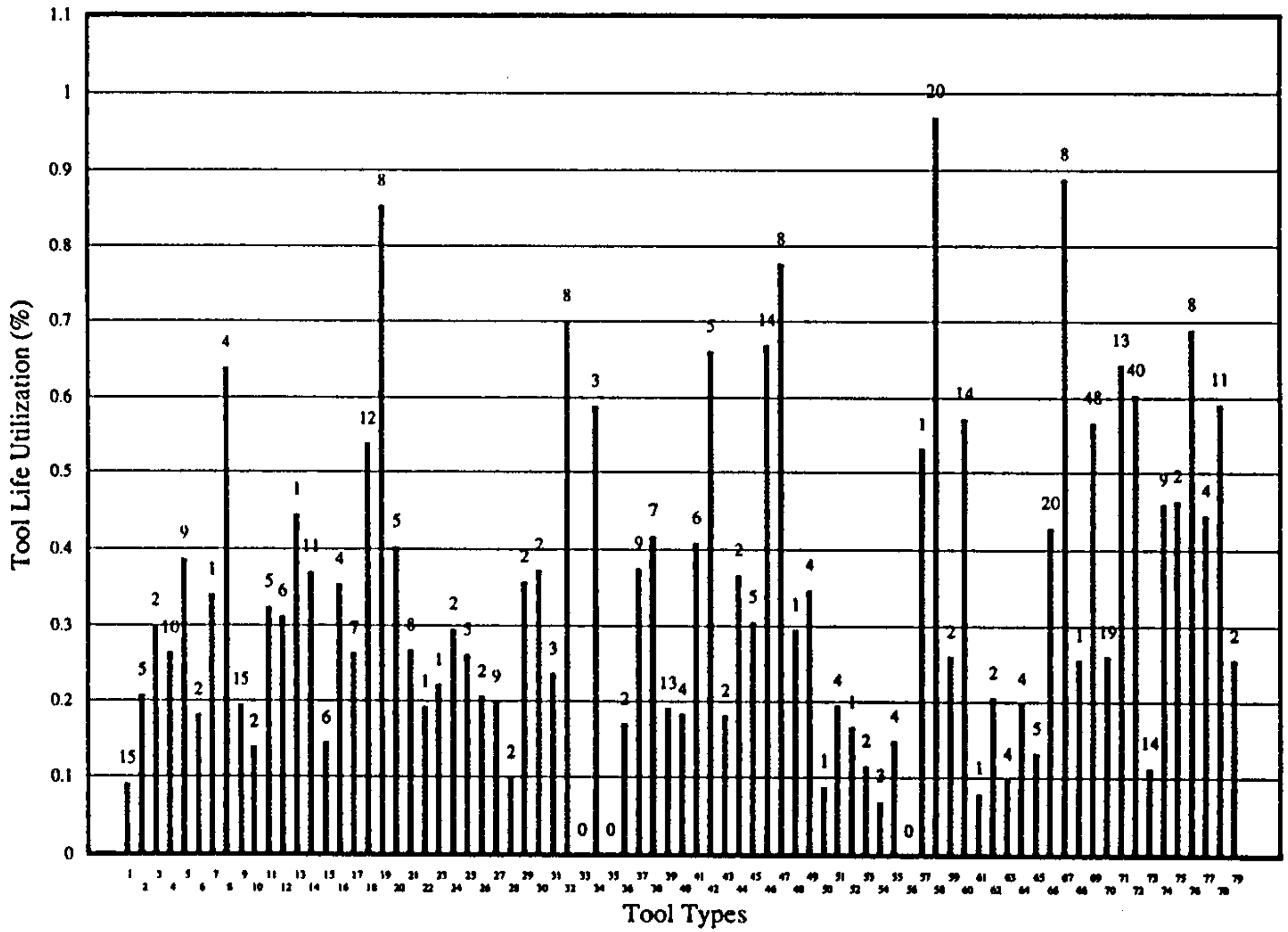
Part Type = 70, # MC = 8, Batch Size <=8, Manufacturing Period = 10 - Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Supplementary Experiment No.7

Throughput Time :	2410.7	Avr.Transport.Util.(%):	3.982
Avr. MC Util.(%):	87.069		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
15	1.36	13.64	0	2	20	15	0.09
5	1.04	3.96	0	2	5	5	0.21
2	0.60	1.40	0	1	2	2	0.30
10	2.64	7.36	0	3	13	10	0.26
8	3.10	4.90	1	4	8	9	0.39
2	0.36	1.64	0	1	3	2	0.18
1	0.34	0.66	0	1	1	1	0.34
4	2.55	1.45	0	3	5	4	0.64
15	2.93	12.07	0	3	17	15	0.20
2	0.28	1.72	0	1	2	2	0.14
5	1.62	3.38	0	2	5	5	0.32
6	1.87	4.13	0	2	6	6	0.31
1	0.44	0.56	0	1	1	1	0.44
11	4.07	6.93	0	5	11	11	0.37
6	0.87	5.13	0	1	6	6	0.14
4	1.41	2.59	0	2	4	4	0.35
7	1.85	5.15	0	2	8	7	0.26
10	5.40	4.60	2	6	11	12	0.54
5	4.27	0.73	3	5	5	8	0.85
5	2.01	2.99	0	3	7	5	0.40
8	2.14	5.86	0	3	8	8	0.27
1	0.19	0.81	0	1	1	1	0.19
1	0.22	0.78	0	1	1	1	0.22
2	0.59	1.41	0	1	2	2	0.30
5	1.31	3.69	0	2	5	5	0.26
2	0.41	1.59	0	1	2	2	0.21
9	1.80	7.20	0	2	9	9	0.20
2	0.20	1.80	0	1	2	2	0.10
2	0.71	1.29	0	1	2	2	0.36
2	0.75	1.25	0	1	2	2	0.37
3	0.71	2.29	0	1	3	3	0.24
6	4.20	1.80	2	5	6	8	0.70
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
2	0.34	1.66	0	1	2	2	0.17
9	3.38	5.62	0	4	9	9	0.38
6	2.50	3.50	1	3	6	7	0.42
13	2.49	10.51	0	3	15	13	0.19
4	0.73	3.27	0	1	4	4	0.18
6	2.45	3.55	0	3	6	6	0.41
4	2.64	1.36	1	3	4	5	0.66
2	0.36	1.64	0	1	2	2	0.18
2	0.73	1.27	0	1	2	2	0.37
5	1.53	3.47	0	2	5	5	0.31
11	7.36	3.64	3	8	12	14	0.67
6	4.66	1.34	2	5	7	8	0.78
1	0.30	0.70	0	1	1	1	0.30
4	1.39	2.61	0	2	4	4	0.35
1	0.09	0.91	0	1	1	1	0.09
4	0.78	3.22	0	1	4	4	0.20
1	0.17	0.83	0	1	1	1	0.17
2	0.23	1.77	0	1	2	2	0.12
3	0.21	2.79	0	1	3	3	0.07
4	0.59	3.41	0	1	4	4	0.15
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
11	10.67	0.33	9	11	11	20	0.97
2	0.52	1.48	0	1	2	2	0.26
10	5.73	4.27	4	6	10	14	0.57
1	0.08	0.92	0	1	1	1	0.08
2	0.41	1.59	0	1	2	2	0.21
4	0.39	3.61	0	1	4	4	0.10
4	0.80	3.21	0	1	4	4	0.20
5	0.66	4.34	0	1	5	5	0.13
18	7.71	10.29	2	8	24	20	0.43
5	4.44	0.56	3	5	5	8	0.89
1	0.26	0.74	0	1	1	1	0.26
40	22.72	17.28	8	23	47	48	0.57
19	4.96	14.04	0	5	26	19	0.26
9	5.79	3.21	4	6	10	13	0.64
29	17.51	11.49	11	18	29	40	0.60
14	1.58	12.42	0	2	18	14	0.11
8	3.68	4.32	1	4	8	9	0.46
2	0.93	1.07	0	1	2	2	0.46
7	4.83	2.17	1	5	7	8	0.69
3	1.33	1.67	1	2	3	4	0.44
9	5.33	3.67	2	6	9	11	0.59
2	0.51	1.49	0	1	2	2	0.26
465	188	277	62	227	510	527	



Part Type = 70, # MC = 8, Batch Size <= 50, Manufacturing Period = 10-Shift, Permissible Tool Life =90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

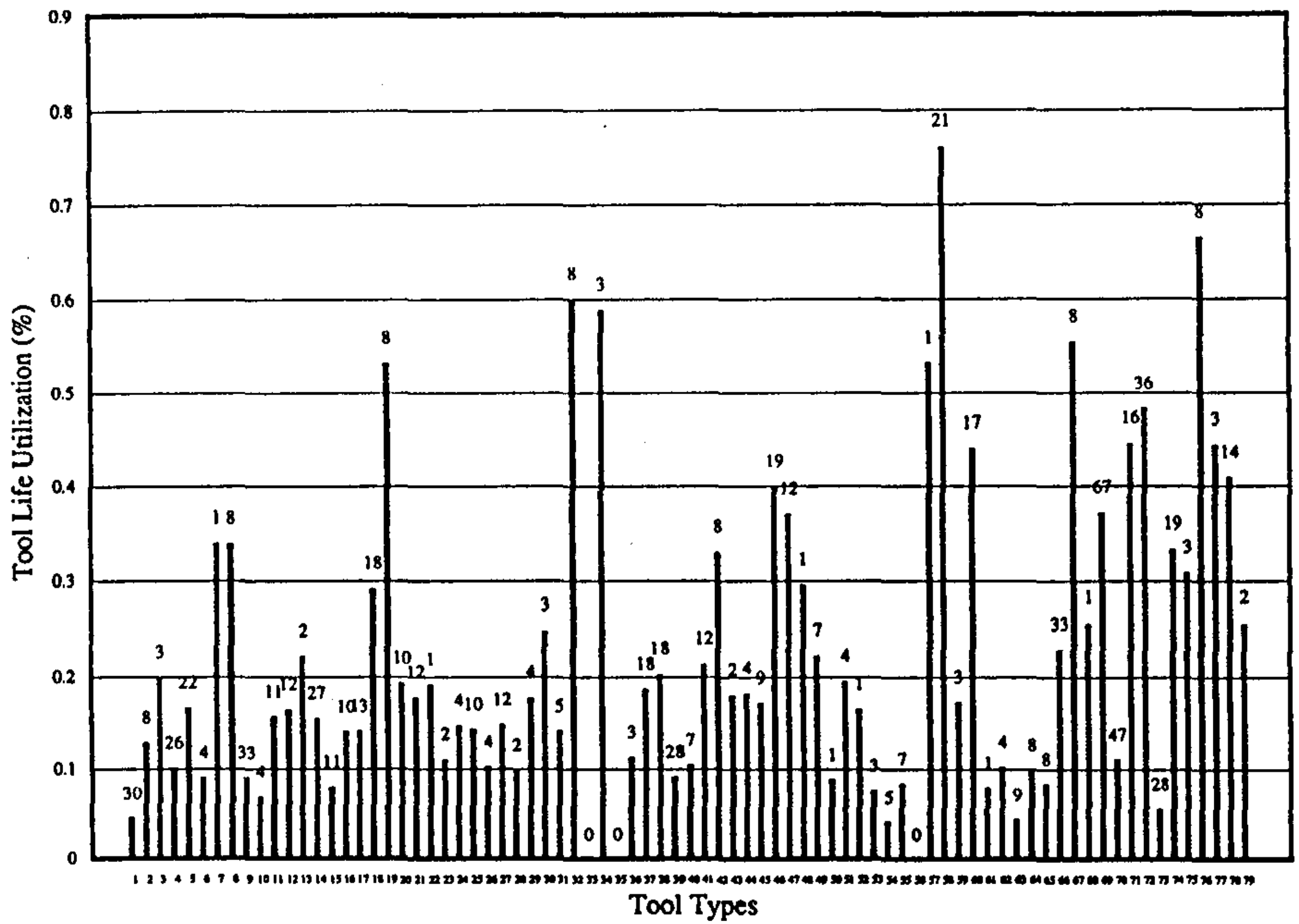
The Supplementary Experiment No. 19

Throughput Time : 4396.5 Avr. Transport.Util.(%): 8.216

Avr. MC Util.(%): 96.820

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	ToolLife Usage
30	1.38	28.62	0	2	48	30	0.05
8	1.04	6.96	0	2	8	8	0.13
3	0.60	2.40	0	1	3	3	0.20
26	2.64	23.36	0	3	31	26	0.10
22	3.68	18.32	0	4	27	22	0.17
4	0.36	3.64	0	1	4	4	0.09
1	0.34	0.66	0	1	1	1	0.34
8	2.72	5.28	0	3	22	8	0.34
33	3.00	30.00	0	4	37	33	0.09
4	0.28	3.72	0	1	4	4	0.07
11	1.73	9.27	0	2	12	11	0.16
12	1.99	10.01	0	2	13	12	0.17
2	0.44	1.56	0	1	3	2	0.22
27	4.22	22.78	0	5	27	27	0.16
11	0.89	10.11	0	1	12	11	0.08
10	1.41	8.59	0	2	12	10	0.14
13	1.85	11.15	0	2	14	13	0.14
18	5.27	12.73	0	6	19	18	0.29
8	4.27	3.73	0	5	8	8	0.53
10	1.94	8.06	0	2	23	10	0.19
12	2.14	9.86	0	3	16	12	0.18
1	0.19	0.81	0	1	1	1	0.19
2	0.22	1.78	0	1	2	2	0.11
4	0.59	3.41	0	1	4	4	0.15
10	1.44	8.56	0	2	10	10	0.14
4	0.41	3.59	0	1	5	4	0.10
12	1.80	10.20	0	2	17	12	0.15
2	0.20	1.80	0	1	2	2	0.10
4	0.71	3.29	0	1	5	4	0.18
3	0.75	2.25	0	1	3	3	0.25
5	0.71	4.29	0	1	5	5	0.14
7	4.20	2.80	1	5	8	8	0.60
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
3	0.34	2.66	0	1	3	3	0.11
18	3.38	14.62	0	4	20	18	0.19
17	3.47	13.53	1	4	19	18	0.20
28	2.57	25.43	0	3	32	28	0.09
7	0.73	6.27	0	1	8	7	0.10
12	2.57	9.43	0	3	13	12	0.21
8	2.64	5.36	0	3	10	8	0.33
2	0.36	1.64	0	1	3	2	0.18
4	0.73	3.27	0	1	4	4	0.18
9	1.56	7.44	0	2	10	9	0.17
18	7.21	10.79	1	8	19	19	0.40
12	4.45	7.55	0	5	19	12	0.37
1	0.30	0.70	0	1	1	1	0.30
7	1.56	5.44	0	2	7	7	0.22
1	0.09	0.91	0	1	1	1	0.09
4	0.78	3.22	0	1	4	4	0.20
1	0.17	0.83	0	1	1	1	0.17
3	0.23	2.77	0	1	3	3	0.08
5	0.21	4.79	0	1	5	5	0.04
7	0.59	6.41	0	1	8	7	0.08
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
14	10.67	3.33	7	11	14	21	0.76
3	0.52	2.48	0	1	3	3	0.17
13	5.73	7.27	4	6	13	17	0.44
1	0.08	0.92	0	1	1	1	0.08
4	0.41	3.59	0	1	5	4	0.10
9	0.40	8.60	0	1	10	9	0.04
8	0.80	7.21	0	1	8	8	0.10
8	0.67	7.33	0	1	8	8	0.08
33	7.57	25.43	0	8	53	33	0.23
8	4.44	3.56	0	5	8	8	0.56
1	0.26	0.74	0	1	1	1	0.26
63	23.43	39.57	4	24	102	67	0.37
46	5.13	40.87	1	6	70	47	0.11
13	5.79	7.21	3	6	14	16	0.45
34	16.43	17.57	2	17	42	36	0.48
28	1.58	26.42	0	2	34	28	0.06
11	3.68	7.32	8	4	13	19	0.33
3	0.93	2.07	0	1	4	3	0.31
7	4.66	2.34	1	5	7	8	0.67
3	1.33	1.67	0	2	3	3	0.44
13	5.33	7.67	1	6	13	14	0.41
2	0.51	1.49	0	1	2	2	0.26
822	189	633	35	229	1027	857	



Part Type = 70, # MC =4, Batch Size <=8, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

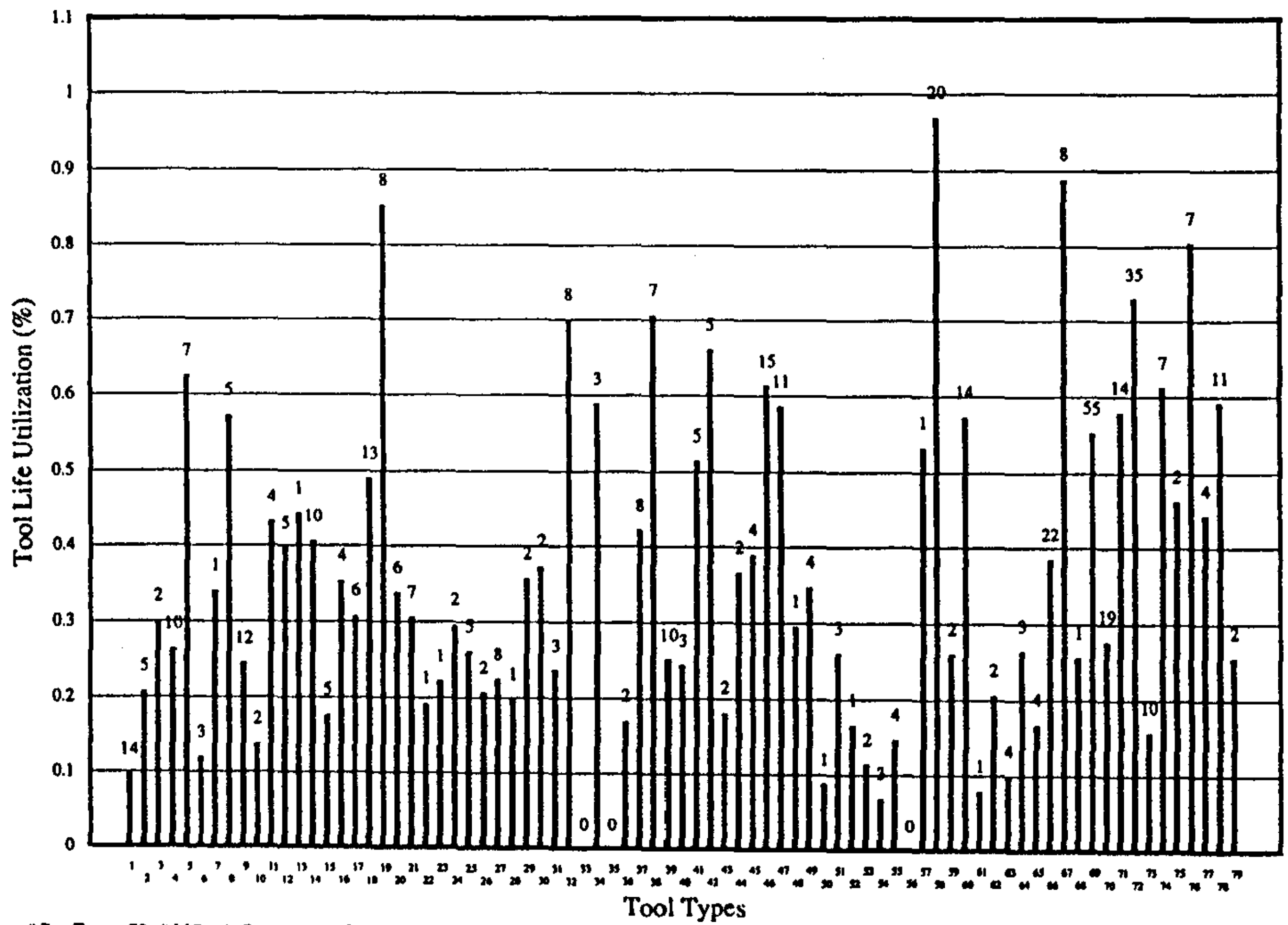
The Taguchi Suggested Experiment No. 20

Throughput Time :	4494.6	Avr.Transport.Util.(%):	3.420
Avr. MC Util.(%):	95.046		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	Tool Usage
14	1.36	12.64	0	2	19	14	0.10
5	1.04	3.96	0	2	0	5	0.21
2	0.60	1.40	0	1	0	2	0.30
10	2.64	7.36	0	3	0	10	0.26
6	3.75	2.25	1	4	0	7	0.63
3	0.36	2.64	0	1	0	3	0.12
1	0.34	0.66	0	1	0	1	0.34
5	2.86	2.14	0	3	0	5	0.57
12	2.94	9.06	0	3	0	12	0.25
2	0.28	1.72	0	1	0	2	0.14
4	1.73	2.27	0	2	0	4	0.43
5	1.99	3.01	0	2	0	5	0.40
1	0.44	0.56	0	1	0	1	0.44
10	4.07	5.93	0	5	0	10	0.41
5	0.89	4.11	0	1	0	5	0.18
4	1.41	2.59	0	2	0	4	0.35
6	1.85	4.15	0	2	0	6	0.31
11	5.40	5.60	2	6	0	13	0.49
5	4.27	0.73	3	5	0	8	0.85
6	2.03	3.97	0	3	0	6	0.34
7	2.14	4.86	0	3	0	7	0.31
1	0.19	0.81	0	1	0	1	0.19
1	0.22	0.78	0	1	0	1	0.22
2	0.59	1.41	0	1	0	2	0.30
5	1.31	3.69	0	2	0	5	0.26
2	0.41	1.59	0	1	0	2	0.21
8	1.80	6.20	0	2	0	8	0.22
1	0.20	0.80	0	1	0	1	0.20
2	0.71	1.29	0	1	0	2	0.36
2	0.75	1.25	0	1	0	2	0.37
3	0.71	2.29	0	1	0	3	0.24
6	4.20	1.80	2	5	0	8	0.70
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	0	3	0.59
0	0.00	0.00	0	0	0	0	0.00
2	0.34	1.66	0	1	0	2	0.17
8	3.38	4.62	0	4	0	8	0.42
5	3.53	1.47	2	4	0	7	0.71
10	2.52	7.48	0	3	0	10	0.25
3	0.73	2.27	0	1	0	3	0.24
5	2.57	2.43	0	3	0	5	0.51
4	2.64	1.36	1	3	0	5	0.66
2	0.36	1.64	0	1	0	2	0.18
2	0.73	1.27	0	1	0	2	0.37
4	1.56	2.44	0	2	0	4	0.39
12	7.36	4.64	3	8	0	15	0.61
8	4.69	3.31	3	5	0	11	0.59
1	0.30	0.70	0	1	0	1	0.30
4	1.39	2.61	0	2	0	4	0.35
1	0.09	0.91	0	1	0	1	0.09
3	0.78	2.22	0	1	0	3	0.26
1	0.17	0.83	0	1	0	1	0.17
2	0.23	1.77	0	1	0	2	0.12
3	0.21	2.79	0	1	0	3	0.07
4	0.59	3.41	0	1	0	4	0.15
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	0	1	0.53
11	10.67	0.33	9	11	0	20	0.97
2	0.52	1.48	0	1	0	2	0.26
10	5.73	4.27	4	6	0	14	0.57
1	0.08	0.92	0	1	0	1	0.08
2	0.41	1.59	0	1	0	2	0.21
4	0.40	3.60	0	1	0	4	0.10
3	0.80	2.21	0	1	0	3	0.27
4	0.67	3.33	0	1	0	4	0.17
20	7.71	12.29	2	8	0	22	0.39
5	4.44	0.56	3	5	0	8	0.89
1	0.26	0.74	0	1	0	1	0.26
44	24.34	19.66	11	25	0	55	0.55
19	5.27	13.73	0	6	0	19	0.28
10	5.79	4.21	4	6	0	14	0.58
24	17.51	6.49	11	18	0	35	0.73
10	1.58	8.42	0	2	0	10	0.16
6	3.68	2.32	1	4	0	7	0.61
2	0.93	1.07	0	1	0	2	0.46
6	4.83	1.17	1	5	0	7	0.81
3	1.33	1.67	1	2	0	4	0.44
9	5.33	3.67	2	6	0	11	0.59
2	0.51	1.49	0	1	0	2	0.26
442	192	250	67	231	19	509	

The Taguchi Suggested Experiment No. 20 - Tool Life Utilization



Part Type = 70, # MC = 4, Batch Size <=50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

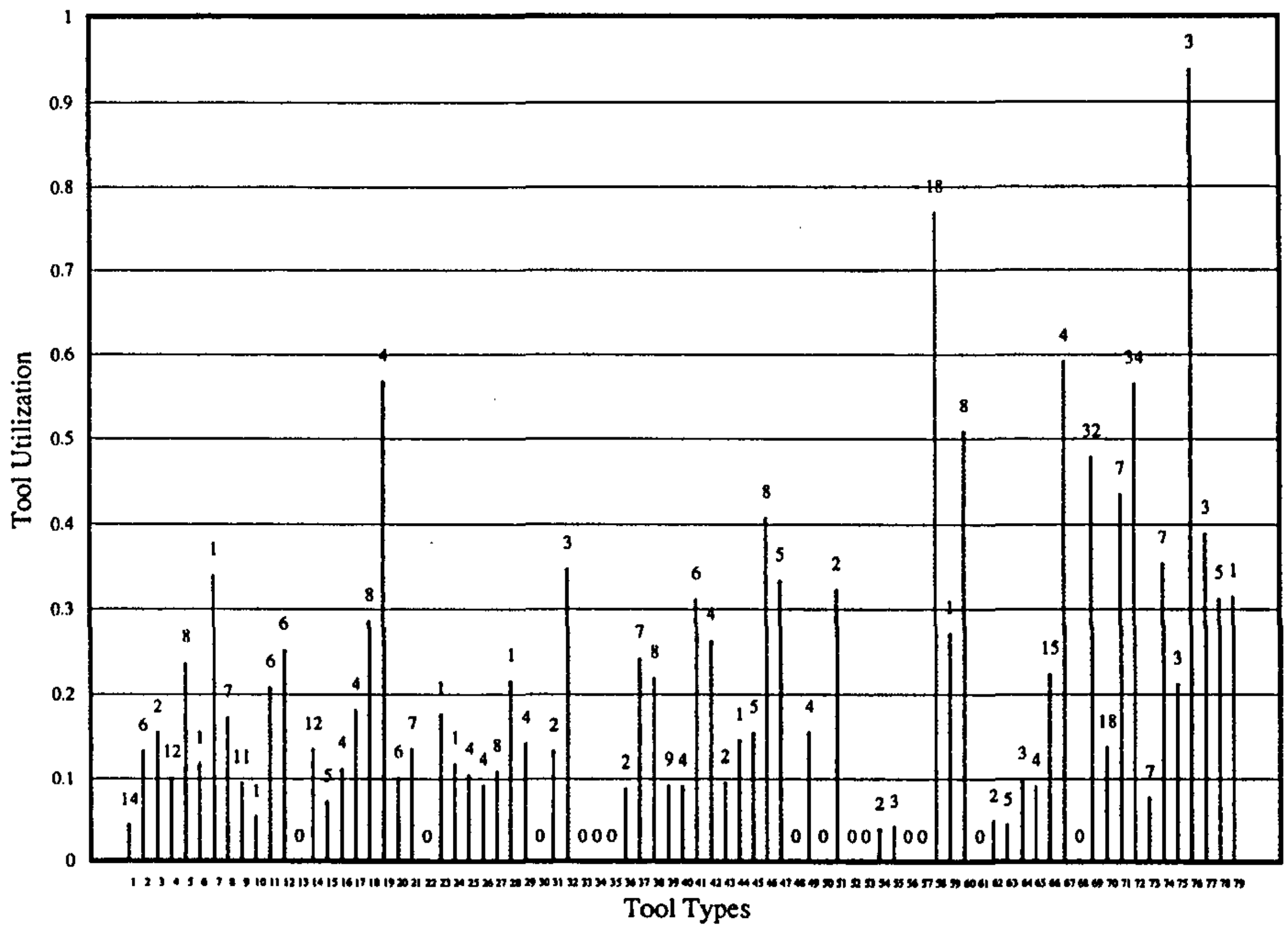
The Supplementary Experiment No.47 - Multi-Cell (Cell 11)

Throughput Time : 2474.75 Avr. Transport.Util.(%): 6.401

Avr. MC Util.(%): 90.857

DIFFERENTIAL KITTING STRATEGY (Cell #1)

Requested Tool Size	Actual Use	Residual Tool Life	No of Spent Tools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
14	0.63	13.37	0	1	21	14	0.04
6	0.80	5.20	0	1	6	6	0.13
2	0.31	1.69	0	1	2	2	0.16
12	1.22	10.78	0	2	14	12	0.10
8	1.90	6.10	0	2	13	8	0.24
1	0.12	0.88	0	1	1	1	0.12
1	0.34	0.66	0	1	1	1	0.34
7	1.21	5.79	0	2	10	7	0.17
11	1.06	9.94	0	2	14	11	0.10
1	0.06	0.94	0	1	1	1	0.06
6	1.26	4.74	0	2	8	6	0.21
6	1.52	4.48	0	2	9	6	0.25
0	0.00	0.00	0	0	0	0	0.00
12	1.63	10.37	0	2	12	12	0.14
5	0.37	4.63	0	1	5	5	0.07
4	0.45	3.55	0	1	4	4	0.11
4	0.73	3.27	0	1	6	4	0.18
8	2.30	5.70	0	3	8	8	0.29
4	2.28	1.72	0	3	4	4	0.57
6	0.61	5.39	0	1	8	6	0.10
7	0.95	6.05	0	1	7	7	0.14
0	0.00	0.00	0	0	0	0	0.00
1	0.18	0.82	0	1	1	1	0.18
1	0.12	0.88	0	1	1	1	0.12
4	0.42	3.58	0	1	4	4	0.11
4	0.37	3.63	0	1	4	4	0.09
8	0.88	7.12	0	1	8	8	0.11
1	0.22	0.78	0	1	1	1	0.22
4	0.57	3.43	0	1	4	4	0.14
0	0.00	0.00	0	0	0	0	0.00
2	0.27	1.73	0	1	2	2	0.13
3	1.04	1.96	0	2	3	3	0.35
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.18	1.82	0	1	2	2	0.09
7	1.70	5.30	0	2	10	7	0.24
8	1.76	6.24	0	2	9	8	0.22
9	0.84	8.16	0	1	11	9	0.09
4	0.37	3.63	0	1	4	4	0.09
6	1.87	4.13	0	2	9	6	0.31
4	1.06	2.94	0	2	4	4	0.26
2	0.19	1.81	0	1	2	2	0.10
1	0.15	0.85	0	1	1	1	0.15
5	0.78	4.22	0	1	5	5	0.16
8	3.26	4.74	0	4	8	8	0.41
5	1.67	3.33	0	2	7	5	0.33
0	0.00	0.00	0	0	0	0	0.00
4	0.63	3.37	0	1	4	4	0.16
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.32
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.08	1.92	0	1	2	2	0.04
3	0.13	2.87	0	1	3	3	0.04
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
12	9.24	2.76	6	10	12	18	0.77
1	0.27	0.73	0	1	1	1	0.27
6	3.06	2.94	2	4	6	8	0.51
0	0.00	0.00	0	0	0	0	0.00
2	0.10	1.90	0	1	2	2	0.05
5	0.23	4.77	0	1	5	5	0.05
3	0.30	2.70	0	1	3	3	0.10
4	0.37	3.63	0	1	4	4	0.09
15	3.38	11.62	0	4	21	15	0.23
4	2.37	1.63	0	3	4	4	0.59
0	0.00	0.00	0	0	0	0	0.00
29	13.91	15.09	3	14	51	32	0.48
18	2.49	15.51	0	3	34	18	0.14
6	2.61	3.39	1	3	7	7	0.44
25	14.16	10.84	9	15	27	34	0.57
7	0.55	6.45	0	1	12	7	0.08
7	2.48	4.52	0	3	8	7	0.35
3	0.64	2.36	0	1	3	3	0.21
3	2.82	0.18	0	3	3	3	0.94
3	1.17	1.83	0	2	3	3	0.39
5	1.57	3.43	0	2	5	5	0.31
1	0.32	0.68	0	1	1	1	0.32
384	101	283	21	139	477	405	



Family 3, # MC (4+4) Batch Size <=8, Manufacturing Period = 10-shift, Strategy = Diff.Kitting
The numbers above the tool life utilization figure indicate the tool inventory level

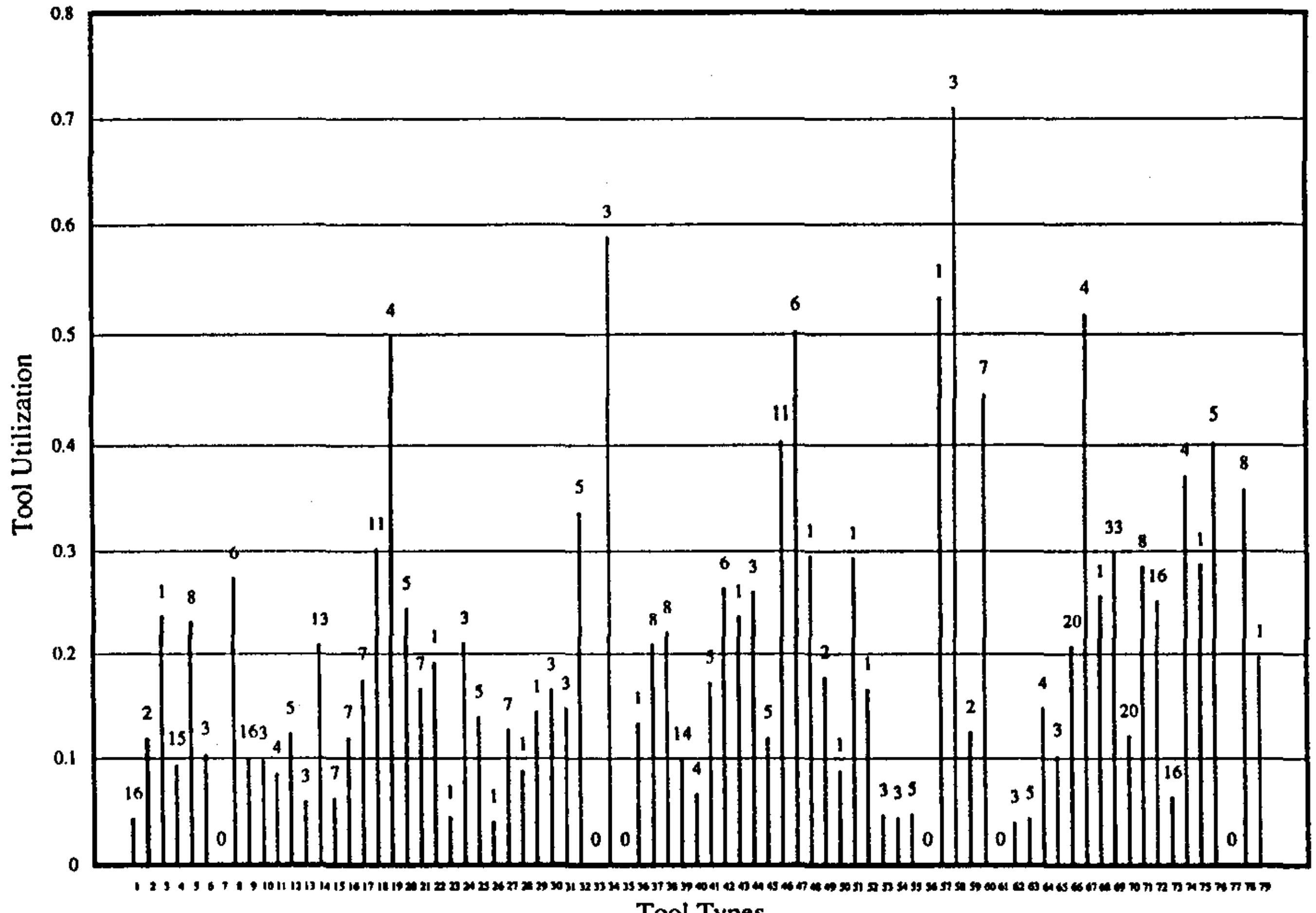
The Supplementary Experiment No.47 - Multi-Cell (Cell 12)

Throughput Time :	2370.65	Avr. Transport Util.(%):	7.880
Avr. MC Util.(%):	96.419		

DIFFERENTIAL KITTING STRATEGY (Cell #2)

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
16	0.69	15.31	0	1	25	16	0.04
2	0.24	1.76	0	1	2	2	0.13
1	0.24	0.76	0	1	1	1	0.20
15	1.41	13.59	0	2	16	15	0.10
8	1.85	6.15	0	2	15	8	0.23
3	0.31	2.69	0	1	3	3	0.11
0	0.00	0.00	0	0	0	0	0.34
6	1.65	4.35	0	2	13	6	0.22
16	1.61	14.39	0	2	22	16	0.10
3	0.30	2.70	0	1	4	3	0.07
4	0.34	3.66	0	1	3	4	0.17
5	0.61	4.39	0	1	5	5	0.18
3	0.18	2.82	0	1	3	3	0.06
13	2.72	10.28	0	3	15	13	0.16
7	0.44	6.56	0	1	6	7	0.07
7	0.84	6.16	0	1	7	7	0.13
7	1.23	5.77	0	2	9	7	0.17
11	3.33	7.67	0	4	12	11	0.30
4	1.99	2.01	0	2	4	4	0.53
5	1.22	3.78	0	2	16	5	0.17
7	1.17	5.83	0	2	9	7	0.16
1	0.19	0.81	0	1	1	1	0.19
1	0.04	0.96	0	1	1	1	0.11
3	0.63	2.37	0	1	4	3	0.15
5	0.70	4.30	0	1	5	5	0.12
1	0.04	0.96	0	1	1	1	0.08
7	0.89	6.11	0	1	9	7	0.12
1	0.09	0.91	0	1	1	1	0.15
1	0.14	0.86	0	1	1	1	0.14
3	0.50	2.50	0	1	2	3	0.25
3	0.44	2.56	0	1	3	3	0.14
5	1.69	3.31	0	2	5	5	0.34
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
1	0.13	0.87	0	1	1	1	0.11
8	1.67	6.33	0	2	10	8	0.23
8	1.77	6.23	0	2	11	8	0.22
14	1.39	12.61	0	2	20	14	0.10
4	0.27	3.73	0	1	3	4	0.09
5	0.86	4.14	0	1	5	5	0.23
6	1.59	4.41	0	2	6	6	0.26
1	0.24	0.76	0	1	1	1	0.14
3	0.78	2.22	0	1	4	3	0.18
5	0.60	4.40	0	1	4	5	0.16
11	4.44	6.56	0	5	12	11	0.41
6	3.02	2.98	0	4	13	6	0.43
1	0.30	0.70	0	1	1	1	0.30
2	0.36	1.64	0	1	2	2	0.16
1	0.09	0.91	0	1	1	1	0.09
1	0.29	0.71	0	1	2	1	0.31
1	0.17	0.83	0	1	1	1	0.17
3	0.14	2.86	0	1	2	3	0.08
3	0.13	2.87	0	1	3	3	0.04
5	0.24	4.76	0	1	5	5	0.05
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
2	1.42	0.58	1	2	2	3	0.76
2	0.25	1.75	0	1	2	2	0.17
6	2.67	3.33	1	3	7	7	0.48
1	0.08	0.92	0	1	1	1	0.08
3	0.12	2.88	0	1	3	3	0.05
5	0.21	4.79	0	1	6	5	0.04
4	0.59	3.41	0	1	6	4	0.11
3	0.31	2.69	0	1	4	3	0.10
20	4.16	15.84	0	5	34	20	0.21
4	2.07	1.93	0	3	4	4	0.56
1	0.26	0.74	0	1	1	1	0.26
33	9.88	23.12	0	10	52	33	0.40
20	2.42	17.58	0	3	37	20	0.14
7	2.00	5.00	1	2	6	8	0.43
16	4.03	11.97	0	5	19	16	0.45
16	1.02	14.98	0	2	23	16	0.07
4	1.49	2.51	0	2	5	4	0.36
1	0.29	0.71	0	1	1	1	0.23
5	2.01	2.99	0	3	5	5	0.60
0	0.00	0.00	0	0	0	0	0.44
8	2.87	5.13	0	3	8	8	0.34
1	0.20	0.80	0	1	1	1	0.51
428	86	342	4	131	560	432	

The Supplementary Experiment No.47 - Multi-Cell (4+4, Cell No.2) - Tool Life Utilization



Family 3, # MC (4+4) Batch Size <=8, Manufacturing Period = 10-shift, Strategy = Diff.Kitting
The numbers above the tool life utilization figure indicate the tool inventory level

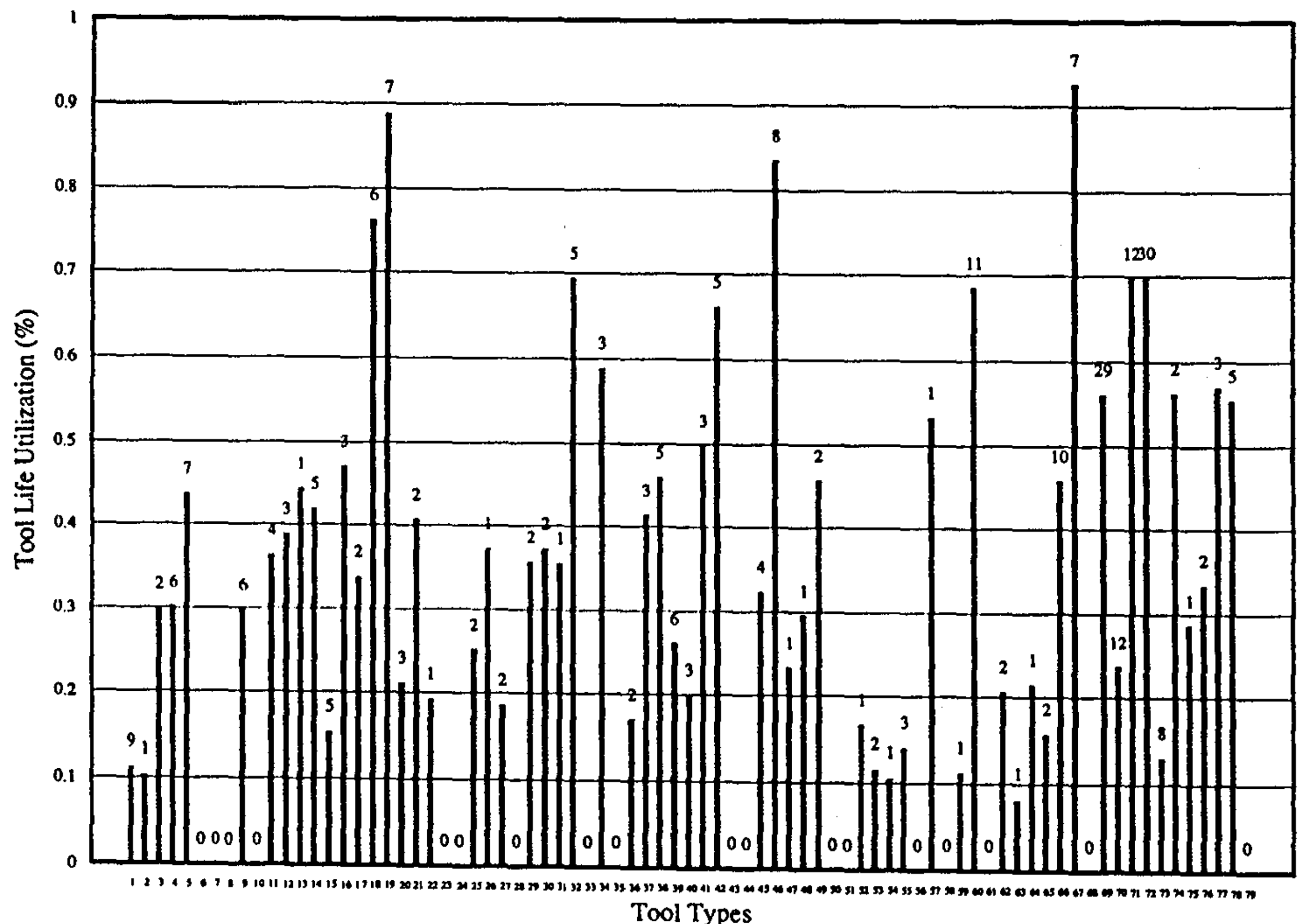
The Supplementary Experiment No.49 (Multi Cell, Cell No.1)

Throughput Time :	2261.4	Avr.Transport.Util.(%):	3.440
Avr. MC Util.(%):	92.470		

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	Tool LifeUse
9	1.01	7.99	0	2	12	9	0.11
1	0.10	0.90	0	1	1	1	0.10
2	0.60	1.40	0	1	2	2	0.30
6	1.81	4.19	0	2	6	6	0.30
6	2.62	3.38	1	3	6	7	0.44
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
6	1.79	4.21	0	2	9	6	0.30
0	0.00	0.00	0	0	0	0	0.00
4	1.46	2.54	0	2	4	4	0.36
3	1.17	1.83	0	2	3	3	0.39
1	0.44	0.56	0	1	1	1	0.44
5	2.10	2.90	0	3	5	5	0.42
5	0.77	4.23	0	1	5	5	0.15
3	1.41	1.59	0	2	4	3	0.47
2	0.68	1.32	0	1	2	2	0.34
4	3.05	0.95	2	4	5	6	0.76
4	3.56	0.44	3	4	4	7	0.89
3	0.64	2.36	0	1	4	3	0.21
2	0.82	1.18	0	1	2	2	0.41
1	0.19	0.81	0	1	1	1	0.19
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.50	1.50	0	1	2	2	0.25
1	0.37	0.63	0	1	1	1	0.37
2	0.37	1.63	0	1	2	2	0.19
0	0.00	0.00	0	0	0	0	0.00
2	0.71	1.29	0	1	2	2	0.36
2	0.75	1.25	0	1	2	2	0.37
1	0.36	0.64	0	1	1	1	0.36
4	2.78	1.22	1	3	4	5	0.69
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
2	0.34	1.66	0	1	2	2	0.17
3	1.24	1.76	0	2	3	3	0.41
4	1.84	2.16	1	2	4	5	0.46
6	1.57	4.43	0	2	8	6	0.26
3	0.60	2.40	0	1	3	3	0.20
3	1.50	1.50	0	2	3	3	0.50
4	2.64	1.36	1	3	4	5	0.66
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	1.30	2.70	0	2	4	4	0.32
5	4.18	0.82	3	5	6	8	0.84
1	0.23	0.77	0	1	1	1	0.23
1	0.30	0.70	0	1	1	1	0.30
2	0.92	1.08	0	1	2	2	0.46
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.17	0.83	0	1	1	1	0.17
2	0.23	1.77	0	1	2	2	0.12
1	0.11	0.89	0	1	1	1	0.11
3	0.42	2.58	0	1	3	3	0.14
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
0	0.00	0.00	0	0	0	0	0.00
1	0.11	0.89	0	1	1	1	0.11
7	4.80	2.20	4	5	7	11	0.69
0	0.00	0.00	0	0	0	0	0.00
2	0.41	1.59	0	1	2	2	0.21
1	0.08	0.92	0	1	1	1	0.08
1	0.22	0.79	0	1	1	1	0.22
2	0.31	1.69	0	1	2	2	0.16
8	3.67	4.33	2	4	10	10	0.46
4	3.70	0.30	3	4	4	7	0.93
0	0.00	0.00	0	0	0	0	0.00
24	13.47	10.53	5	14	25	29	0.56
12	2.84	9.16	0	3	14	12	0.24
8	5.59	2.41	4	6	9	12	0.70
20	13.98	6.02	10	14	20	30	0.70
8	1.04	6.96	0	2	10	8	0.13
2	1.12	0.88	0	2	2	2	0.56
1	0.29	0.71	0	1	1	1	0.29
2	0.67	1.33	0	1	2	2	0.33
2	1.14	0.86	1	2	2	3	0.57
4	2.22	1.78	1	3	4	5	0.55
0	0.00	0.00	0	0	0	0	0.00
238	105		43	139	258	281	

The Supplementary Experiment No.49 (Multi Cell, Cell No.1) - Tool Life Utilization



Part Type = 70, Batch Size <=50, # MC 4 + 4, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

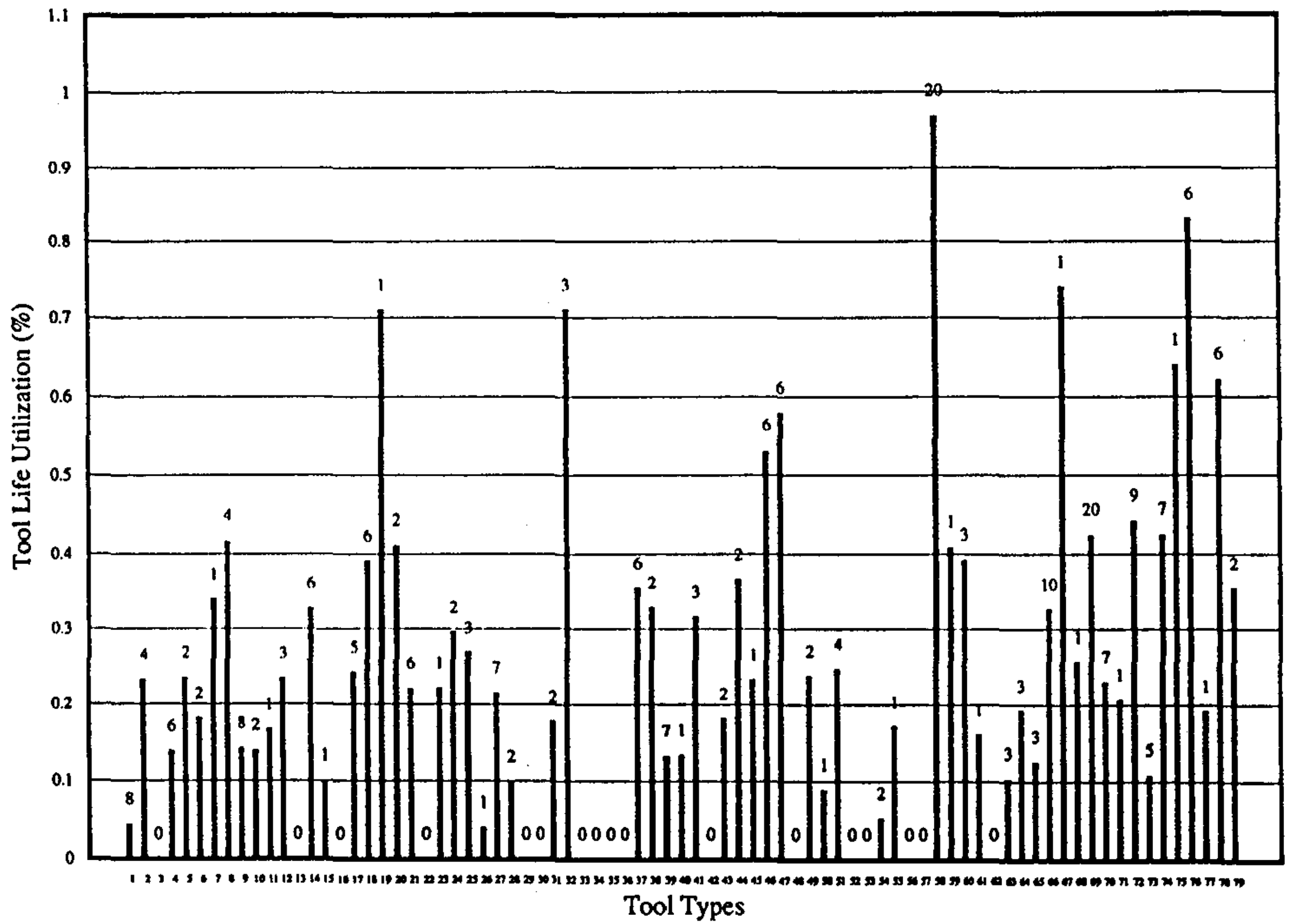
The Supplementary Experiment No.49 (Multi Cell, Cell No.2)

Throughput Time : 2143.25 Avr.Transport.Util.(%): 3.663

Avr. MC Util.(%): 91.725

DIFFERENTIAL KITTING STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inventory	Tool LifeUse
8	0.35	7.65	0	1	8	8	0.04
4	0.93	3.07	0	1	4	4	0.23
0	0.00	0.00	0	0	0	0	0.00
6	0.83	5.17	0	1	7	6	0.14
2	0.47	1.53	0	1	2	2	0.24
2	0.36	1.64	0	1	3	2	0.18
1	0.34	0.66	0	1	1	1	0.34
4	1.67	2.33	0	2	4	4	0.42
8	1.14	6.86	0	2	8	8	0.14
2	0.28	1.72	0	1	2	2	0.14
1	0.17	0.83	0	1	1	1	0.17
3	0.70	2.30	0	1	3	3	0.23
0	0.00	0.00	0	0	0	0	0.00
6	1.97	4.03	0	2	6	6	0.33
1	0.10	0.90	0	1	1	1	0.10
0	0.00	0.00	0	0	0	0	0.00
5	1.21	3.79	0	2	7	5	0.24
6	2.35	3.65	0	3	6	6	0.39
1	0.71	0.29	0	1	1	1	0.71
2	0.82	1.18	0	1	2	2	0.41
6	1.33	4.67	0	2	6	6	0.22
0	0.00	0.00	0	0	0	0	0.00
1	0.22	0.78	0	1	1	1	0.22
2	0.59	1.41	0	1	2	2	0.30
3	0.81	2.19	0	1	3	3	0.27
1	0.04	0.96	0	1	1	1	0.04
7	1.51	5.49	0	2	8	7	0.22
2	0.20	1.80	0	1	2	2	0.10
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.36	1.64	0	1	2	2	0.18
2	1.42	0.58	1	2	2	3	0.71
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
6	2.13	3.87	0	3	6	6	0.36
2	0.66	1.34	0	1	2	2	0.33
7	0.92	6.08	0	1	7	7	0.13
1	0.13	0.87	0	1	1	1	0.13
3	0.95	2.05	0	1	3	3	0.32
0	0.00	0.00	0	0	0	0	0.00
2	0.36	1.64	0	1	2	2	0.18
2	0.73	1.27	0	1	2	2	0.37
1	0.23	0.77	0	1	1	1	0.23
6	3.19	2.81	0	4	6	6	0.53
5	2.90	2.10	1	3	4	6	0.58
0	0.00	0.00	0	0	0	0	0.00
2	0.48	1.52	0	1	2	2	0.24
1	0.09	0.91	0	1	1	1	0.09
4	0.99	3.01	0	1	5	4	0.25
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.11	1.89	0	1	2	2	0.05
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
11	10.67	0.33	9	11	11	20	0.97
1	0.41	0.59	0	1	1	1	0.41
3	1.18	1.82	0	2	4	3	0.39
1	0.16	0.84	0	1	2	1	0.16
0	0.00	0.00	0	0	0	0	0.00
3	0.31	2.69	0	1	3	3	0.10
3	0.58	2.42	0	1	3	3	0.19
3	0.38	2.63	0	1	4	3	0.13
10	3.28	6.72	0	4	14	10	0.33
1	0.74	0.26	0	1	1	1	0.74
1	0.26	0.74	0	1	1	1	0.26
19	8.06	10.94	1	9	21	20	0.42
7	1.61	5.39	0	2	11	7	0.23
1	0.21	0.79	0	1	1	1	0.21
8	3.54	4.46	1	4	9	9	0.44
5	0.54	4.46	0	1	8	5	0.11
6	2.55	3.45	1	3	6	7	0.43
1	0.64	0.36	0	1	1	1	0.64
5	4.16	0.84	1	5	5	6	0.83
1	0.19	0.81	0	1	1	1	0.19
5	3.11	1.89	1	4	5	6	0.62
2	0.71	1.29	0	1	3	2	0.36
230	78		16	113	253	246	



Part Type = 70, Batch Size <=50, # MC 4 + 4 (Cell No.2), Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.
The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

Tool-Oriented Experiments Output

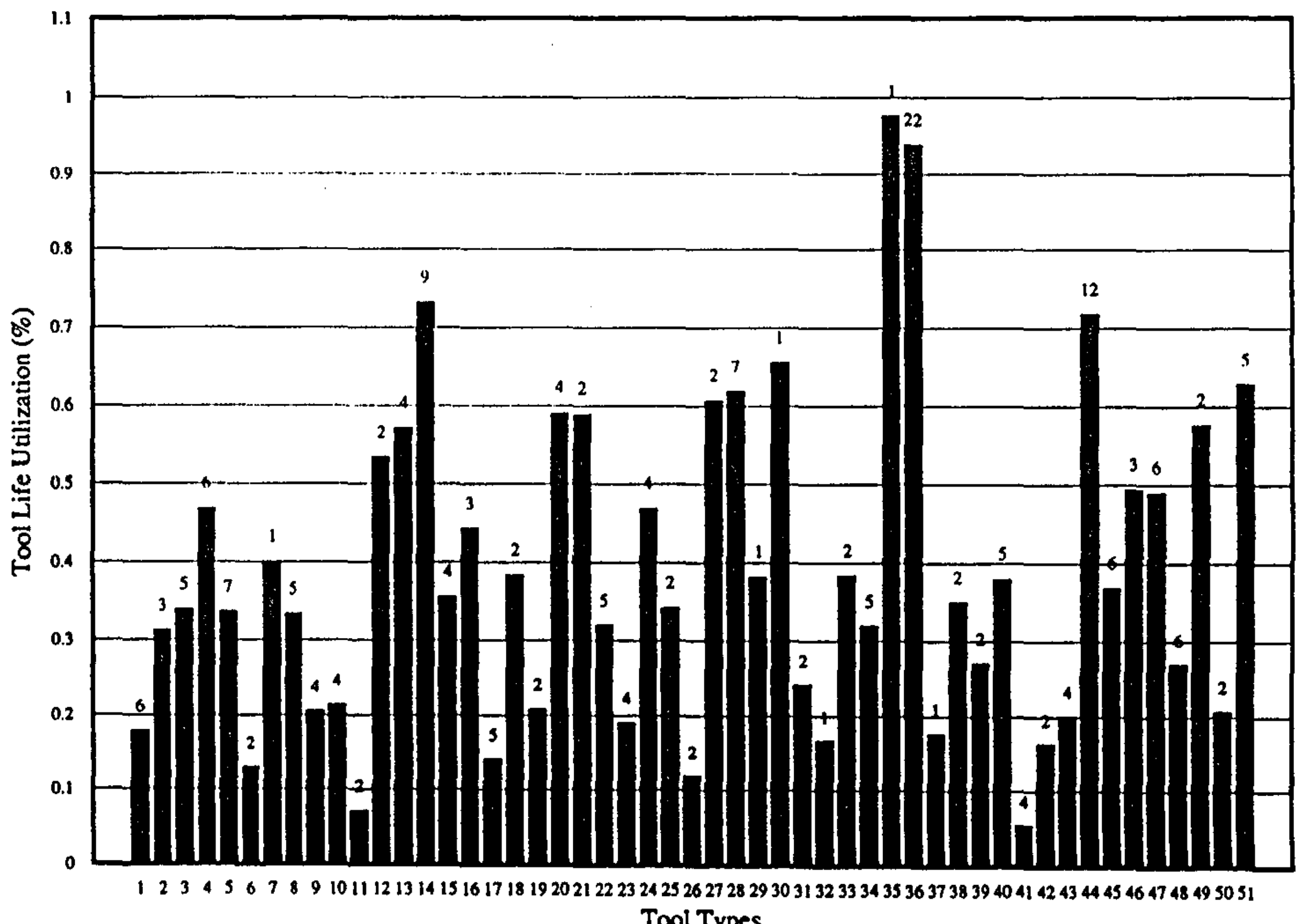
Tables & Graphs

Dynamic Cluster Analysis Computational Experiment No.13

Makespan: 1787.2 MC Utili.(%): 92.03 Transp.Utili.(%): 2.921

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max Use	Tool Life Minutes	Cumulative Use Time	Min.Tool Reqr.	Total No. Of Tools	No. Of Spent Tools	Tool Inventory	Tool Usage
1	90	360	348.4	1.08	6	0	6	0.18
2	90	120	86	0.94	3	0	3	0.31
3	90	90	150	1.70	5	0	5	0.34
4	90	150	379.2	2.81	6	0	6	0.47
5	90	120	226.6	2.35	7	0	7	0.34
6	90	120	28	0.26	2	0	2	0.13
7	90	60	24	0.40	1	0	1	0.40
8	90	120	184.8	1.67	5	0	5	0.33
9	90	90	62.9	0.82	4	0	4	0.21
10	90	90	69.2	0.85	4	0	4	0.21
11	90	120	11.7	0.14	2	0	2	0.07
12	90	60	57.6	1.07	2	0	2	0.53
13	90	120	201.8	2.28	4	0	4	0.57
14	90	60	359.6	6.58	9	0	9	0.73
15	90	45	57.6	1.42	4	0	4	0.36
16	90	60	83.2	1.33	3	0	3	0.44
17	90	80	41	0.71	5	0	5	0.14
18	90	60	41.4	0.77	2	0	2	0.38
19	90	20	50	0.42	2	0	2	0.21
20	90	25	76.3	2.36	4	0	4	0.59
21	90	30	31.8	1.18	2	0	2	0.59
22	90	60	86.2	1.60	5	0	5	0.32
23	90	120	58.4	0.76	4	0	4	0.19
24	90	50	84.4	1.88	4	0	4	0.47
25	90	100	61.6	0.68	2	0	2	0.34
26	90	120	25.6	0.24	2	0	2	0.12
27	90	110	120	1.21	2	0	2	0.61
28	90	120	457	4.32	7	0	7	0.62
29	90	120	44.4	0.38	1	0	1	0.38
30	90	100	72.1	0.66	1	0	1	0.66
31	90	100	48.1	0.48	2	0	2	0.24
32	90	100	15	0.17	1	0	1	0.17
33	90	135	51.2	0.77	2	0	2	0.38
34	90	135	193.8	1.60	5	0	5	0.32
35	90	25	38.5	0.98	1	0	1	0.98
36	90	30	304	11.26	12	10	22	0.94
37	90	300	47.6	0.18	1	0	1	0.18
38	90	80	46.8	0.70	2	0	2	0.35
39	90	180	83	0.54	2	0	2	0.27
40	90	240	130.6	1.52	4	1	5	0.38
41	90	300	59.2	0.22	4	0	4	0.05
42	90	200	58.8	0.33	2	0	2	0.16
43	90	200	113.8	0.80	4	0	4	0.20
44	90	50	361.5	7.89	11	1	12	0.72
45	90	120	239	2.21	6	0	6	0.37
46	90	60	86.4	1.48	3	0	3	0.49
47	90	65	162.2	2.45	5	1	6	0.49
48	90	300	240.8	1.62	6	0	6	0.27
49	90	270	405.8	1.15	2	0	2	0.58
50	90	45	20.8	0.42	2	0	2	0.21
51	90	120	351.6	3.14	5	0	5	0.63
					192	13	205	



Part Type =15, # MC = 4, Batch Size <= 4, Stratgey = Differential Clustering, Permissible Tool Life =90%
The Manufacturing period is 3-Shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

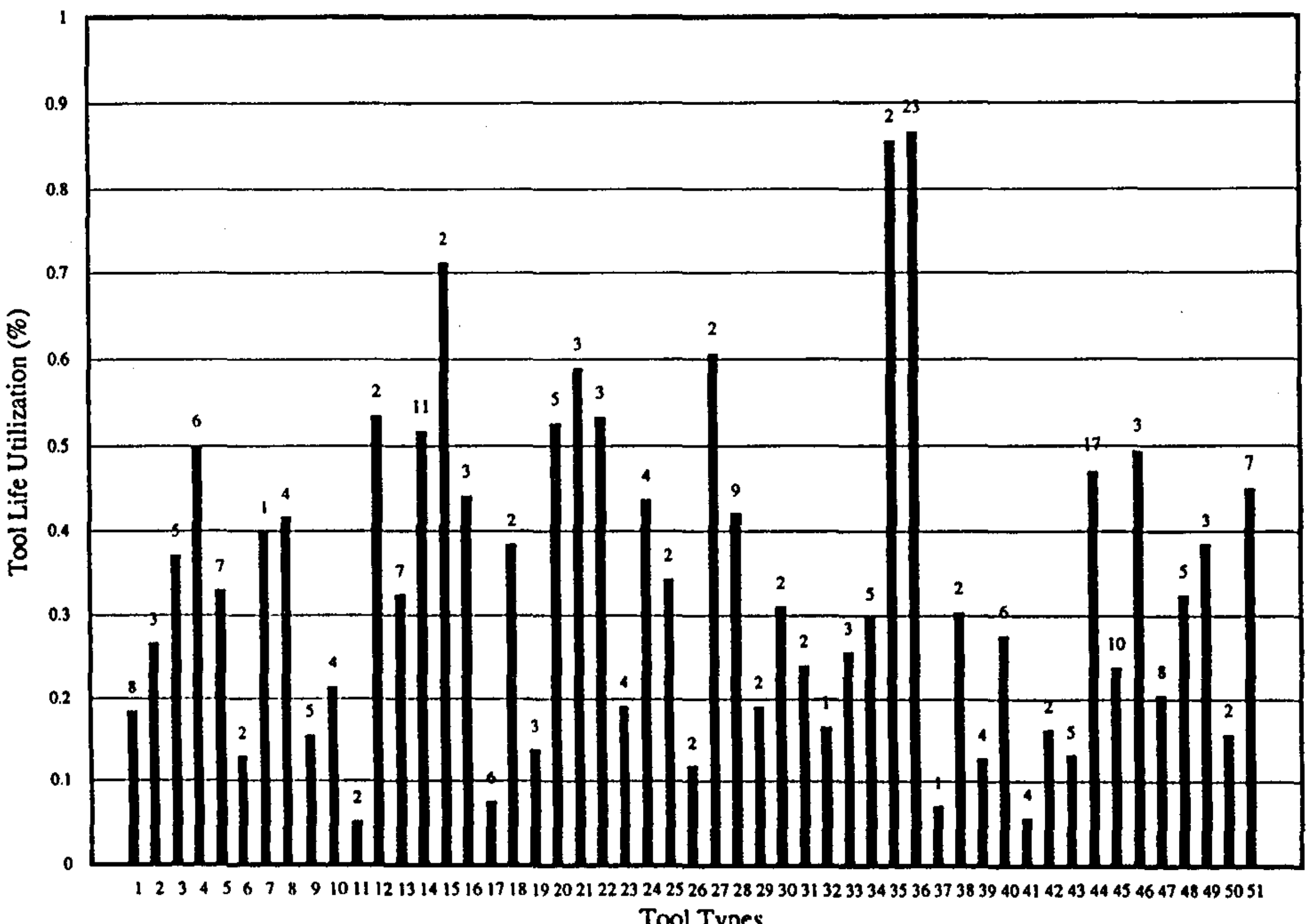
Dynamic Cluster Analysis Computational Experiment No. 20

Through.Time: 948.4 Avr MC Utilis.(%): 77.236 Avr Transp.Util.(%):

DYNAMIC CLUSTER ANALYSIS

Tool Type	Tool Life Minutes	Max % Use	Cumulative Use Time	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	Tool Inv	Tool Usage
1	360	90	432	1.47	0	8	8	0.18
2	120	90	172.8	0.80	0	3	3	0.27
3	90	90	223.4	1.85	0	5	5	0.37
4	150	90	395.6	2.99	0	6	6	0.50
5	120	90	300.4	2.30	0	7	7	0.33
6	120	90	101	0.26	0	2	2	0.13
7	60	90	126.1	0.40	0	1	1	0.40
8	120	90	197.6	1.67	0	4	4	0.42
9	90	90	102.9	0.78	0	5	5	0.16
10	90	90	80.4	0.85	0	4	4	0.21
11	120	90	43.7	0.10	0	2	2	0.05
12	60	90	93.6	1.07	0	2	2	0.53
13	120	90	202	2.26	0	7	7	0.32
14	60	90	321.7	4.64	2	9	11	0.52
15	45	90	48.4	1.42	0	2	2	0.71
16	60	90	92.7	1.33	0	3	3	0.44
17	80	90	43	0.45	0	6	6	0.07
18	60	90	47.9	0.77	0	2	2	0.38
19	20	90	56	0.42	0	3	3	0.14
20	25	90	53.8	2.62	0	5	5	0.52
21	30	90	36.8	1.18	1	2	3	0.59
22	60	90	90.7	1.60	0	3	3	0.53
23	120	90	58.4	0.76	0	4	4	0.19
24	50	90	50.4	1.75	0	4	4	0.44
25	100	90	30.8	0.68	0	2	2	0.34
26	120	90	25.6	0.24	0	2	2	0.12
27	110	90	120	1.21	0	2	2	0.61
28	120	90	373.8	3.37	1	8	9	0.42
29	120	90	44.4	0.38	0	2	2	0.19
30	100	90	65.6	0.62	0	2	2	0.31
31	100	90	29.6	0.48	0	2	2	0.24
32	100	90	15	0.17	0	1	1	0.17
33	135	90	51.2	0.77	0	3	3	0.26
34	135	90	155.4	1.48	0	5	5	0.30
35	25	90	12	1.71	0	2	2	0.86
36	30	90	304	11.26	10	13	23	0.87
37	300	90	47.6	0.07	0	1	1	0.07
38	80	90	28.8	0.61	0	2	2	0.30
39	180	90	56	0.51	0	4	4	0.13
40	240	90	97.6	1.38	1	5	6	0.28
41	300	90	42.4	0.22	0	4	4	0.05
42	200	90	29.4	0.33	0	2	2	0.16
43	200	90	108.8	0.66	0	5	5	0.13
44	50	90	288.2	7.08	2	15	17	0.47
45	120	90	198.6	2.38	0	10	10	0.24
46	60	90	54.4	1.48	0	3	3	0.49
47	65	90	142.6	1.43	1	7	8	0.20
48	300	90	183.8	1.62	0	5	5	0.32
49	270	90	405.8	1.15	0	3	3	0.38
50	45	90	12.8	0.32	0	2	2	0.16
51	120	90	276.6	3.16	0	7	7	0.45
					18	218	236	

Dynamic Cluster Analysis Computational Experiment No.20 - Tool Utilization



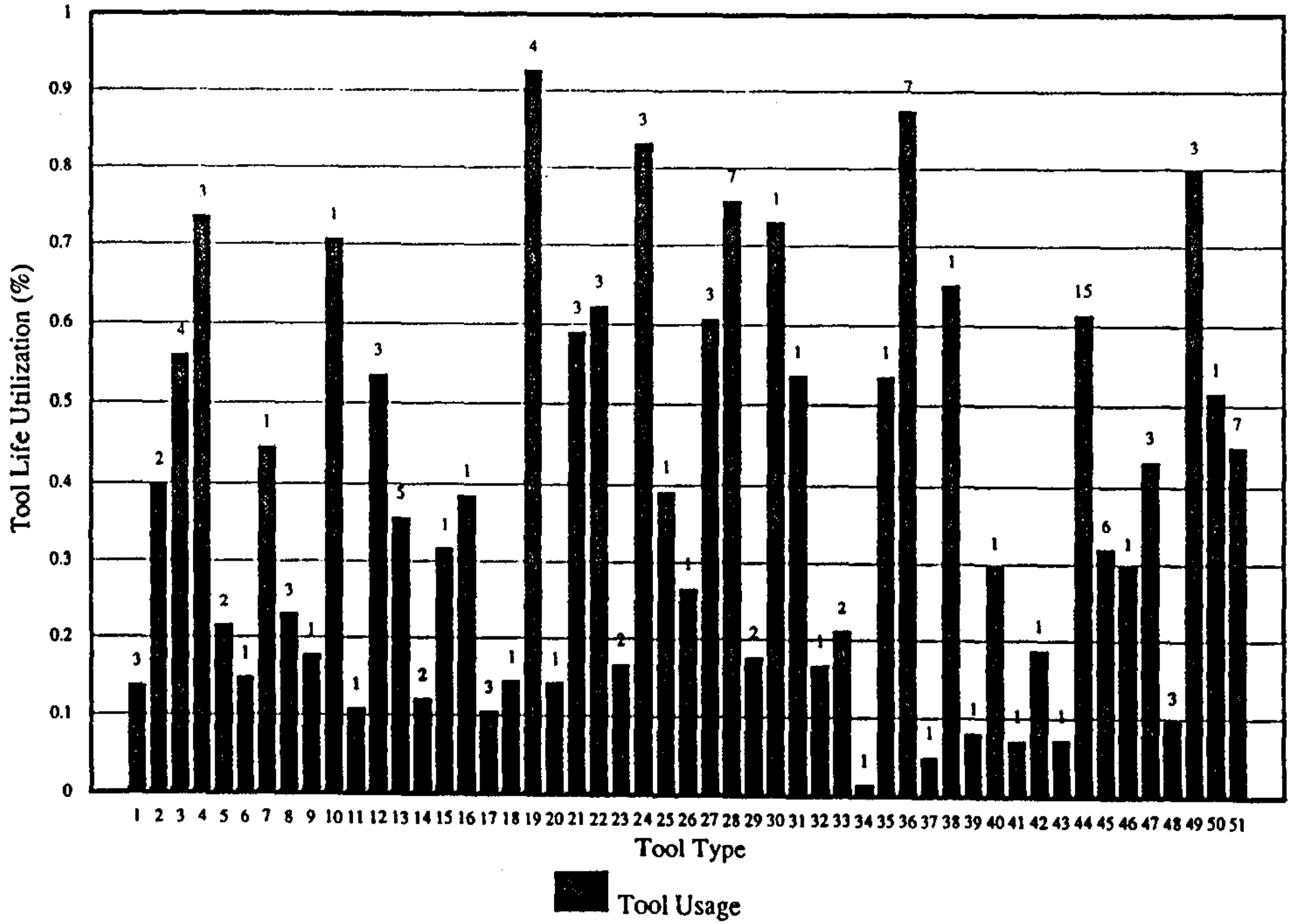
part types = 15, Batch Size <=4, # MC = 8, # Jobs = 92, Stragey = Differential Clustering, Permissible Tool Life = 90%.
The manufacturing period is 3-shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

Dynamic Cluster Analysis Computational Experiment No.34

Through.Time: 713.6 MC Utilis.(%): 70.430 Transport.Util.(%): 2.458

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumula. Use Time	Min.Tool Usage	Diff. Cl Tool Req.	Spent Tools	Tool Inv	Tool Usage(%)
1	90	360	134	0.41	3	0	3	0.14
2	90	120	86	0.80	2	0	2	0.40
3	90	90	135.6	1.67	3	1	4	0.56
4	90	150	297.6	2.20	3	0	3	0.73
5	90	120	46.6	0.43	2	0	2	0.22
6	90	120	16	0.15	1	0	1	0.15
7	90	60	24	0.44	1	0	1	0.44
8	90	120	74.8	0.69	3	0	3	0.23
9	90	90	16	0.18	1	0	1	0.18
10	90	90	57.2	0.71	1	0	1	0.71
11	90	120	11.7	0.11	1	0	1	0.11
12	90	60	57.6	1.07	2	1	3	0.53
13	90	120	192.2	1.78	5	0	5	0.36
14	90	60	13	0.24	2	0	2	0.12
15	90	45	12.8	0.32	1	0	1	0.32
16	90	60	20.8	0.39	1	0	1	0.39
17	90	80	22.6	0.31	3	0	3	0.10
18	90	60	7.8	0.14	1	0	1	0.14
19	90	20	50	2.78	3	1	4	0.93
20	90	25	3.2	0.14	1	0	1	0.14
21	90	30	31.8	1.18	2	1	3	0.59
22	90	60	67.2	1.24	2	1	3	0.62
23	90	120	36	0.33	2	0	2	0.17
24	90	50	74.8	1.66	2	1	3	0.83
25	90	100	35.2	0.39	1	0	1	0.39
26	90	120	32	0.27	1	0	1	0.27
27	90	110	120	1.21	2	1	3	0.61
28	90	120	409.2	3.79	5	2	7	0.76
29	90	120	38.2	0.35	2	0	2	0.18
30	90	100	65.6	0.73	1	0	1	0.73
31	90	100	48.1	0.53	1	0	1	0.53
32	90	100	15	0.17	1	0	1	0.17
33	90	135	51.2	0.42	2	0	2	0.21
34	90	135	1.8	0.01	1	0	1	0.01
35	90	25	12	0.53	1	0	1	0.53
36	90	30	94.4	3.50	4	3	7	0.87
37	90	300	13.6	0.05	1	0	1	0.05
38	90	80	46.8	0.65	1	0	1	0.65
39	90	180	13	0.08	1	0	1	0.08
40	90	240	64	0.30	1	0	1	0.30
41	90	300	19.2	0.07	1	0	1	0.07
42	90	200	33.6	0.19	1	0	1	0.19
43	90	200	13	0.07	1	0	1	0.07
44	90	50	330.9	7.35	12	3	15	0.61
45	90	120	207.2	1.92	6	0	6	0.32
46	90	60	16	0.30	1	0	1	0.30
47	90	65	75.4	1.29	3	0	3	0.43
48	90	300	77.6	0.29	3	0	3	0.10
49	90	270	387.2	1.59	2	1	3	0.80
50	90	45	20.8	0.51	1	0	1	0.51
51	90	120	338.4	3.13	7	0	7	0.45
					112	16	128	



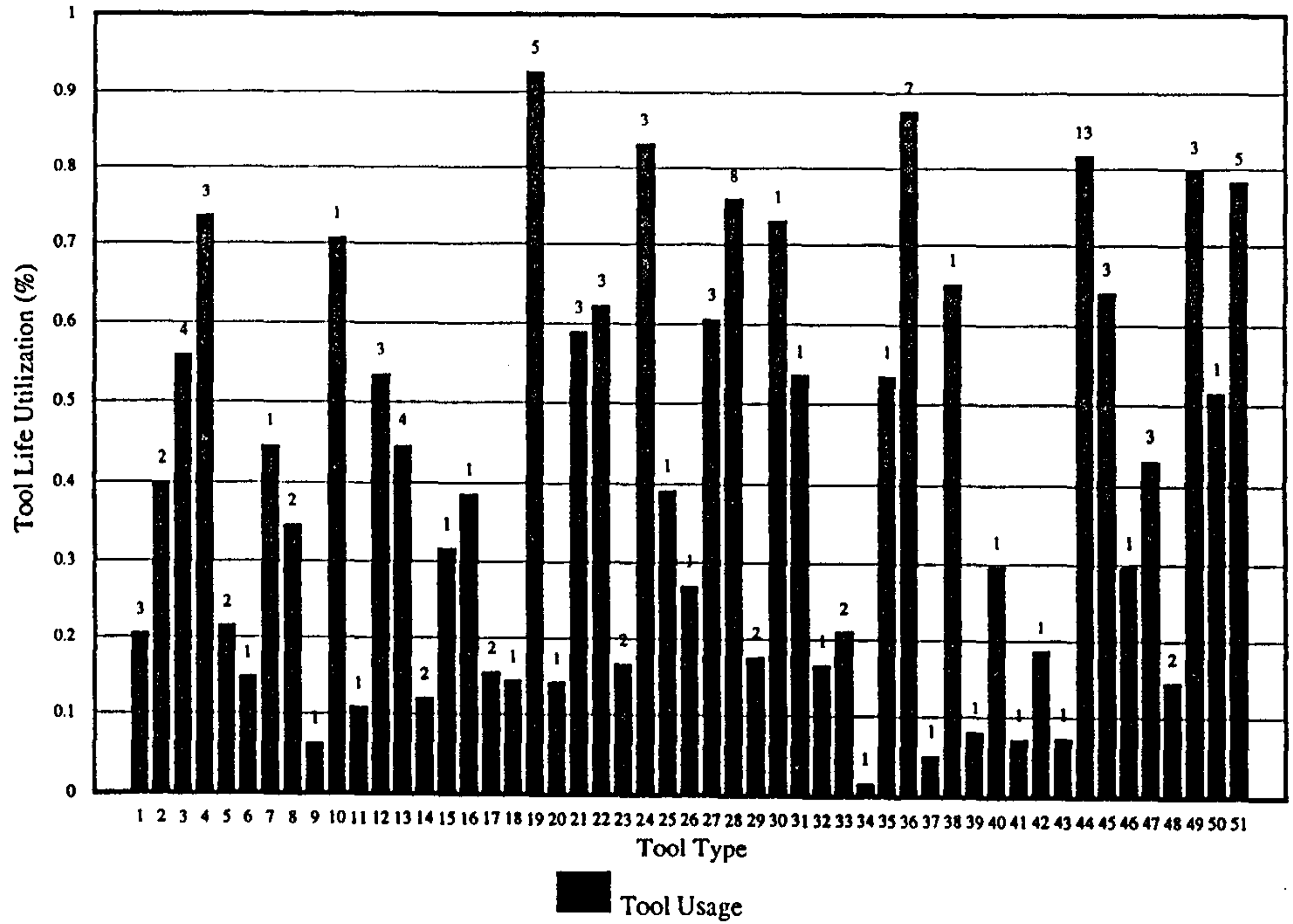
Part Type = 15, Batch Size <= 50, # MC = 8, Strategy = Full Clustering, Permissible Tool Life =90%.
The Manufacturing period is 3-shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

Dynamic Cluster Analysis Computational Experiment No.38

Makespan: 1235 Avr MC Utilis.(%): 81.000 Transport Util (%): 2.230

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life Minutes	Cumulat. Use Time	Min. No. Of Tools	Spent Tools	Diff.Clus. Tool Req.	Tool Invent.	Tool Usage
1	90	360	134	0.41	0	2	3	0.21
2	90	120	86	0.80	0	2	2	0.40
3	90	90	135.6	1.67	1	3	4	0.56
4	90	150	297.6	2.20	0	3	3	0.73
5	90	120	46.6	0.43	0	2	2	0.22
6	90	120	16	0.15	0	1	1	0.15
7	90	60	24	0.44	0	1	1	0.44
8	90	120	74.8	0.69	0	2	2	0.35
9	90	90	16	0.18	0	1	1	0.06
10	90	90	57.2	0.71	0	1	1	0.71
11	90	120	11.7	0.11	0	1	1	0.11
12	90	60	57.6	1.07	1	2	3	0.53
13	90	120	192.2	1.78	0	4	4	0.45
14	90	60	13	0.24	0	2	2	0.12
15	90	45	12.8	0.32	0	1	1	0.32
16	90	60	20.8	0.39	0	1	1	0.39
17	90	80	22.6	0.31	0	2	2	0.16
18	90	60	7.8	0.14	0	1	1	0.14
19	90	20	50	2.78	2	3	5	0.93
20	90	25	3.2	0.14	0	1	1	0.14
21	90	30	31.8	1.18	1	2	3	0.59
22	90	60	67.2	1.24	1	2	3	0.62
23	90	120	36	0.33	0	2	2	0.17
24	90	50	74.8	1.66	1	2	3	0.83
25	90	100	35.2	0.39	0	1	1	0.39
26	90	120	32	0.27	1	0	1	0.27
27	90	110	120	1.21	1	2	3	0.61
28	90	120	409.2	3.79	3	5	8	0.76
29	90	120	38.2	0.35	0	2	2	0.18
30	90	100	65.6	0.73	0	1	1	0.73
31	90	100	48.1	0.53	0	1	1	0.53
32	90	100	15	0.17	0	1	1	0.17
33	90	135	51.2	0.42	0	2	2	0.21
34	90	135	1.8	0.01	0	1	1	0.01
35	90	25	12	0.53	0	1	1	0.53
36	90	30	94.4	3.50	3	4	7	0.87
37	90	300	13.6	0.05	0	1	1	0.05
38	90	80	46.8	0.65	0	1	1	0.65
39	90	180	13	0.08	0	1	1	0.08
40	90	240	64	0.30	0	1	1	0.30
41	90	300	19.2	0.07	0	1	1	0.07
42	90	200	33.6	0.19	0	1	1	0.19
43	90	200	13	0.07	0	1	1	0.07
44	90	50	330.9	7.35	4	9	13	0.82
45	90	120	207.2	1.92	0	3	3	0.64
46	90	60	16	0.30	0	1	1	0.30
47	90	65	75.4	1.29	0	3	3	0.43
48	90	300	77.6	0.29	0	2	2	0.15
49	90	270	387.2	1.59	1	2	3	0.80
50	90	45	20.8	0.51	0	1	1	0.51
51	90	120	338.4	3.13	1	4	5	0.78
					21	97	119	



Part Type = 15, Batch Size <= 50, # MC = 4, Strategy = Differential Clustering, Permissible Tool Life =90%. (Experiment No.38)
The Manufacturing period is 3-shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

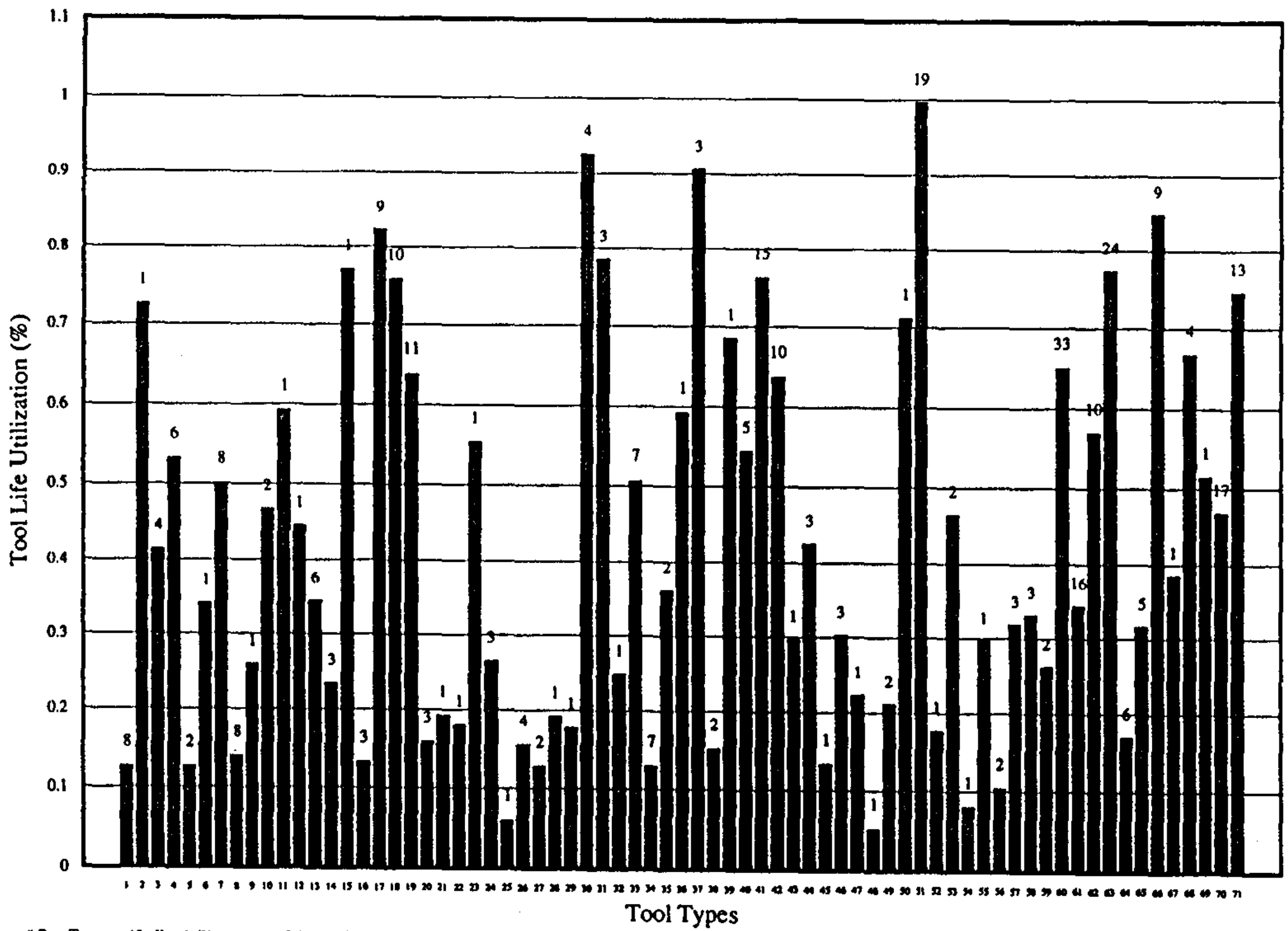
Dynamic Cluster Analysis Computational Experiment No.15

Throug.Time: 3062.9 Avr. MC Utilis.(%): 89.334 Transport Time(%): 2.161

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumulat. Use Time	Min. No. Of Tools	Diff. SpentTools	Differen Tool Req.	Tool Inventory	Tool Usage
1	90	360	334.8	1.03	0	7	7	0.15
2	90	60	39.2	0.73	0	1	1	0.73
3	90	120	148.6	1.38	0	4	4	0.34
4	90	90	215.4	2.66	1	4	5	0.66
5	90	60	13.6	0.25	0	2	2	0.13
6	90	60	18.4	0.34	0	1	1	0.34
7	90	150	415.2	3.08	2	6	8	0.51
8	90	120	122.2	1.13	0	5	5	0.23
9	90	120	28	0.26	0	1	1	0.26
10	90	60	60	1.11	0	2	2	0.56
11	90	60	32	0.59	0	1	1	0.59
12	90	60	24	0.44	0	1	1	0.44
13	90	120	226	2.09	1	6	7	0.35
14	90	90	54.6	0.67	0	2	2	0.34
15	90	90	62.4	0.77	0	1	1	0.77
16	90	120	42.9	0.40	0	3	3	0.13
17	90	60	266.4	4.93	3	6	9	0.82
18	90	25	92.8	4.12	4	5	9	0.82
19	90	120	210.4	1.95	0	4	4	0.49
20	90	125	45.8	0.41	0	2	2	0.20
21	90	60	10.4	0.19	0	1	1	0.19
22	90	45	8.1	0.20	0	1	1	0.20
23	90	45	22.4	0.55	0	1	1	0.55
24	90	60	43	0.80	0	3	3	0.27
25	90	100	5.4	0.06	0	1	1	0.06
26	90	80	47.9	0.67	0	3	3	0.22
27	90	45	12	0.30	0	2	2	0.15
28	90	60	10.4	0.19	0	1	1	0.19
29	90	40	19.2	0.53	0	2	2	0.27
30	90	20	50	2.78	1	3	4	0.93
31	90	30	42.4	1.57	1	2	3	0.79
32	90	60	22.4	0.41	0	1	1	0.41
33	90	60	140.4	2.60	2	4	6	0.65
34	90	120	89.5	0.83	0	5	5	0.17
35	90	60	46.2	0.86	0	2	2	0.43
36	90	60	48	0.89	0	1	1	0.89
37	90	50	81.6	1.81	1	2	3	0.91
38	90	60	21.4	0.40	0	2	2	0.20
39	90	100	61.6	0.68	0	1	1	0.68
40	90	120	166.2	1.54	0	2	2	0.77
41	90	110	679.4	6.86	6	9	15	0.76
42	90	120	448.8	4.16	3	5	8	0.83
43	90	120	32	0.30	0	1	1	0.30
44	90	100	114.6	1.27	0	3	3	0.42
45	90	100	12	0.13	0	1	1	0.13
46	90	100	81.7	0.91	0	3	3	0.30
47	90	100	20	0.22	0	1	1	0.22
48	90	135	19.2	0.16	0	2	2	0.08
49	90	135	51.2	0.42	0	2	2	0.21
50	90	25	16	0.71	0	1	1	0.71
51	90	30	268.8	9.96	9	10	19	1.00
52	90	300	194.8	0.72	0	2	2	0.36
53	90	80	66.8	0.93	0	2	2	0.46
54	90	180	13	0.08	0	1	1	0.08
55	90	240	64	0.30	0	1	1	0.30
56	90	300	33.6	0.12	0	1	1	0.12
57	90	200	165.6	0.92	0	2	2	0.46
58	90	200	161.8	0.90	0	2	2	0.45
59	90	90	31.2	0.39	0	1	1	0.39
60	90	50	768.8	17.05	10	26	36	0.66
61	90	120	444.1	4.89	0	8	8	0.61
62	90	60	279.6	5.18	4	7	11	0.74
63	90	65	717.6	12.27	9	13	22	0.94
64	90	300	135.6	0.50	0	3	3	0.17
65	90	65	77.8	1.33	0	3	3	0.44
66	90	300	1145.6	4.24	4	5	9	0.85
67	90	90	31.2	0.39	0	1	1	0.39
68	90	270	485.6	2.00	1	3	4	0.67
69	90	45	20.8	0.51	0	1	1	0.51
70	90	120	730.4	6.76	4	13	17	0.52
71	90	60	232	4.30	4	5	9	0.86
					70	242	312	

Dynamic Cluster Analysis Computational Experiment No.10 - Tool Usage.



Part Types = 40, Batch Size <=8, # Jobs =103, # MC = 8, Strategy = Full Clustering, Permissible Tool Life = 90%.
The manufacturing period is 10-shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

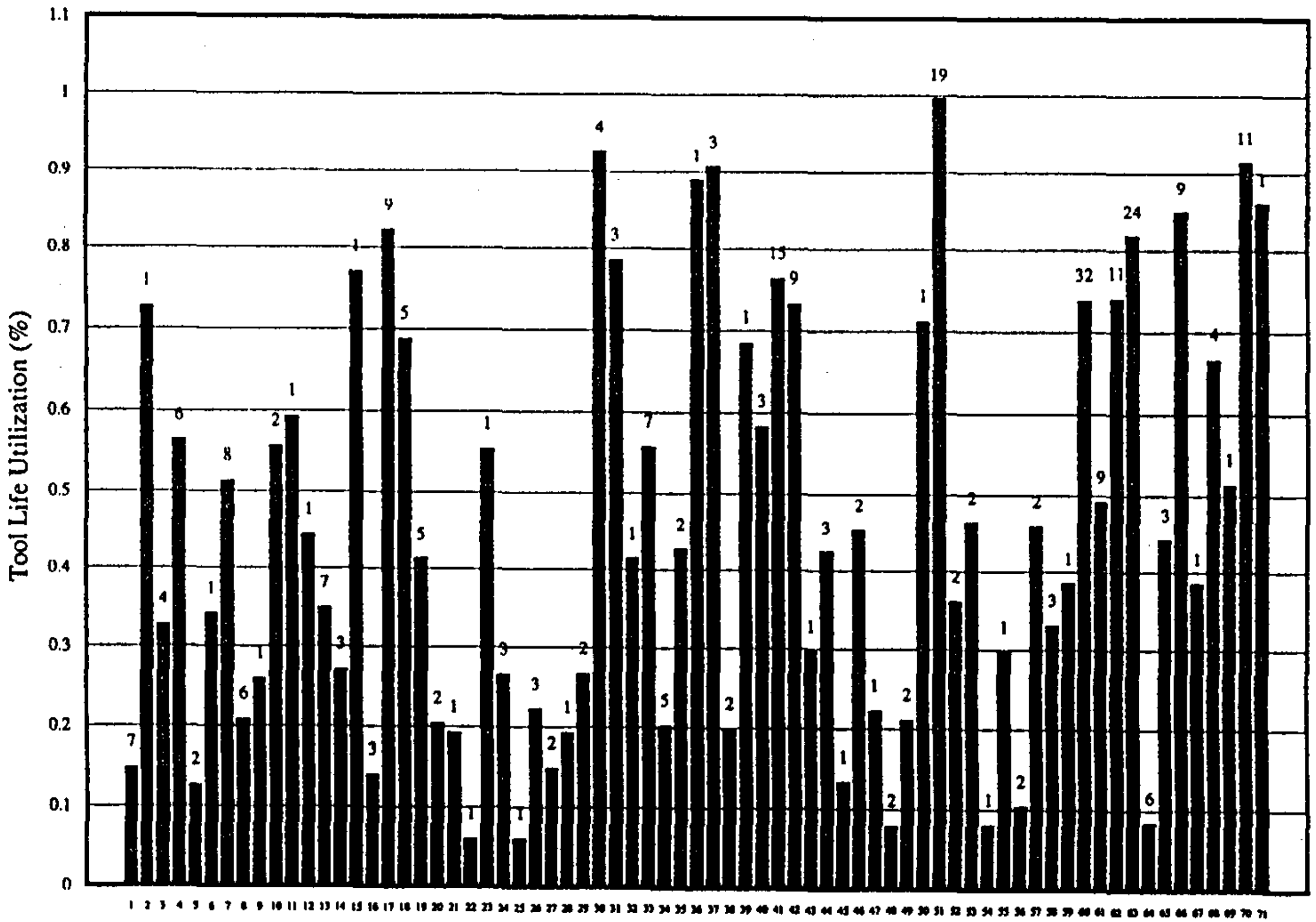
Dynamic Cluster Analysis Computational Experiment No.22

Throug.Time: 1720.8 Avr. MC Utilisation(%): 77.786 Transport Time(%): 3.940

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumula. Use Time	Min. No. Of Tools	Spent Tools	Differen Tool Req.	ToolInv.	Tool Use
1	90	360	326.8	1.01	0	8	8	0.13
2	90	60	39.2	0.73	0	1	1	0.73
3	90	120	146.4	1.65	0	4	4	0.41
4	90	90	215.2	2.66	1	5	6	0.53
5	90	60	13.6	0.25	0	2	2	0.13
6	90	60	18.4	0.34	0	1	1	0.34
7	90	150	404.8	3.00	2	6	8	0.50
8	90	120	120.4	1.11	0	5	5	0.22
9	90	120	28	0.26	0	1	1	0.26
10	90	60	50.4	0.93	0	2	2	0.47
11	90	60	32	0.59	0	1	1	0.59
12	90	60	24	0.44	0	1	1	0.44
13	90	120	186	1.72	1	5	6	0.34
14	90	90	57	0.70	0	3	3	0.23
15	90	90	62.4	0.77	0	1	1	0.77
16	90	120	42.9	0.40	0	2	2	0.20
17	90	60	266.4	4.93	3	6	9	0.82
18	90	25	102.4	4.55	4	6	10	0.76
19	90	120	223	5.10	3	8	11	0.64
20	90	125	41.8	0.48	0	2	2	0.24
21	90	60	10.4	0.19	0	1	1	0.19
22	90	45	8.1	0.18	0	1	1	0.18
23	90	45	22.4	0.55	0	1	1	0.55
24	90	60	43	0.80	0	3	3	0.27
25	90	100	5.4	0.06	0	1	1	0.06
26	90	80	44.7	0.62	0	3	3	0.21
27	90	45	12	0.26	0	2	2	0.13
28	90	60	10.4	0.19	0	1	1	0.19
29	90	40	6.4	0.18	0	1	1	0.18
30	90	20	50	2.78	1	3	4	0.93
31	90	30	42.4	1.57	1	2	3	0.79
32	90	60	22.4	0.25	0	1	1	0.25
33	90	60	136.6	2.53	2	5	7	0.51
34	90	120	97.9	0.91	0	4	4	0.23
35	90	60	39	0.72	0	2	2	0.36
36	90	60	48	0.59	0	1	1	0.59
37	90	50	81.6	1.81	1	2	3	0.91
38	90	60	18.2	0.30	0	2	2	0.15
39	90	100	61.6	0.68	0	1	1	0.68
40	90	120	162.2	2.17	1	4	5	0.54
41	90	110	679.4	6.86	6	9	15	0.76
42	90	120	481.2	4.46	3	7	10	0.64
43	90	120	32	0.30	0	1	1	0.30
44	90	100	114.6	1.27	0	3	3	0.42
45	90	100	12	0.13	0	1	1	0.13
46	90	100	81.7	0.91	0	3	3	0.30
47	90	100	20	0.22	0	1	1	0.22
48	90	135	6.4	0.05	0	1	1	0.05
49	90	135	51.2	0.42	0	2	2	0.21
50	90	25	16	0.71	0	1	1	0.71
51	90	30	268.8	9.96	9	10	19	1.00
52	90	300	47.6	0.18	0	1	1	0.18
53	90	80	66.8	0.93	0	2	2	0.46
54	90	180	13	0.08	0	1	1	0.08
55	90	240	64	0.30	0	1	1	0.30
56	90	300	56	0.21	0	2	2	0.10
57	90	200	172	0.96	0	3	3	0.32
58	90	200	178.6	0.99	0	3	3	0.33
59	90	90	42.4	0.52	0	2	2	0.26
60	90	50	730.6	16.24	8	22	30	0.74
61	90	120	454.5	5.16	1	10	11	0.52
62	90	60	219.2	3.98	3	7	10	0.57
63	90	65	678.4	11.60	9	14	23	0.83
64	90	300	132.8	1.02	0	6	6	0.17
65	90	65	125.4	1.58	0	5	5	0.32
66	90	300	1145.6	4.24	4	5	9	0.85
67	90	90	31.2	0.39	0	1	1	0.39
68	90	270	485.6	2.00	1	3	4	0.67
69	90	45	20.8	0.51	0	1	1	0.51
70	90	120	657.2	6.09	4	11	15	0.55
71	90	60	299.6	5.97	5	8	13	0.75
					73	258	331	

Dynamic Cluster Analysis Computational Experiment No.21 - Tool Usage



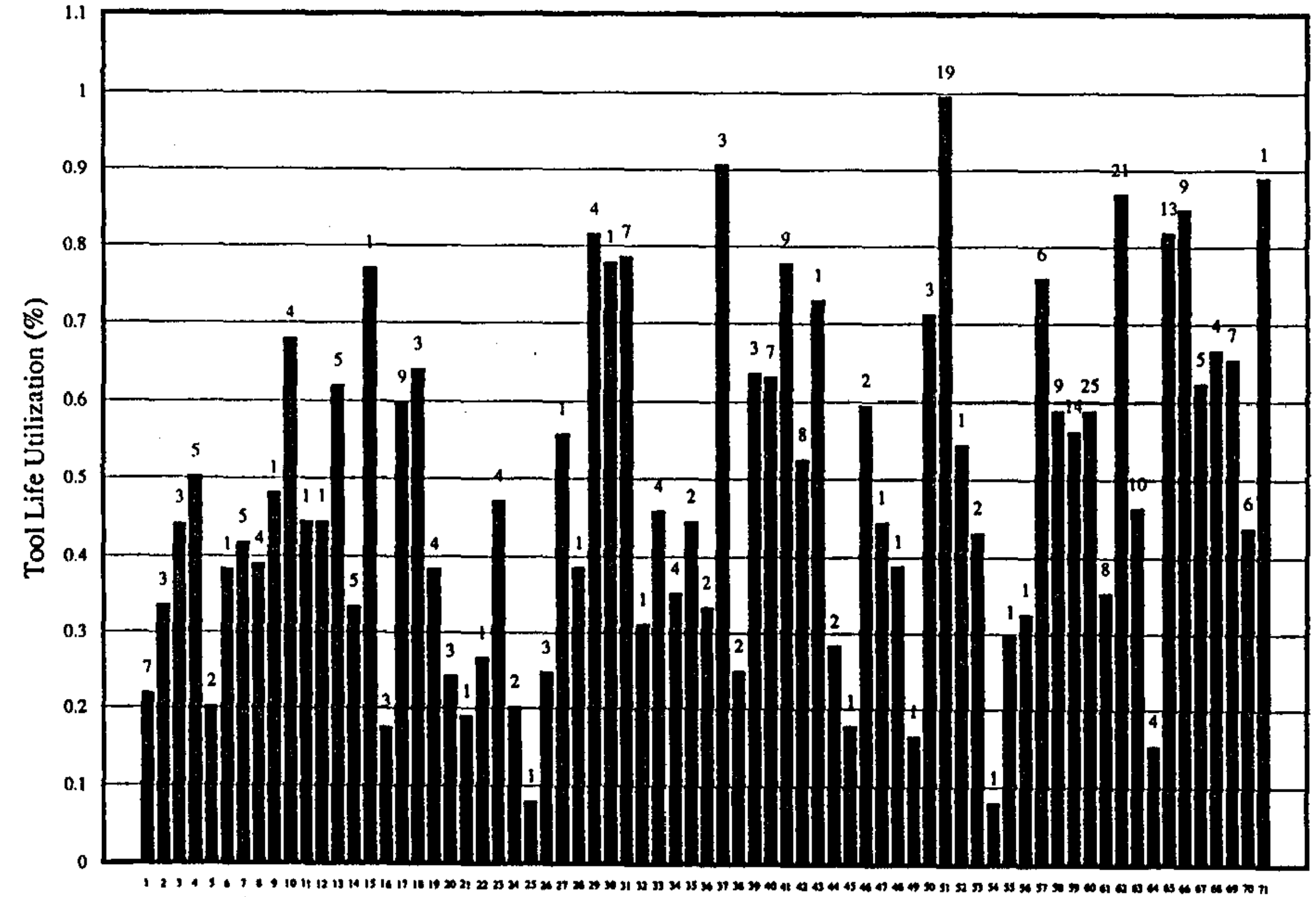
Part Type = 40, Batch Size <= 8, # MC = 6, # Jobs = 103, Strategy = Differential Clustering, Permissible Tool Life = 90%.
The manufacturing period is 10-shift. The numbers above tool life utilization figure indicate the tool inventory level of that particular tool type.

Dynamic Cluster Analysis Computational Experiment No.36

Throug.Time: 1677.23 Avr MC Utilisation(%): 85.235 Avr Transport Util.(%): 2.063

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumula. Use Time	Min Tool Reqr.	Spent Tools	Diff.Clus. Tool Req.	Tool Inventory	Tool Use
1	90	360	377	1.53	0	7	7	0.22
2	90	60	54.4	1.01	0	3	3	0.34
3	90	120	143.1	1.33	0	3	3	0.44
4	90	90	162.8	2.01	1	4	5	0.50
5	90	60	21.8	0.40	0	2	2	0.20
6	90	60	20.7	0.38	0	1	1	0.38
7	90	150	225.5	1.67	1	4	5	0.42
8	90	120	168.6	1.56	0	4	4	0.39
9	90	120	52	0.48	0	1	1	0.48
10	90	60	118	2.04	1	3	4	0.68
11	90	60	24	0.44	0	1	1	0.44
12	90	60	24	0.44	0	1	1	0.44
13	90	120	267.2	2.47	1	4	5	0.62
14	90	90	125	1.34	1	4	5	0.33
15	90	90	62.4	0.77	0	1	1	0.77
16	90	120	57	0.53	0	3	3	0.18
17	90	60	226	4.19	2	7	9	0.60
18	90	25	28.8	1.28	1	2	3	0.64
19	90	120	165.6	1.53	0	4	4	0.38
20	90	125	70.6	0.73	0	3	3	0.24
21	90	60	10.4	0.19	0	1	1	0.19
22	90	45	10.8	0.27	0	1	1	0.27
23	90	45	62.4	1.41	1	3	4	0.47
24	90	60	21.8	0.40	0	2	2	0.20
25	90	100	7.2	0.08	0	1	1	0.08
26	90	80	53.6	0.74	0	3	3	0.25
27	90	45	22.6	0.56	0	1	1	0.56
28	90	60	20.8	0.39	0	1	1	0.39
29	90	40	52	2.44	1	3	4	0.81
30	90	20	14	0.78	0	1	1	0.78
31	90	30	84.8	3.14	3	4	7	0.79
32	90	60	16.8	0.31	0	1	1	0.31
33	90	60	74.2	1.37	1	3	4	0.46
34	90	120	152	1.41	0	4	4	0.35
35	90	60	100.4	0.89	0	2	2	0.44
36	90	60	36	0.67	0	2	2	0.33
37	90	50	81.6	1.81	1	2	3	0.91
38	90	60	27	0.50	0	2	2	0.25
39	90	100	114.4	1.27	1	2	3	0.64
40	90	120	396	3.15	2	5	7	0.63
41	90	110	538.6	5.44	2	7	9	0.78
42	90	120	323	3.16	2	6	8	0.53
43	90	120	65.6	0.73	0	1	1	0.73
44	90	100	51	0.57	0	2	2	0.28
45	90	100	16	0.18	0	1	1	0.18
46	90	100	107.1	1.19	0	2	2	0.60
47	90	100	40	0.44	0	1	1	0.44
48	90	135	47.2	0.39	0	1	1	0.39
49	90	135	20	0.16	0	1	1	0.16
50	90	25	32	1.42	1	2	3	0.71
51	90	30	268.8	9.96	9	10	19	1.00
52	90	300	147.2	0.55	0	1	1	0.55
53	90	80	62.1	0.86	0	2	2	0.43
54	90	180	13	0.08	0	1	1	0.08
55	90	240	64	0.30	0	1	1	0.30
56	90	300	88	0.33	0	1	1	0.33
57	90	200	545.6	3.03	2	4	6	0.76
58	90	200	636.4	3.54	3	6	9	0.59
59	90	90	271.5	5.62	4	10	14	0.56
60	90	50	561.9	11.17	6	19	25	0.59
61	90	120	404.1	2.83	0	8	8	0.35
62	90	60	617.2	10.42	9	12	21	0.87
63	90	65	247.4	3.70	2	8	10	0.46
64	90	300	166.1	0.62	0	4	4	0.15
65	90	65	1490.6	7.36	4	9	13	0.82
66	90	300	1145.4	4.24	4	5	9	0.85
67	90	90	575	2.49	1	4	5	0.62
68	90	270	485.6	2.00	1	3	4	0.67
69	90	45	394.2	3.92	1	6	7	0.65
70	90	120	164	2.19	1	5	6	0.44
71	90	60	232	0.89	0	1	1	0.89
					70	249	319	



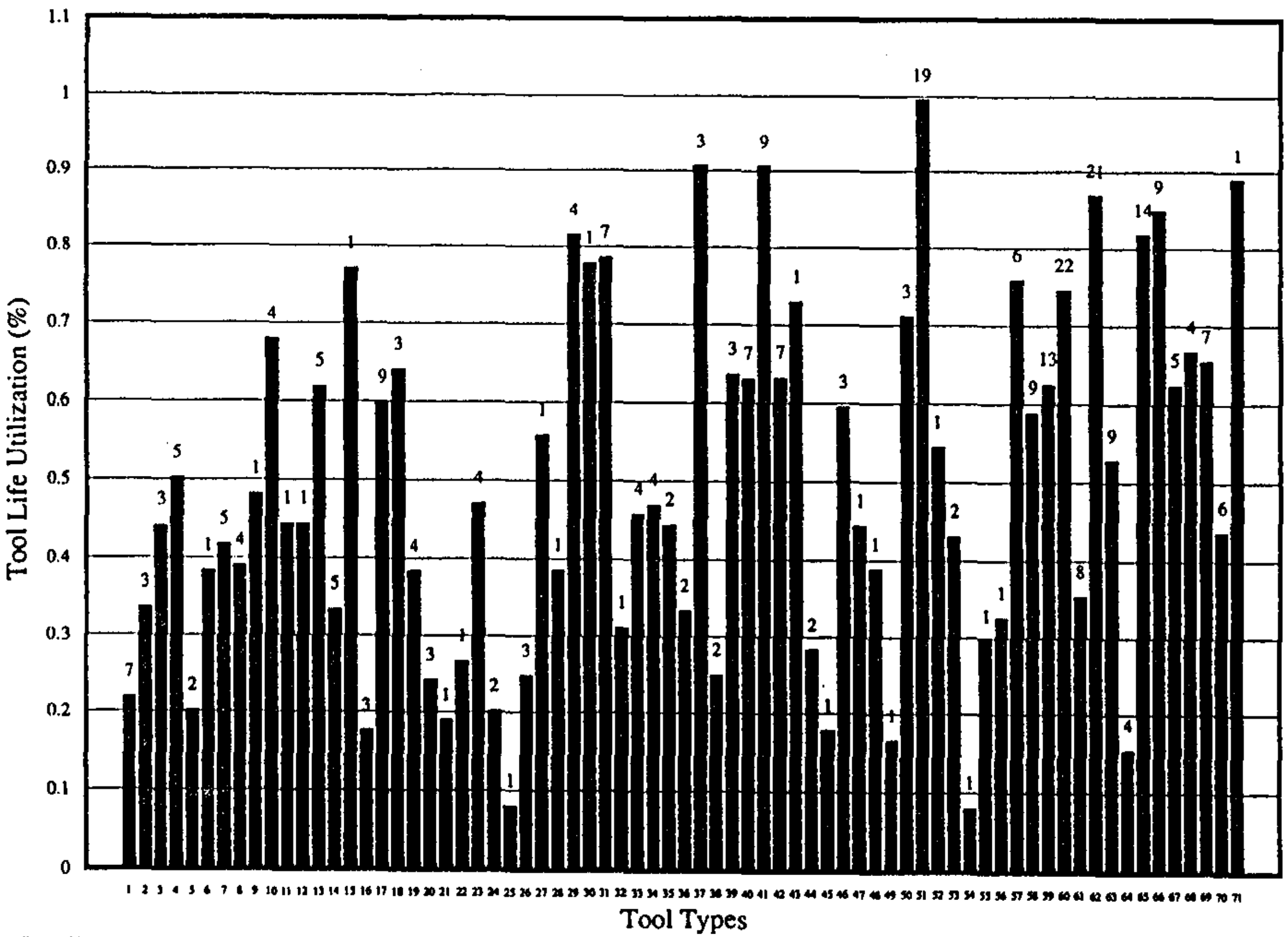
Part Types = 40, Batch Size <=50, # MC =8, # Jobs = 43, Strategy = Differential Clustering, Permissible Tool Life = 90%.
The manufacturing period is 10-Shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

Dynamic Cluster Analysis Computational Experiment No.39

Throug.Time: 2880 Avr MC Utilisation(%): 93.100 Avr Transport Util.(%): 1.201

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumula. Use Time	Min Tool Reqr.	Spent Tools	Diff.Clus. Tool Req.	Tool Inventory	Tool Use
1	90	360	377	1.53	0	7	7	0.22
2	90	60	54.4	1.01	0	3	3	0.34
3	90	120	143.1	1.33	0	3	3	0.44
4	90	90	162.8	2.01	1	4	5	0.50
5	90	60	21.8	0.40	0	2	2	0.20
6	90	60	20.7	0.38	0	1	1	0.38
7	90	150	225.5	1.67	1	4	5	0.42
8	90	120	168.6	1.56	0	4	4	0.39
9	90	120	52	0.48	0	1	1	0.48
10	90	60	118	2.04	1	3	4	0.68
11	90	60	24	0.44	0	1	1	0.44
12	90	60	24	0.44	0	1	1	0.44
13	90	120	267.2	2.47	1	4	5	0.62
14	90	90	125	1.34	1	4	5	0.33
15	90	90	62.4	0.77	0	1	1	0.77
16	90	120	57	0.53	0	3	3	0.18
17	90	60	226	4.19	2	7	9	0.60
18	90	25	28.8	1.28	1	2	3	0.64
19	90	120	165.6	1.53	0	4	4	0.38
20	90	125	70.6	0.73	0	3	3	0.24
21	90	60	10.4	0.19	0	1	1	0.19
22	90	45	10.8	0.27	0	1	1	0.27
23	90	45	62.4	1.41	1	3	4	0.47
24	90	60	21.8	0.40	0	2	2	0.20
25	90	100	7.2	0.08	0	1	1	0.08
26	90	80	53.6	0.74	0	3	3	0.25
27	90	45	22.6	0.56	0	1	1	0.56
28	90	60	20.8	0.39	0	1	1	0.39
29	90	40	52	2.44	1	3	4	0.81
30	90	20	14	0.78	0	1	1	0.78
31	90	30	84.8	3.14	3	4	7	0.79
32	90	60	16.8	0.31	0	1	1	0.31
33	90	60	74.2	1.37	1	3	4	0.46
34	90	120	152	1.41	1	3	4	0.47
35	90	60	100.4	0.89	0	2	2	0.44
36	90	60	36	0.67	0	2	2	0.33
37	90	50	81.6	1.81	1	2	3	0.91
38	90	60	27	0.50	0	2	2	0.25
39	90	100	114.4	1.27	1	2	3	0.64
40	90	120	396	3.15	2	5	7	0.63
41	90	110	538.6	5.44	3	6	9	0.91
42	90	120	323	3.16	2	5	7	0.63
43	90	120	65.6	0.73	0	1	1	0.73
44	90	100	51	0.57	0	2	2	0.28
45	90	100	16	0.18	0	1	1	0.18
46	90	100	107.1	1.19	1	2	3	0.60
47	90	100	40	0.44	0	1	1	0.44
48	90	135	47.2	0.39	0	1	1	0.39
49	90	135	20	0.16	0	1	1	0.16
50	90	25	32	1.42	1	2	3	0.71
51	90	30	268.8	9.96	9	10	19	1.00
52	90	300	147.2	0.55	0	1	1	0.55
53	90	80	62.1	0.86	0	2	2	0.43
54	90	180	13	0.08	0	1	1	0.08
55	90	240	64	0.30	0	1	1	0.30
56	90	300	88	0.33	0	1	1	0.33
57	90	200	545.6	3.03	2	4	6	0.76
58	90	200	636.4	3.54	3	6	9	0.59
59	90	90	271.5	5.62	4	9	13	0.62
60	90	50	561.9	11.17	7	15	22	0.74
61	90	120	404.1	2.83	0	8	8	0.35
62	90	60	617.2	10.42	9	12	21	0.87
63	90	65	247.4	3.70	2	7	9	0.53
64	90	300	166.1	0.62	0	4	4	0.15
65	90	65	1490.6	7.36	5	9	14	0.82
66	90	300	1145.4	4.24	4	5	9	0.85
67	90	90	575	2.49	1	4	5	0.62
68	90	270	485.6	2.00	1	3	4	0.67
69	90	45	394.2	3.92	1	6	7	0.65
70	90	120	164	2.19	1	5	6	0.44
71	90	60	232	0.89	0	1	1	0.89
					75	240	315	



Part Types = 40, Batch Size <=50, # MC =4, # Jobs = 43, Strategy = Differential Clustering, Permissible Tool Life = 90%.
The manufacturing period is 10-Shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

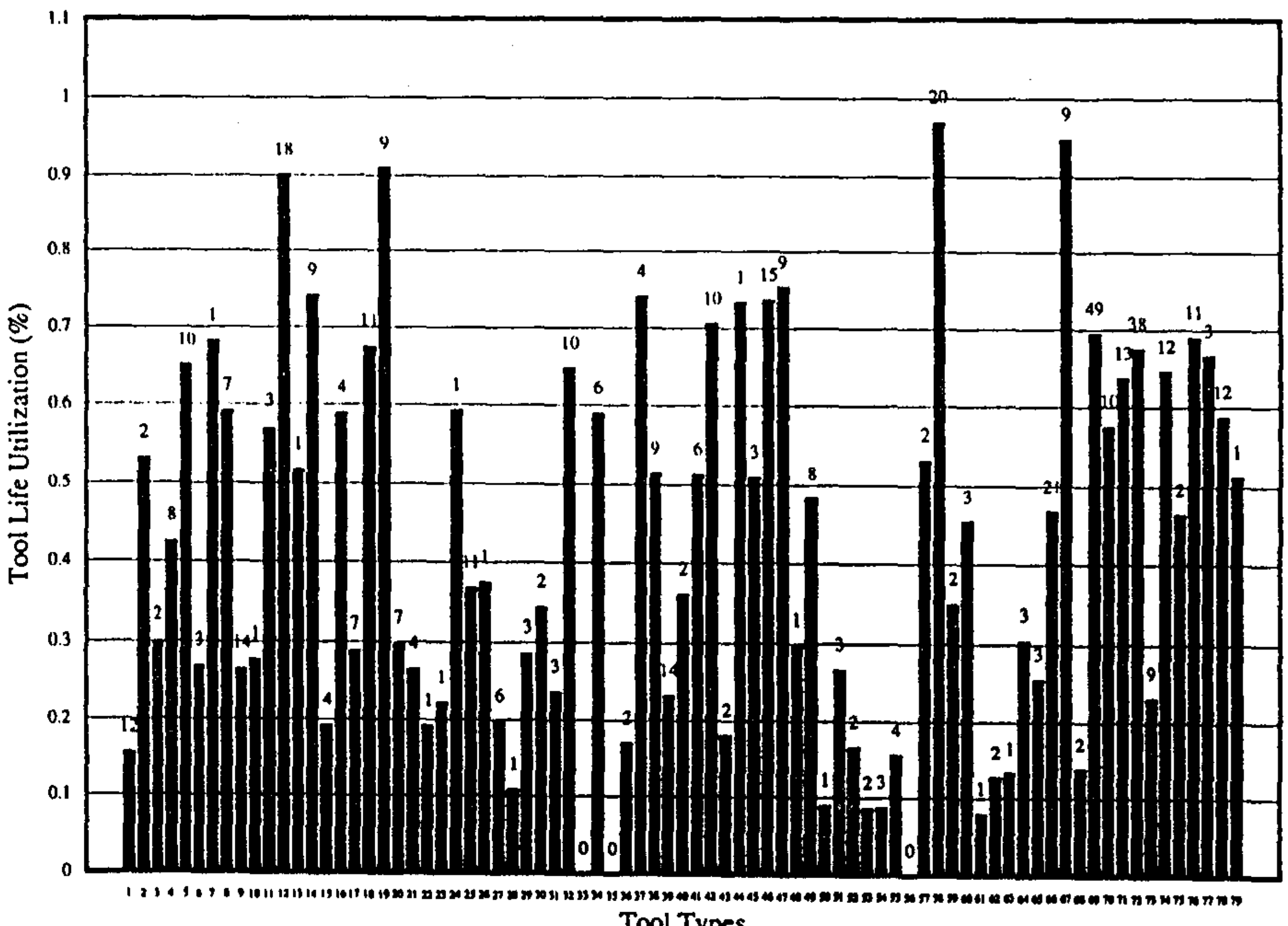
Dynamic Cluster Analysis Computational Experiment No.17

Throug.Time: 4653.4 Avr MC Utilisation(%): 92.222 Transport Utilisation(%): 2.46

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life	Cumula. Use Time	Min. No. Of Tools	Sister Tools	Total Tools	Tool Inventory	Tool Usage
1	90	360	594.90	1.87	0	12	12	0.16
2	90	60	57.60	1.07	0	2	2	0.53
3	90	60	32.40	0.60	0	2	2	0.30
4	90	120	367.20	3.40	0	8	8	0.43
5	90	90	445.40	5.20	2	8	10	0.65
6	90	60	35.60	0.81	0	3	3	0.27
7	90	60	53.60	0.68	0	1	1	0.68
8	90	150	434.16	2.96	2	5	7	0.59
9	90	120	371.20	3.71	0	14	14	0.27
10	90	120	42.00	0.28	0	1	1	0.28
11	90	60	92.60	1.71	0	3	3	0.57
12	90	60	406.80	9.91	7	11	18	0.90
13	90	60	28.00	0.52	0	1	1	0.52
14	90	120	560.40	5.19	2	7	9	0.74
15	90	90	62.50	0.77	0	4	4	0.19
16	90	90	192.80	2.36	0	4	4	0.59
17	90	120	211.50	2.03	0	7	7	0.29
18	90	60	291.60	5.40	3	8	11	0.68
19	90	25	102.40	4.55	4	5	9	0.91
20	90	120	191.88	1.78	1	6	7	0.30
21	90	125	119.40	1.06	0	4	4	0.27
22	90	60	10.40	0.19	0	1	1	0.19
23	90	45	9.00	0.22	0	1	1	0.22
24	90	45	24.00	0.59	0	1	1	0.59
25	90	60	186.00	3.67	1	10	11	0.37
26	90	100	33.60	0.37	0	1	1	0.37
27	90	80	85.80	1.19	0	6	6	0.20
28	90	45	4.40	0.11	0	1	1	0.11
29	90	60	46.40	0.86	0	3	3	0.29
30	90	25	15.40	0.68	0	2	2	0.34
31	90	40	25.60	0.71	0	3	3	0.24
32	90	20	81.60	4.53	3	7	10	0.65
33	90	25	0.00	0.00	0	0	0	0.00
34	90	30	63.60	2.36	2	4	6	0.59
35	90	25	0.00	0.00	0	0	0	0.00
36	90	60	18.40	0.34	0	2	2	0.17
37	90	60	160.00	2.96	0	4	4	0.74
38	90	60	198.80	3.61	2	7	9	0.52
39	90	120	346.00	3.26	0	14	14	0.23
40	90	60	38.80	0.72	0	2	2	0.36
41	90	60	139.00	2.57	1	5	6	0.51
42	90	50	190.40	4.23	4	6	10	0.71
43	90	60	19.60	0.36	0	2	2	0.18
44	90	100	66.00	0.73	0	1	1	0.73
45	90	120	165.60	1.53	0	3	3	0.51
46	90	110	729.00	7.36	5	10	15	0.74
47	90	120	488.32	4.52	3	6	9	0.75
48	90	120	32.00	0.30	0	1	1	0.30
49	90	100	304.40	3.38	1	7	8	0.48
50	90	100	10.00	0.09	0	1	1	0.09
51	90	100	62.50	0.80	0	3	3	0.27
52	90	100	30.00	0.33	0	2	2	0.17
53	90	135	21.00	0.17	0	2	2	0.09
54	90	135	25.60	0.27	0	3	3	0.09
55	90	135	76.00	0.63	0	4	4	0.16
56	90	135	0.00	0.00	0	0	0	0.00
57	90	25	24.00	1.07	0	2	2	0.53
58	90	30	288.00	10.67	9	11	20	0.97
59	90	300	188.40	0.70	0	2	2	0.35
60	90	80	98.00	1.36	0	3	3	0.45
61	90	180	13.00	0.08	0	1	1	0.08
62	90	240	55.20	0.26	0	2	2	0.13
63	90	300	36.00	0.13	0	1	1	0.13
64	90	200	164.10	0.91	0	3	3	0.30
65	90	200	138.30	0.77	0	3	3	0.26
66	90	120	848.52	7.95	4	17	21	0.47
67	90	60	256.00	4.74	4	5	9	0.95
68	90	90	3.60	0.28	0	2	2	0.14
69	90	50	1120.08	24.32	14	35	49	0.69
70	90	120	559.24	5.18	1	9	10	0.58
71	90	60	311.20	5.73	4	9	13	0.64
72	90	65	1045.80	17.56	12	26	38	0.68
73	90	300	459.20	2.09	0	9	9	0.23
74	90	65	340.00	5.81	3	9	12	0.65
75	90	300	250.40	0.93	0	2	2	0.46
76	90	300	1304.40	4.83	4	7	11	0.69
77	90	90	108.00	1.33	1	2	3	0.67
78	90	270	1142.40	4.70	4	8	12	0.59
79	90	45	20.80	0.51	0	1	1	0.51
				211.42	103	410	513	

Dynamic Cluster Analysis Computational Experiment No.17 - Tool Usage



Part Types = 70, Batch Size <= 8, # MC = 4, # Jobs = 186, Strategy = Differential Clustering, Permissible Tool Life = 90%
Manufacturing period = 10-shift, The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

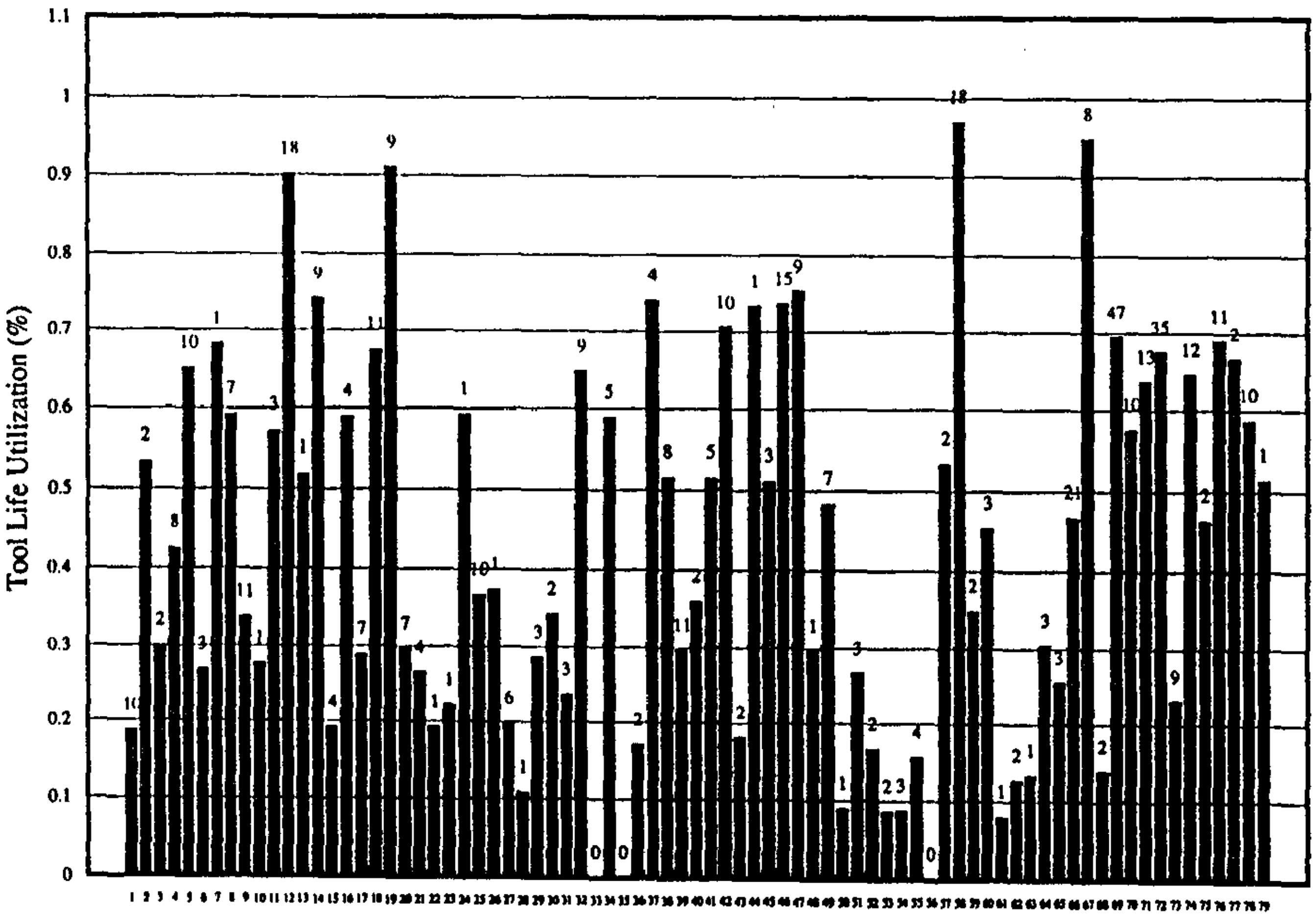
Dynamic Cluster Analysis Computational Experiment No.24

Throug.Time: 2428.6 Avr MC Utilisation(%): 0.83 Transport Utilisation(%): 4.682

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life Minutes	Cumula. Use Time	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	Tool Inventory	Tool Usage
1	90	360	594.90	1.87	0	10	10	0.19
2	90	60	57.60	1.07	0	2	2	0.53
3	90	60	32.40	0.60	0	2	2	0.30
4	90	120	367.20	3.40	0	8	8	0.43
5	90	90	445.40	5.20	2	8	10	0.65
6	90	60	35.60	0.81	0	3	3	0.27
7	90	60	53.60	0.68	0	1	1	0.68
8	90	150	434.16	2.96	2	5	7	0.59
9	90	120	371.20	3.71	0	11	11	0.34
10	90	120	42.00	0.28	0	1	1	0.28
11	90	60	92.60	1.71	0	3	3	0.57
12	90	60	406.80	9.91	7	11	18	0.90
13	90	60	28.00	0.52	0	1	1	0.52
14	90	120	560.40	5.19	2	7	9	0.74
15	90	90	62.50	0.77	0	4	4	0.19
16	90	90	192.80	2.36	0	4	4	0.59
17	90	120	211.50	2.03	0	7	7	0.29
18	90	60	291.60	5.40	3	8	11	0.68
19	90	25	102.40	4.55	4	5	9	0.91
20	90	120	191.88	1.78	1	6	7	0.30
21	90	125	119.40	1.06	0	4	4	0.27
22	90	60	10.40	0.19	0	1	1	0.19
23	90	45	9.00	0.22	0	1	1	0.22
24	90	45	24.00	0.59	0	1	1	0.59
25	90	60	186.00	3.67	0	10	10	0.37
26	90	100	33.60	0.37	0	1	1	0.37
27	90	80	85.80	1.19	0	6	6	0.20
28	90	45	4.40	0.11	0	1	1	0.11
29	90	60	46.40	0.86	0	3	3	0.29
30	90	25	15.40	0.68	0	2	2	0.34
31	90	40	25.60	0.71	0	3	3	0.24
32	90	20	81.60	4.53	2	7	9	0.65
33	90	25	0.00	0.00	0	0	0	0.00
34	90	30	63.60	2.36	1	4	5	0.59
35	90	25	0.00	0.00	0	0	0	0.00
36	90	60	18.40	0.34	0	2	2	0.17
37	90	60	160.00	2.96	0	4	4	0.74
38	90	60	198.80	3.61	1	7	8	0.52
39	90	120	346.00	3.26	0	11	11	0.30
40	90	60	38.80	0.72	0	2	2	0.36
41	90	60	139.00	2.57	0	5	5	0.51
42	90	50	190.40	4.23	4	6	10	0.71
43	90	60	19.60	0.36	0	2	2	0.18
44	90	100	66.00	0.73	0	1	1	0.73
45	90	120	165.60	1.53	0	3	3	0.51
46	90	110	729.00	7.36	5	10	15	0.74
47	90	120	488.32	4.52	3	6	9	0.75
48	90	120	32.00	0.30	0	1	1	0.30
49	90	100	304.40	3.38	0	7	7	0.48
50	90	100	10.00	0.09	0	1	1	0.09
51	90	100	62.50	0.80	0	3	3	0.27
52	90	100	30.00	0.33	0	2	2	0.17
53	90	135	21.00	0.17	0	2	2	0.09
54	90	135	25.60	0.27	0	3	3	0.09
55	90	135	76.00	0.63	0	4	4	0.16
56	90	135	0.00	0.00	0	0	0	0.00
57	90	25	24.00	1.07	0	2	2	0.53
58	90	30	288.00	10.67	7	11	18	0.97
59	90	300	188.40	0.70	0	2	2	0.35
60	90	80	98.00	1.36	0	3	3	0.45
61	90	180	13.00	0.08	0	1	1	0.08
62	90	240	55.20	0.26	0	2	2	0.13
63	90	300	36.00	0.13	0	1	1	0.13
64	90	200	164.10	0.91	0	3	3	0.30
65	90	200	138.30	0.77	0	3	3	0.26
66	90	120	848.52	7.95	4	17	21	0.47
67	90	60	256.00	4.74	3	5	8	0.95
68	90	90	3.60	0.28	0	2	2	0.14
69	90	50	1120.08	24.32	12	35	47	0.69
70	90	120	559.24	5.18	1	9	10	0.58
71	90	60	311.20	5.73	4	9	13	0.64
72	90	65	1045.80	17.56	9	26	35	0.68
73	90	300	459.20	2.09	0	9	9	0.23
74	90	65	340.00	5.81	3	9	12	0.65
75	90	300	250.40	0.93	0	2	2	0.46
76	90	300	1304.40	4.83	4	7	11	0.69
77	90	90	108.00	1.33	0	2	2	0.67
78	90	270	1142.40	4.70	2	8	10	0.59
79	90	45	20.80	0.51	0	1	1	0.51
				211.42	86	402	488	

Dynamic Cluster Analysis Computational Experiment No.24 - Tool Usage



Part Types = 70, Batch Size <= 8, # MC = 8, # Jobs = 186, Strategy = Differential Clustering, Permissible Tool Life = 90%
Manufacturing period = 10-shift, The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

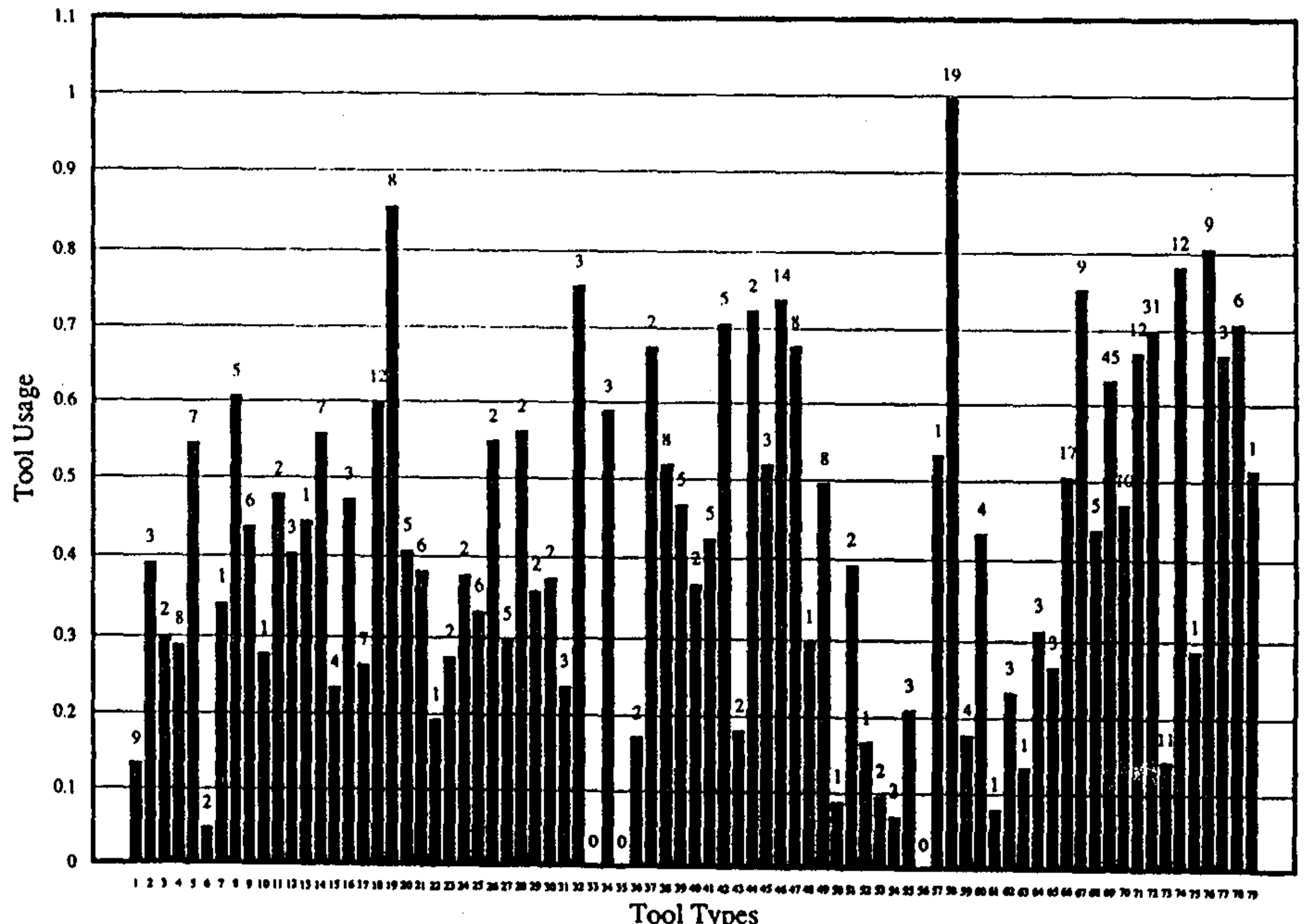
Dynamic Cluster Analysis Computational Experiment No.26

Makespan: 2552.9 Avr MC Utilisation(%): 78.21 Avr Transport Util.(%): 4.29

DYNAMIC DIFFERENTIAL CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life Minutes	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	ToolInven.	Tool Usage
1	90	360	1.19	0	9	9	0.13
2	90	60	1.17	0	3	3	0.39
3	90	60	0.60	0	2	2	0.30
4	90	120	2.30	0	8	8	0.29
5	90	90	3.27	1	6	7	0.54
6	90	60	0.10	0	2	2	0.05
7	90	60	0.34	0	1	1	0.34
8	90	150	3.03	0	5	5	0.61
9	90	120	2.62	0	6	6	0.44
10	90	120	0.28	0	1	1	0.28
11	90	60	0.96	0	2	2	0.48
12	90	60	1.21	0	3	3	0.40
13	90	60	0.44	0	1	1	0.44
14	90	120	3.34	1	6	7	0.56
15	90	90	0.94	0	4	4	0.23
16	90	90	1.41	0	3	3	0.47
17	90	120	1.85	0	7	7	0.26
18	90	60	5.40	3	9	12	0.60
19	90	25	4.27	3	5	8	0.85
20	90	120	2.03	0	5	5	0.41
21	90	125	2.28	0	6	6	0.38
22	90	60	0.19	0	1	1	0.19
23	90	45	0.55	0	2	2	0.27
24	90	45	0.75	0	2	2	0.38
25	90	60	1.99	0	6	6	0.33
26	90	100	1.10	0	2	2	0.55
27	90	80	1.49	0	5	5	0.30
28	90	45	1.12	0	2	2	0.56
29	90	60	0.71	0	2	2	0.36
30	90	25	0.75	0	2	2	0.37
31	90	40	0.71	0	3	3	0.24
32	90	20	2.26	0	3	3	0.75
33	90	25	0.00	0	0	0	0.00
34	90	30	1.18	1	2	3	0.59
35	90	25	0.00	0	0	0	0.00
36	90	60	0.34	0	2	2	0.17
37	90	60	1.35	0	2	2	0.67
38	90	60	3.12	2	6	8	0.52
39	90	120	2.34	0	5	5	0.47
40	90	60	0.73	0	2	2	0.37
41	90	60	1.69	1	4	5	0.42
42	90	50	2.12	2	3	5	0.71
43	90	60	0.36	0	2	2	0.18
44	90	100	1.44	0	2	2	0.72
45	90	120	1.56	0	3	3	0.52
46	90	110	7.36	4	10	14	0.74
47	90	120	4.06	2	6	8	0.68
48	90	120	0.30	0	1	1	0.30
49	90	100	3.47	1	7	8	0.50
50	90	100	0.09	0	1	1	0.09
51	90	100	0.78	0	2	2	0.39
52	90	100	0.17	0	1	1	0.17
53	90	135	0.19	0	2	2	0.10
54	90	135	0.21	0	3	3	0.07
55	90	135	0.63	0	3	3	0.21
56	90	135	0.00	0	0	0	0.00
57	90	25	0.53	0	1	1	0.53
58	90	30	9.96	9	10	19	1.00
59	90	300	0.71	0	4	4	0.18
60	90	80	1.73	0	4	4	0.43
61	90	180	0.08	0	1	1	0.08
62	90	240	0.70	0	3	3	0.23
63	90	300	0.13	0	1	1	0.13
64	90	200	0.94	0	3	3	0.31
65	90	200	0.80	0	3	3	0.27
66	90	120	7.57	2	15	17	0.50
67	90	60	4.51	3	6	9	0.75
68	90	90	1.75	1	4	5	0.44
69	90	50	22.12	10	35	45	0.63
70	90	120	4.69	0	10	10	0.47
71	90	60	5.35	4	8	12	0.67
72	90	65	15.37	9	22	31	0.70
73	90	300	1.56	0	11	11	0.14
74	90	65	8.58	1	11	12	0.78
75	90	300	0.29	0	1	1	0.29
76	90	300	4.83	3	6	9	0.81
77	90	90	1.33	1	2	3	0.67
78	90	270	3.54	1	5	6	0.71
79	90	45	0.51	0	1	1	0.51
			181.73	65	360	425	

Dynamic Cluster Analysis Computational Experiment No.26 - Tool Usage



Part Type = 70, Batch Size <=50, # MC = 8, Diff.Clustering, Permissible Tool Life = 90%.
Manufacturing Period = 10-Shift, Magazine Cap. 120-Tool. The numbers above the tool life utilization figures indicate the tool inventory level of that particular tool type.

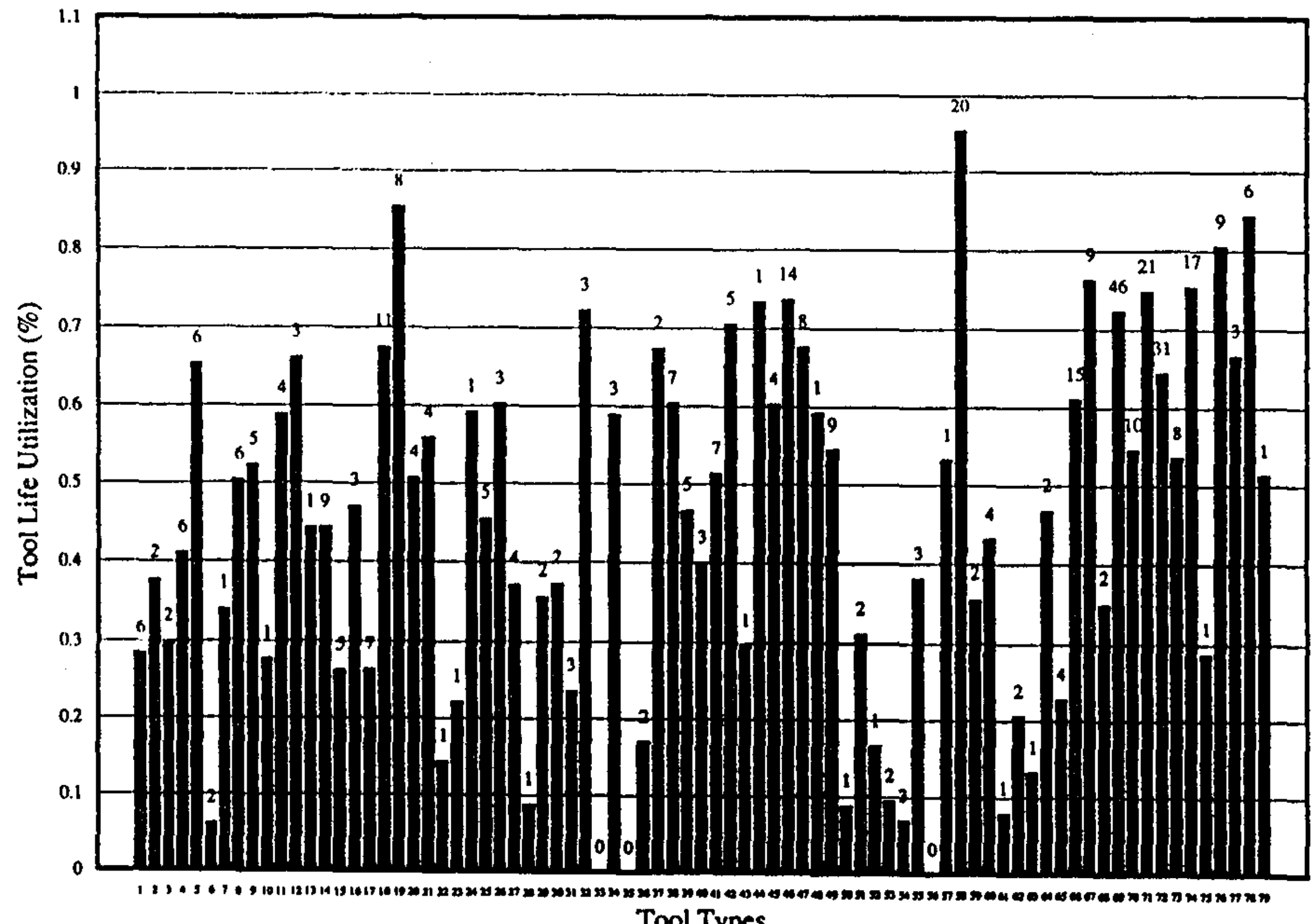
Dynamic Cluster Analysis Computational Experiment No.41

Makespan: 4329.3 Avr MC Utilisation(%): 96.41 Avr Transport Util.(%): 2.49

DYNAMIC CLUSTER ANALYSIS

Tool Type	Max % Use	Tool Life Minutes	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	Tool Inventory	Tool Usage
1	90	360	1.71	0	6	6	0.28
2	90	60	0.76	0	2	2	0.38
3	90	60	0.60	0	2	2	0.30
4	90	120	2.47	0	6	6	0.41
5	90	90	3.27	1	5	6	0.65
6	90	60	0.13	0	2	2	0.06
7	90	60	0.34	0	1	1	0.34
8	90	150	3.03	0	6	6	0.50
9	90	120	2.62	0	5	5	0.52
10	90	120	0.28	0	1	1	0.28
11	90	60	2.36	0	4	4	0.59
12	90	60	1.99	0	3	3	0.66
13	90	60	0.44	0	1	1	0.44
14	90	120	3.55	1	8	9	0.44
15	90	90	1.32	0	5	5	0.26
16	90	90	1.41	0	3	3	0.47
17	90	120	1.85	0	7	7	0.26
18	90	60	5.40	3	8	11	0.68
19	90	25	4.27	3	5	8	0.85
20	90	120	2.03	0	4	4	0.51
21	90	125	2.24	0	4	4	0.56
22	90	60	0.14	0	1	1	0.14
23	90	45	0.22	0	1	1	0.22
24	90	45	0.59	0	1	1	0.59
25	90	60	2.28	0	5	5	0.46
26	90	100	1.81	0	3	3	0.60
27	90	80	1.49	0	4	4	0.37
28	90	45	0.09	0	1	1	0.09
29	90	60	0.71	0	2	2	0.36
30	90	25	0.75	0	2	2	0.37
31	90	40	0.71	0	3	3	0.24
32	90	20	1.44	1	2	3	0.72
33	90	25	0.00	0	0	0	0.00
34	90	30	1.18	1	2	3	0.59
35	90	25	0.00	0	0	0	0.00
36	90	60	0.34	0	2	2	0.17
37	90	60	1.35	0	2	2	0.67
38	90	60	3.02	2	5	7	0.60
39	90	120	2.34	0	5	5	0.47
40	90	60	1.20	0	3	3	0.40
41	90	60	2.57	2	5	7	0.51
42	90	50	2.12	2	3	5	0.71
43	90	60	0.30	0	1	1	0.30
44	90	100	0.73	0	1	1	0.73
45	90	120	2.41	0	4	4	0.60
46	90	110	7.36	4	10	14	0.74
47	90	120	4.06	2	6	8	0.68
48	90	120	0.59	0	1	1	0.59
49	90	100	3.82	2	7	9	0.55
50	90	100	0.09	0	1	1	0.09
51	90	100	0.62	0	2	2	0.31
52	90	100	0.17	0	1	1	0.17
53	90	135	0.19	0	2	2	0.10
54	90	135	0.21	0	3	3	0.07
55	90	135	1.14	0	3	3	0.38
56	90	135	0.00	0	0	0	0.00
57	90	25	0.53	0	1	1	0.53
58	90	30	10.49	9	11	20	0.95
59	90	300	0.71	0	2	2	0.36
60	90	80	1.73	0	4	4	0.43
61	90	180	0.08	0	1	1	0.08
62	90	240	0.41	0	2	2	0.21
63	90	300	0.13	0	1	1	0.13
64	90	200	0.94	0	2	2	0.47
65	90	200	0.91	0	4	4	0.23
66	90	120	7.94	2	13	15	0.61
67	90	60	4.57	3	6	9	0.76
68	90	90	0.70	0	2	2	0.35
69	90	50	24.56	12	34	46	0.72
70	90	120	5.47	0	10	10	0.55
71	90	60	9.72	8	13	21	0.75
72	90	65	13.54	10	21	31	0.64
73	90	300	4.29	0	8	8	0.54
74	90	65	8.29	6	11	17	0.75
75	90	300	0.29	0	1	1	0.29
76	90	300	4.83	3	6	9	0.81
77	90	90	1.33	1	2	3	0.67
78	90	270	3.38	2	4	6	0.84
79	90	45	0.51	0	1	1	0.51
				80	342	422	

Dynamic Cluster Analysis Computational Experiment No.41 - Tool Usage



Part Type = 70, Batch Size <= 50, # MC = 4, # Jobs =73, Strategy = Differential Clsuetring, Permissible Tool Life = 90%.
Manufacturing Period = 10-Shift. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

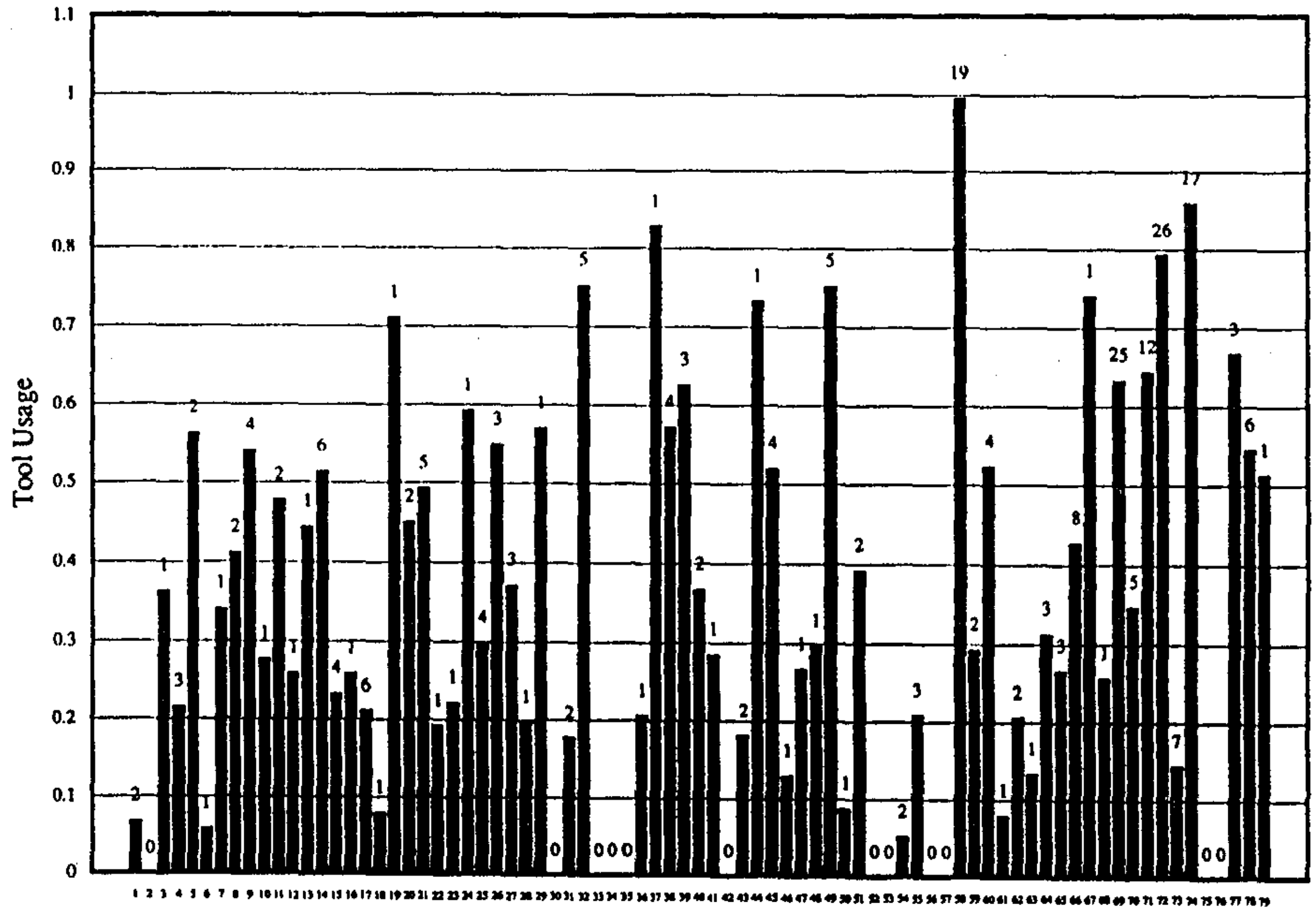
Dynamic Cluster Analysis Computational Experiment No. 53 (4 + 4 , Cell No.1)

Makespan: 2537.9 Avr MC Utiliz.%): 79.71 Avr Transport Util.(%):

DYNAMIC DIFFERENTIAL CLUSTER ANALYSIS (Cell #1)

Tool Type	Max % Use	Tool Life Minutes	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	Tool Inventory	Tool Usage
1	90	360	0.14	0	2	2	0.07
2	90	60	0.00	0	0	0	0.00
3	90	60	0.36	0	1	1	0.36
4	90	120	0.65	0	3	3	0.22
5	90	90	1.13	0	2	2	0.56
6	90	60	0.06	0	1	1	0.06
7	90	60	0.34	0	1	1	0.34
8	90	150	0.82	0	2	2	0.41
9	90	120	2.16	0	4	4	0.54
10	90	120	0.28	0	1	1	0.28
11	90	60	0.96	0	2	2	0.48
12	90	60	0.26	0	1	1	0.26
13	90	60	0.44	0	1	1	0.44
14	90	120	2.57	1	5	6	0.51
15	90	90	0.94	0	4	4	0.23
16	90	90	0.26	0	1	1	0.26
17	90	120	1.27	0	6	6	0.21
18	90	60	0.08	0	1	1	0.08
19	90	25	0.71	0	1	1	0.71
20	90	120	0.90	0	2	2	0.45
21	90	125	1.97	1	4	5	0.49
22	90	60	0.19	0	1	1	0.19
23	90	45	0.22	0	1	1	0.22
24	90	45	0.59	0	1	1	0.59
25	90	60	1.19	0	4	4	0.30
26	90	100	1.10	1	2	3	0.55
27	90	80	1.11	0	3	3	0.37
28	90	45	0.20	0	1	1	0.20
29	90	60	0.57	0	1	1	0.57
30	90	25	0.00	0	0	0	0.00
31	90	40	0.36	0	2	2	0.18
32	90	20	2.26	2	3	5	0.75
33	90	25	0.00	0	0	0	0.00
34	90	30	0.00	0	0	0	0.00
35	90	25	0.00	0	0	0	0.00
36	90	60	0.21	0	1	1	0.21
37	90	60	0.83	0	1	1	0.83
38	90	60	1.72	1	3	4	0.57
39	90	120	1.88	0	3	3	0.63
40	90	60	0.73	0	2	2	0.37
41	90	60	0.29	0	1	1	0.29
42	90	50	0.00	0	0	0	0.00
43	90	60	0.36	0	2	2	0.18
44	90	100	0.73	0	1	1	0.73
45	90	120	1.56	1	3	4	0.52
46	90	110	0.13	0	1	1	0.13
47	90	120	0.27	0	1	1	0.27
48	90	120	0.30	0	1	1	0.30
49	90	100	2.26	2	3	5	0.75
50	90	100	0.09	0	1	1	0.09
51	90	100	0.78	0	2	2	0.39
52	90	100	0.00	0	0	0	0.00
53	90	135	0.00	0	0	0	0.00
54	90	135	0.11	0	2	2	0.05
55	90	135	0.63	0	3	3	0.21
56	90	135	0.00	0	0	0	0.00
57	90	25	0.00	0	0	0	0.00
58	90	30	9.96	9	10	19	1.00
59	90	300	0.59	0	2	2	0.29
60	90	80	1.57	1	3	4	0.52
61	90	180	0.08	0	1	1	0.08
62	90	240	0.41	0	2	2	0.21
63	90	300	0.13	0	1	1	0.13
64	90	200	0.94	0	3	3	0.31
65	90	200	0.80	0	3	3	0.27
66	90	120	2.99	1	7	8	0.43
67	90	60	0.74	0	1	1	0.74
68	90	90	0.26	0	1	1	0.26
69	90	50	12.03	6	19	25	0.63
70	90	120	1.74	0	5	5	0.35
71	90	60	5.15	4	8	12	0.64
72	90	65	13.48	9	17	26	0.79
73	90	300	1.01	0	7	7	0.14
74	90	65	8.60	7	10	17	0.86
75	90	300	0.00	0	0	0	0.00
76	90	300	0.11	0	0	0	0.00
77	90	90	1.33	1	2	3	0.67
78	90	270	2.73	1	5	6	0.55
79	90	45	0.51	0	1	1	0.51
				48	203	251	

Dynamic Cluster Analysis Computational Experiment No 53 - (4 + 4 , Cell No.1)



Part Type = 70, # MC = 4+4 (Cell #1), Batch Size <=50, Permissible Tool Life = 90%, Strategy = Differential Clustering.
Manufacturing Period = 10-Shift. The numbers above the tool life figures indicate the tool inventory level of that particular tool type.

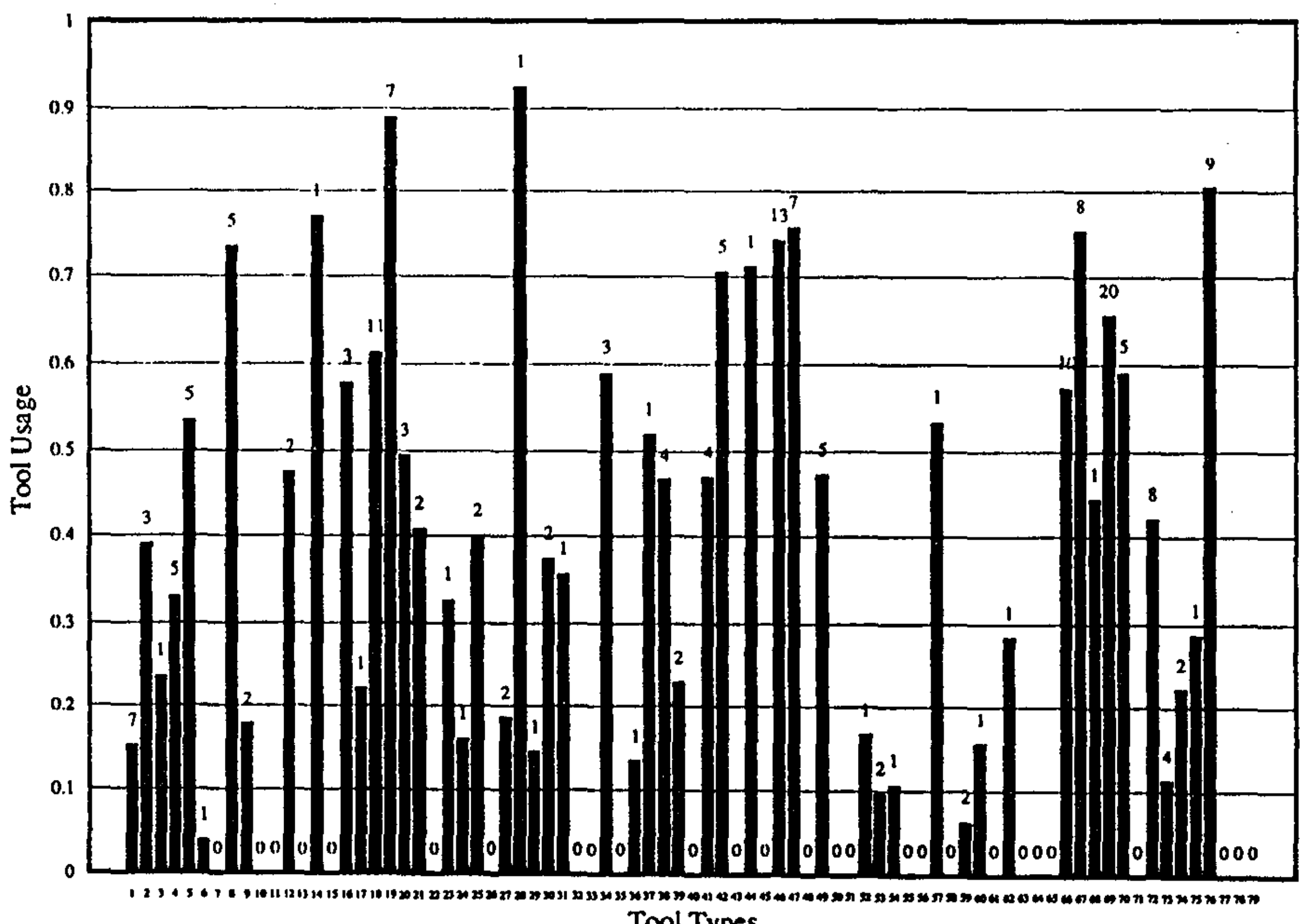
Dynamic Cluster Analysis Computational Experiment No. 53 (4 + 4 , Cell No.2)

Makespan: 2346.8 Avr MC Utilisation(%): 81.581 Avr Transport Util.(%): 3.8009

DYNAMIC CLUSTER ANALYSIS (Cell #2)

Tool Tyı	Max % Use	Tool Life Minutes	Cumulative Use Time	Min. No. Of Tools	No. Of SpentTools	Total No. Of Tools	Tool Inventory	Tool Use
1	90	360	342.4	1.0568	0	7	7	0.15
2	90	60	63.2	1.1704	0	3	3	0.39
3	90	60	12.8	0.237	0	1	1	0.24
4	90	120	178.7	1.6546	0	5	5	0.33
5	90	90	173.4	2.1407	1	4	5	0.54
6	90	60	3.6	0.04	0	1	1	0.04
7	90	60	0	0	0	0	0	0.00
8	90	150	297.6	2.2044	2	3	5	0.73
9	90	120	38.4	0.3556	0	2	2	0.18
10	90	120	0	0	0	0	0	0.00
11	90	60	0	0	0	0	0	0.00
12	90	60	51.2	0.9481	0	2	2	0.47
13	90	60	0	0	0	0	0	0.00
14	90	120	83.2	0.7704	0	1	1	0.77
15	90	90	0	0	0	0	0	0.00
16	90	90	93.6	1.1556	1	2	3	0.58
17	90	120	24	0.2222	0	1	1	0.22
18	90	60	264.4	4.8963	3	8	11	0.61
19	90	25	80	3.5556	3	4	7	0.89
20	90	120	160.2	1.4833	0	3	3	0.49
21	90	125	91.8	0.816	0	2	2	0.41
22	90	60	0	0	0	0	0	0.00
23	90	45	17.6	0.3259	0	1	1	0.33
24	90	45	14.4	0.16	0	1	1	0.16
25	90	60	43.2	0.8	0	2	2	0.40
26	90	100	0	0	0	0	0	0.00
27	90	80	26.8	0.3722	0	2	2	0.19
28	90	45	20.8	0.9244	0	1	1	0.92
29	90	60	7.8	0.1444	0	1	1	0.14
30	90	25	16.8	0.7467	0	2	2	0.37
31	90	40	12.8	0.3556	0	1	1	0.36
32	90	20	0	0	0	0	0	0.00
33	90	25	0	0	0	0	0	0.00
34	90	30	31.8	1.1778	1	2	3	0.59
35	90	25	0	0	0	0	0	0.00
36	90	60	7.2	0.1333	0	1	1	0.13
37	90	60	28	0.5185	0	1	1	0.52
38	90	60	75.6	1.4	1	3	4	0.47
39	90	120	49.6	0.4593	0	2	2	0.23
40	90	60	0	0	0	0	0	0.00
41	90	60	76	1.4074	1	3	4	0.47
42	90	50	95.2	2.1156	2	3	5	0.71
43	90	60	0	0	0	0	0	0.00
44	90	100	64	0.7111	0	1	1	0.71
45	90	120	0	0	0	0	0	0.00
46	90	110	661.8	6.6848	4	9	13	0.74
47	90	120	409.2	3.7889	2	5	7	0.76
48	90	120	0	0	0	0	0	0.00
49	90	100	170.1	1.89	1	4	5	0.47
50	90	100	0	0	0	0	0	0.00
51	90	100	0	0	0	0	0	0.00
52	90	100	15	0.1667	0	1	1	0.17
53	90	135	23.2	0.1909	0	2	2	0.10
54	90	135	12.8	0.1053	0	1	1	0.11
55	90	135	0	0	0	0	0	0.00
56	90	135	0	0	0	0	0	0.00
57	90	25	12	0.5333	0	1	1	0.53
58	90	30	0	0	0	0	0	0.00
59	90	300	34.4	0.1274	0	2	2	0.06
60	90	80	11.2	0.1556	0	1	1	0.16
61	90	180	0	0	0	0	0	0.00
62	90	240	12.8	0.2844	0	1	1	0.28
63	90	300	0	0	0	0	0	0.00
64	90	200	0	0	0	0	0	0.00
65	90	200	0	0	0	0	0	0.00
66	90	120	495	4.5833	2	8	10	0.57
67	90	60	207	3.7685	3	5	8	0.75
68	90	90	36	0.4444	0	1	1	0.44
69	90	50	442.3	9.8289	5	15	20	0.66
70	90	120	319	2.9537	0	5	5	0.59
71	90	60	0	0	0	0	0	0.00
72	90	65	394.1	2.9446	1	7	8	0.42
73	90	300	121.2	0.4489	0	4	4	0.11
74	90	65	80	0.4463	0	2	2	0.22
75	90	300	77.6	0.2874	0	1	1	0.29
76	90	300	1304.4	4.8311	3	6	9	0.81
77	90	90	0	0	0	0	0	0.00
78	90	270	0	0	0	0	0	0.00
79	90	45	0	0	0	0	0	0.00
					36	157	193	

Dynamic Cluster Analysis Computational Experiment No. 53 (4 + 4 , Cell No.2)



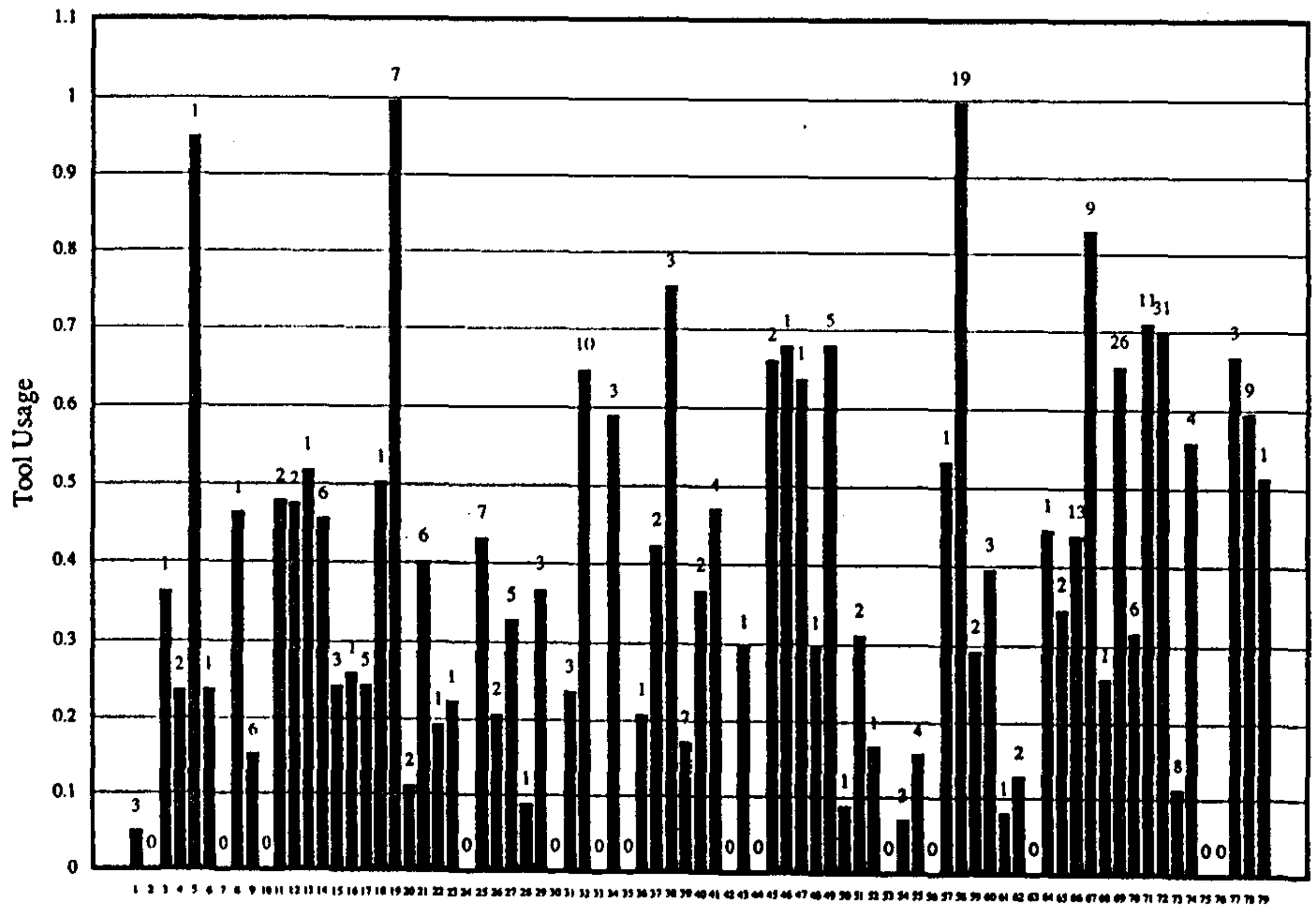
Part Type = 70, # MC = 4+4 (Cell #2), Batch Size <=50, Permissible Tool Life = 90%, Strategy = Differential Clustering.
Manufacturing Period = 10-Shift. The numbers above the tool life figures indicate the tool inventory level of that particular tool type.

Dynamic Cluster Analysis Computational Experiment No.54 (4 + 4 MC - Cell 1)

Throughput Time: 2037.4 Avr MC Utilisation(%): 95.52 Transp.Util.(%): 3.25

DYNAMIC CLUSTER ANALYSIS (CELL 1)

Tool Type	Tool Life	Cumulative ToolUse	Minimum ToolReq.	Differential Tool Req.	SpentTools	ToolInventory	Tool Usage
1	324	48.2	0.15	3	0	3	0.05
2	54	0	0.00	0	0	0	0.00
3	54	19.6	0.36	1	0	1	0.36
4	108	51	0.47	2	0	2	0.24
5	81	76.8	0.95	1	0	1	0.95
6	54	12.8	0.24	1	0	1	0.24
7	54	0	0.00	0	0	0	0.00
8	135	62.4	0.46	1	0	1	0.46
9	108	98	0.91	6	0	6	0.15
10	108	0	0.00	0	0	0	0.00
11	54	51.6	0.96	2	0	2	0.48
12	54	51.2	0.95	2	0	2	0.47
13	54	28	0.52	1	0	1	0.52
14	108	245.2	2.27	5	1	6	0.45
15	81	59	0.73	3	0	3	0.24
16	81	21	0.26	1	0	1	0.26
17	108	131.3	1.22	5	0	5	0.24
18	54	27.2	0.50	1	0	1	0.50
19	22.5	89.6	3.98	4	3	7	1.00
20	108	24	0.22	2	0	2	0.11
21	112.5	225.2	2.00	5	1	6	0.40
22	54	10.4	0.19	1	0	1	0.19
23	40.5	9	0.22	1	0	1	0.22
24	40.5	0	0.00	0	0	0	0.00
25	54	139.6	2.59	6	1	7	0.43
26	90	37.2	0.41	2	0	2	0.21
27	72	118.2	1.64	5	0	5	0.33
28	40.5	3.6	0.09	1	0	1	0.09
29	54	59.4	1.10	3	0	3	0.37
30	22.5	0	0.00	0	0	0	0.00
31	36	25.6	0.71	3	0	3	0.24
32	18	81.6	4.53	7	3	10	0.65
33	22.5	0	0.00	0	0	0	0.00
34	27	31.8	1.18	2	1	3	0.59
35	22.5	0	0.00	0	0	0	0.00
36	54	11.2	0.21	1	0	1	0.21
37	54	45.6	0.84	2	0	2	0.42
38	54	81.6	1.51	2	1	3	0.76
39	108	129.2	1.20	7	0	7	0.17
40	54	39.6	0.73	2	0	2	0.37
41	54	76	1.41	3	1	4	0.47
42	45	0	0.00	0	0	0	0.00
43	54	16	0.30	1	0	1	0.30
44	90	0	0.00	0	0	0	0.00
45	108	142.8	1.32	2	0	2	0.66
46	99	67.2	0.68	1	0	1	0.68
47	108	68.8	0.64	1	0	1	0.64
48	108	32	0.30	1	0	1	0.30
49	90	244.8	2.72	4	1	5	0.68
50	90	8	0.09	1	0	1	0.09
51	90	56.1	0.62	2	0	2	0.31
52	90	15	0.17	1	0	1	0.17
53	121.5	0	0.00	0	0	0	0.00
54	121.5	25.6	0.21	3	0	3	0.07
55	121.5	76	0.63	4	0	4	0.16
56	121.5	0	0.00	0	0	0	0.00
57	22.5	12	0.53	1	0	1	0.53
58	27	268.8	9.96	10	9	19	1.00
59	270	158	0.59	2	0	2	0.29
60	72	85.2	1.18	3	0	3	0.39
61	162	13	0.08	1	0	1	0.08
62	216	55.2	0.26	2	0	2	0.13
63	270	0	0.00	0	0	0	0.00
64	180	80.1	0.45	1	0	1	0.45
65	180	124.6	0.69	2	0	2	0.35
66	108	520	4.81	11	2	13	0.44
67	54	224	4.15	5	4	9	0.83
68	81	20.8	0.26	1	0	1	0.26
69	45	588.7	13.08	20	6	26	0.65
70	108	204.8	1.90	6	0	6	0.32
71	54	268	4.96	7	4	11	0.71
72	58.5	817.4	13.97	20	11	31	0.70
73	270	243	0.90	8	0	8	0.11
74	58.5	130.8	2.24	4	0	4	0.56
75	270	0	0.00	0	0	0	0.00
76	270	0	0.00	0	0	0	0.00
77	81	108	1.33	2	1	3	0.67
78	243	867.2	3.57	6	3	9	0.59
79	40.5	20.8	0.51	1	0	1	0.51
				228	53	281	



Part Type = 70, Batch Size <=8, # MC 4+4, Manufacturing Period =10-Shift, Permissible Tool Life = 90%.
The numbers above the tool utilization figure indicate the tool inventory level of that particular tool type.

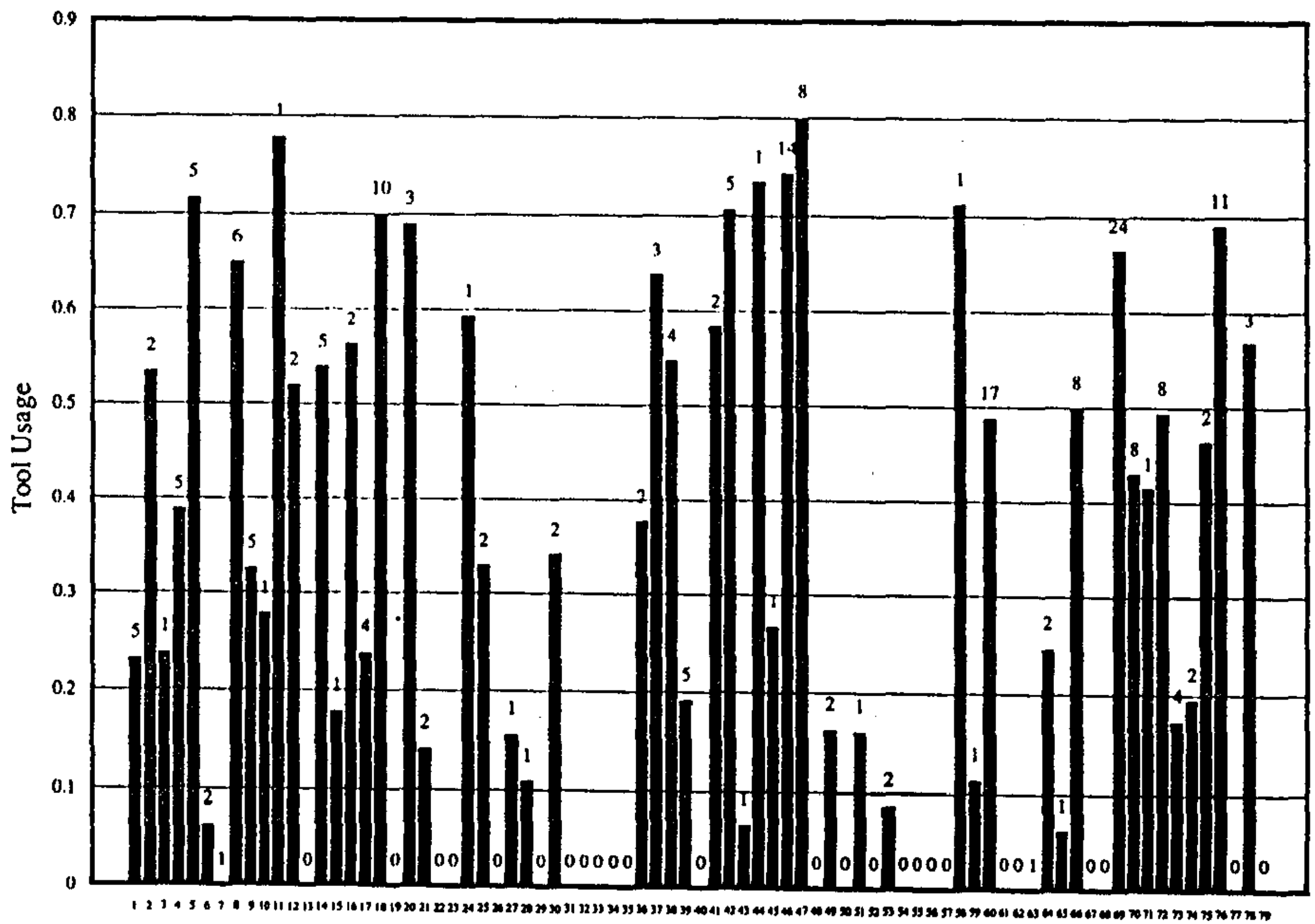
Dynamic Cluster Analysis Computational Experiment No.54 (4 + 4 MC - Cell 2)

Throughput Time: 2428.6 Avr MC Utilisation(%): 85.10 Transp.Utili.(%): 2.50

DYNAMIC CLUSTER ANALYSIS (CELL 2)

Tool Type	Tool Life	Cumulative ToolUse	Minimum ToolReq.	Differential Tool Req.	SpentTools	ToolInventory	Tool Usage
1	324	374.8	1.16	5	0	5	0.23
2	54	57.6	1.07	2	0	2	0.53
3	54	12.8	0.24	1	0	1	0.24
4	108	209.8	1.94	5	0	5	0.39
5	81	231.8	2.86	4	1	5	0.72
6	54	6.8	0.13	2	0	2	0.06
7	54	36.8	0.68	1	0	1	0.00
8	135	350.4	2.60	4	2	6	0.65
9	108	176	1.63	5	0	5	0.33
10	108	30	0.28	1	0	1	0.28
11	54	42	0.78	1	0	1	0.78
12	54	56	1.04	2	0	2	0.52
13	54	0	0.00	0	0	0	0.00
14	108	232	2.15	4	1	5	0.54
15	81	14.4	0.18	1	0	1	0.18
16	81	91	1.12	2	0	2	0.56
17	108	102.6	0.95	4	0	4	0.24
18	54	264.4	4.90	7	3	10	0.70
19	22.5	0	0.00	0	0	0	0.00
20	108	148.8	1.38	2	1	3	0.69
21	112.5	31.8	0.28	2	0	2	0.14
22	54	0	0.00	0	0	0	0.00
23	40.5	0	0.00	0	0	0	0.00
24	40.5	24	0.59	1	0	1	0.59
25	54	35.6	0.66	2	0	2	0.33
26	90	0	0.00	0	0	0	0.00
27	72	11.2	0.16	1	0	1	0.16
28	40.5	4.4	0.11	1	0	1	0.11
29	54	0	0.00	0	0	0	0.00
30	22.5	15.4	0.68	2	0	2	0.34
31	36	0	0.00	0	0	0	0.00
32	18	0	0.00	0	0	0	0.00
33	22.5	0	0.00	0	0	0	0.00
34	27	0	0.00	0	0	0	0.00
35	22.5	0	0.00	0	0	0	0.00
36	54	40.8	0.76	2	0	2	0.38
37	54	103.2	1.91	3	0	3	0.64
38	54	88.4	1.64	3	1	4	0.55
39	108	103.2	0.96	5	0	5	0.19
40	54	0	0.00	0	0	0	0.00
41	54	63	1.17	2	0	2	0.58
42	45	95.2	2.12	3	2	5	0.71
43	54	3.6	0.07	1	0	1	0.07
44	90	66	0.73	1	0	1	0.73
45	108	28.8	0.27	1	0	1	0.27
46	99	661.8	6.68	9	5	14	0.74
47	108	431.6	4.00	5	3	8	0.80
48	108	0	0.00	0	0	0	0.00
49	90	29.2	0.32	2	0	2	0.16
50	90	0	0.00	0	0	0	0.00
51	90	14.4	0.16	1	0	1	0.16
52	90	0	0.00	0	0	0	0.00
53	121.5	21	0.17	2	0	2	0.09
54	121.5	0	0.00	0	0	0	0.00
55	121.5	0	0.00	0	0	0	0.00
56	121.5	0	0.00	0	0	0	0.00
57	22.5	0	0.00	0	0	0	0.00
58	27	19.2	0.71	1	0	1	0.71
59	270	30.4	0.11	1	0	1	0.11
60	72	350.8	4.87	10	7	17	0.49
61	162	0	0.00	0	0	0	0.00
62	216	0	0.00	0	0	0	0.00
63	270	36	0.13	1	0	1	0.00
64	180	88.6	0.49	2	0	2	0.25
65	180	11.2	0.06	1	0	1	0.06
66	108	323	2.99	6	2	8	0.50
67	54	0	0.00	0	0	0	0.00
68	81	0	0.00	0	0	0	0.00
69	45	508.4	11.30	17	7	24	0.66
70	108	325	3.01	7	1	8	0.43
71	54	22.4	0.41	1	0	1	0.41
72	58.5	202	3.45	7	1	8	0.49
73	270	186.4	0.69	4	0	4	0.17
74	58.5	22.8	0.39	2	0	2	0.19
75	270	250.4	0.93	2	0	2	0.46
76	270	1304.4	4.83	7	4	11	0.69
77	81	0	0.00	0	0	0	0.00
78	243	275.2	1.13	2	1	3	0.57
79	40.5	0	0.00	0	0	0	0.00
				173	42	215	

Dynamic Cluster Analysis Computational Experiment No.54 (4 + 4 MC - Cell 2)



Part Type = 70, Batch Size <=8, # MC 4+4, (Cell #2) Manufacturing Period =10-Shift, Permissible Tool Life = 90%.
The numbers above the tool utilization figure indicate the tool inventory level of that particular tool type.

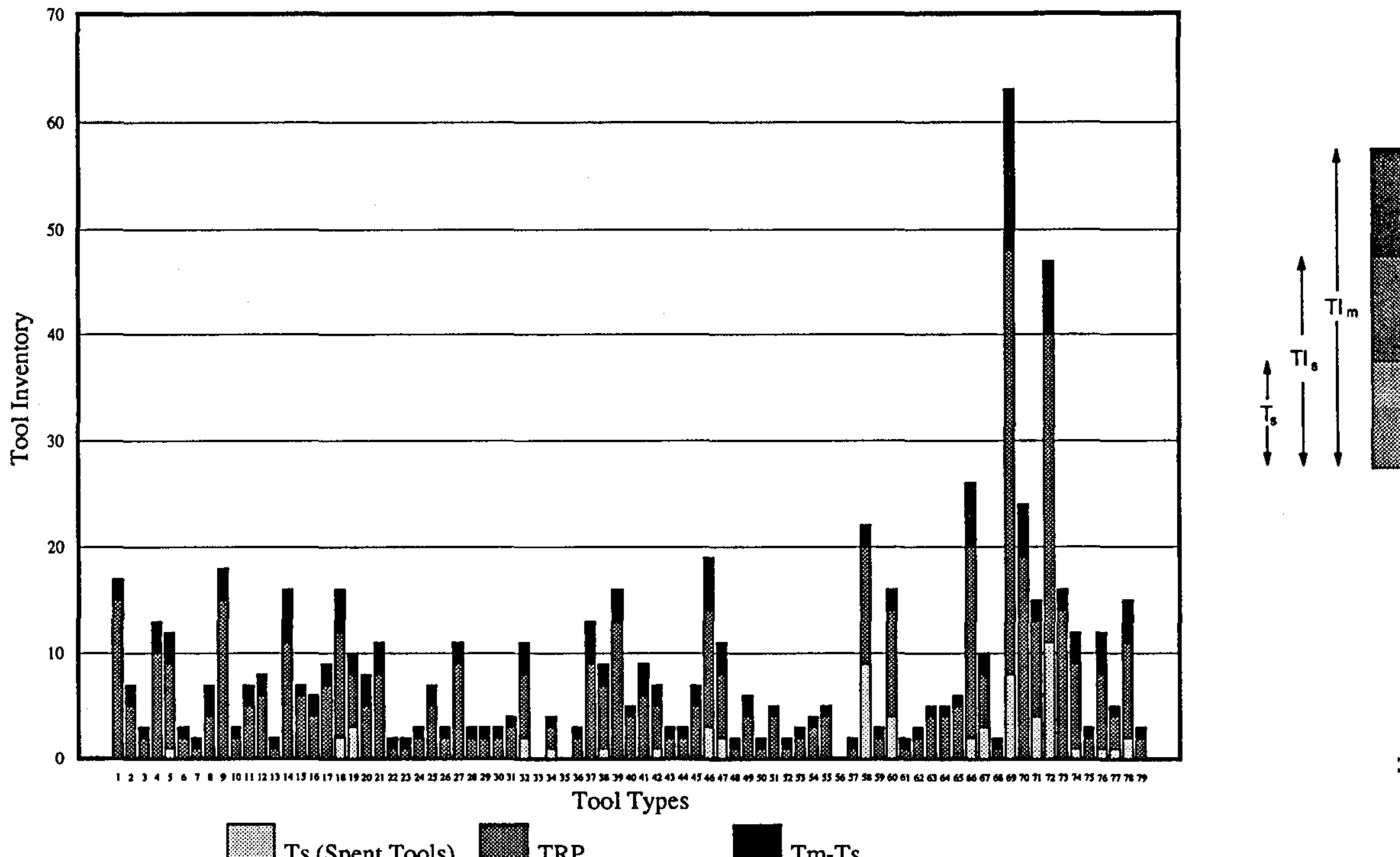
Individual Tool Inventory Performance

Tables & Graphs

(Complementary to Chapter 18)

Supplementary Experiment No.7 - Tool Inventory

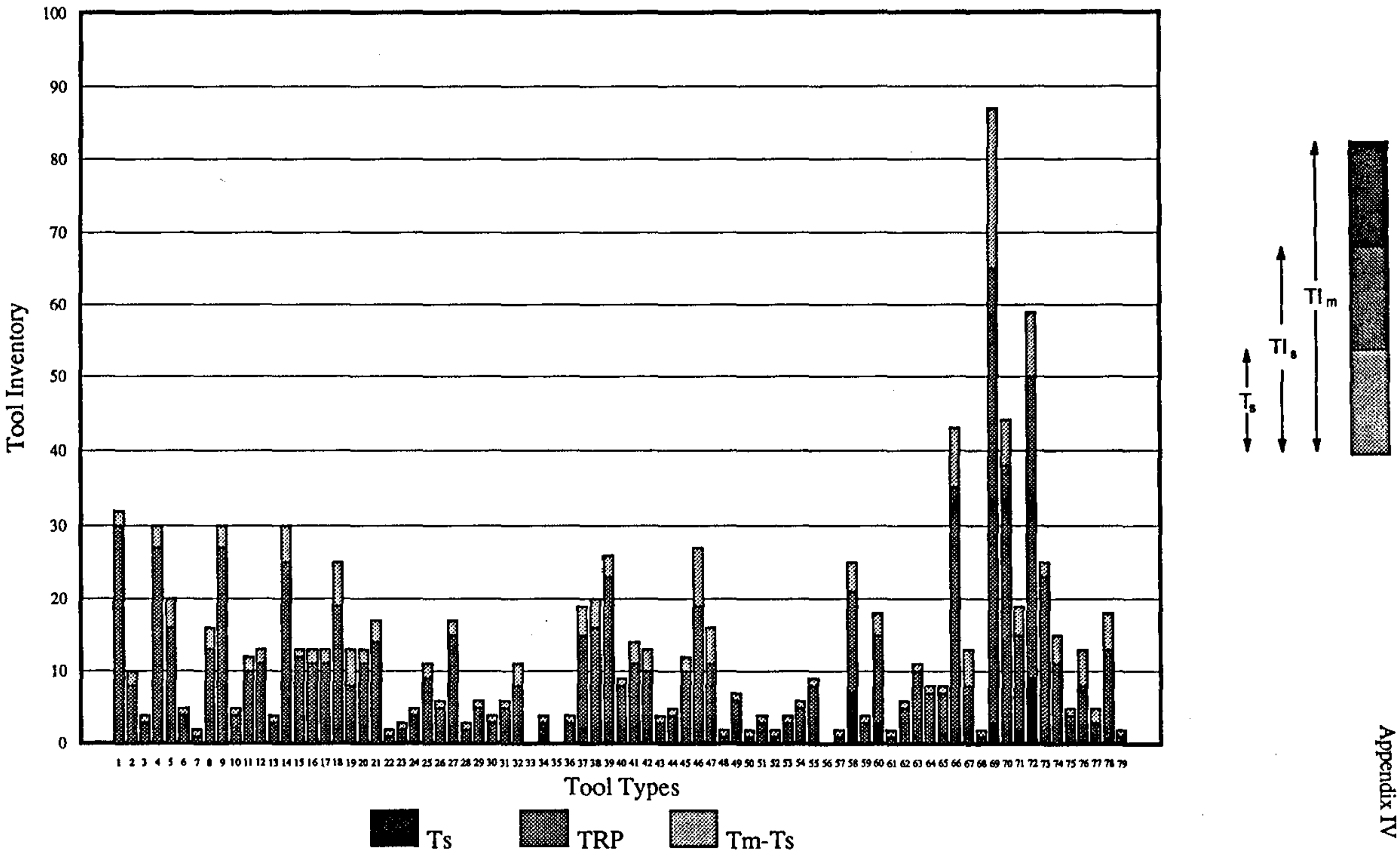
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
15	17	15	0	2	2	20	0.75	0	1
5	7	5	0	2	2	5	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
10	13	10	0	3	3	13	0.77	0	1
9	11	8	1	4	3	9	1.00	0.25	1.125
2	3	2	0	1	1	3	0.67	0	1
1	2	1	0	1	1	1	1.00	0	1
4	7	4	0	3	3	5	0.80	0	1
15	18	15	0	3	3	17	0.88	0	1
2	3	2	0	1	1	2	1.00	0	1
5	7	5	0	2	2	5	1.00	0	1
6	8	6	0	2	2	6	1.00	0	1
1	2	1	0	1	1	1	1.00	0	1
11	16	11	0	5	5	11	1.00	0	1
6	7	6	0	1	1	6	1.00	0	1
4	6	4	0	2	2	4	1.00	0	1
7	9	7	0	2	2	8	0.88	0	1
12	14	10	2	6	4	13	0.92	0.33	1.2
8	7	5	3	5	2	8	1.00	0.6	1.6
5	8	5	0	3	3	7	0.71	0	1
8	11	8	0	3	3	8	1.00	0	1
1	2	1	0	1	1	1	1.00	0	1
1	2	1	0	1	1	1	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
5	7	5	0	2	2	5	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
9	11	9	0	2	2	9	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
3	4	3	0	1	1	3	1.00	0	1
8	9	6	2	5	3	8	1.00	0.4	1.33
0	0	0	0	0	0	0	0.00	0	0
3	3	2	1	2	1	3	1.00	0.5	1.5
0	0	0	0	0	0	0	0.00	0	0
2	3	2	0	1	1	2	1.00	0	1
9	13	9	0	4	4	9	1.00	0	1
7	8	6	1	3	2	7	1.00	0.33	1.17
13	16	13	0	3	3	15	0.87	0	1
4	5	4	0	1	1	4	1.00	0	1
6	9	6	0	3	3	6	1.00	0	1
5	6	4	1	3	2	5	1.00	0.33	1.25
2	3	2	0	1	1	2	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
5	7	5	0	2	2	5	1.00	0	1
14	16	11	3	8	5	15	0.93	0.375	1.27
8	9	6	2	5	3	9	0.89	0.4	1.33
1	2	1	0	1	1	1	1.00	0	1
4	6	4	0	2	2	4	1.00	0	1
1	2	1	0	1	1	1	1.00	0	1
4	5	4	0	1	1	4	1.00	0	1
1	2	1	0	1	1	1	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
3	4	3	0	1	1	3	1.00	0	1
4	5	4	0	1	1	4	1.00	0	1
0	0	0	0	0	0	0	0.00	0	0
1	2	1	0	1	1	1	1.00	0	1
20	13	11	9	11	2	20	1.00	0.82	1.82
2	3	2	0	1	1	2	1.00	0	1
14	12	10	4	6	2	14	1.00	0.67	1.4
1	2	1	0	1	1	1	1.00	0	1
2	3	2	0	1	1	2	1.00	0	1
4	5	4	0	1	1	4	1.00	0	1
4	5	4	0	1	1	4	1.00	0	1
5	6	5	0	1	1	5	1.00	0	1
20	24	18	2	8	6	26	0.77	0.25	1.11
8	7	5	3	5	2	8	1.00	0.6	1.6
1	2	1	0	1	1	1	1.00	0	1
48	55	40	8	23	15	55	0.87	0.35	1.2
19	24	19	0	5	5	26	0.73	0	1
13	11	9	4	6	2	14	0.93	0.67	1.44
40	36	29	11	18	7	40	1.00	0.61	1.38
14	16	14	0	2	2	18	0.78	0	1
9	11	8	1	4	3	9	1.00	0.25	1.125
2	3	2	0	1	1	2	1.00	0	1
8	11	7	1	5	4	8	1.00	0.2	1.14
4	4	3	1	2	1	4	1.00	0.5	1.33
11	13	9	2	6	4	11	1.00	0.33	1.22
2	3	2	0	1	1	2	1.00	0	1
527	630	465	62	227	165	572			



Part Type = 70, # MC = 8, Batch Size <=50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.

Supplementary Experiment No.25 - Tool Inventory

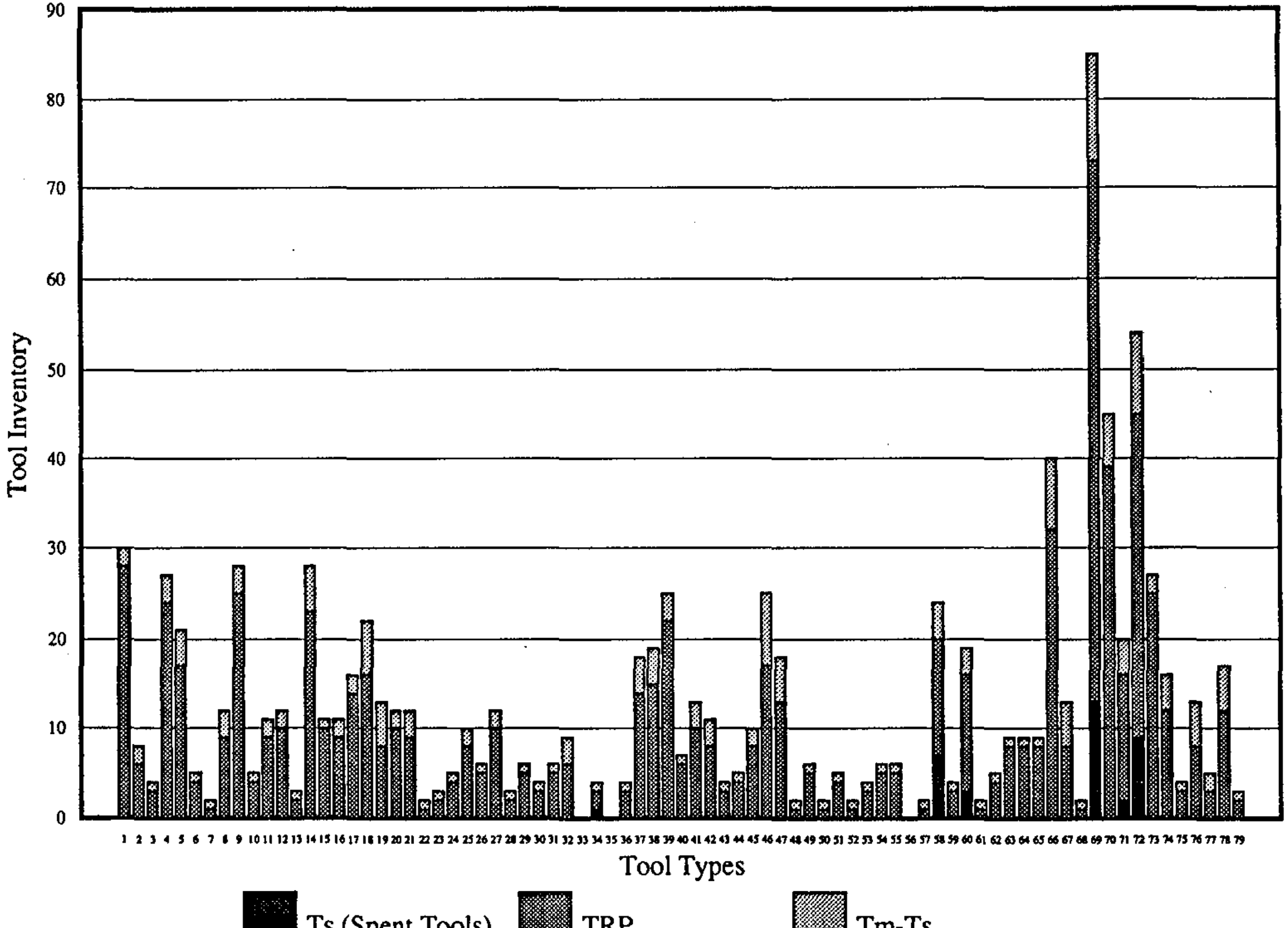
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
30	32	30	0	2	2	48	0.63	0	1.00
8	10	8	0	2	2	8	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
27	30	27	0	3	3	31	0.87	0	1.00
16	20	16	0	4	4	28	0.57	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
13	16	13	0	3	3	23	0.57	0	1.00
27	30	27	0	3	3	36	0.75	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
10	12	10	0	2	2	12	0.83	0	1.00
11	13	11	0	2	2	13	0.85	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
25	30	25	0	5	5	26	0.96	0	1.00
12	13	12	0	1	1	12	1.00	0	1.00
11	13	11	0	2	2	12	0.92	0	1.00
11	13	11	0	2	2	14	0.79	0	1.00
19	25	19	0	6	6	20	0.95	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
11	13	11	0	2	2	24	0.46	0	1.00
14	17	14	0	3	3	16	0.88	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
9	11	9	0	2	2	9	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
15	17	15	0	2	2	17	0.88	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
8	11	8	0	3	3	8	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	3	2	1	2	1	3	1.00	1	1.50
0	0	0	0	0	0	0	0.00	0	0.00
3	4	3	0	1	1	3	1.00	0	1.00
15	19	15	0	4	4	20	0.75	0	1.00
16	20	16	0	4	4	20	0.80	0	1.00
23	26	23	0	3	3	31	0.74	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
11	14	11	0	3	3	13	0.85	0	1.00
10	13	10	0	3	3	10	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
10	12	10	0	2	2	10	1.00	0	1.00
19	27	19	0	8	8	20	0.95	0	1.00
11	16	11	0	5	5	20	0.55	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
6	7	6	0	1	1	6	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
21	18	14	7	11	4	21	1.00	1	1.50
3	4	3	0	1	1	3	1.00	0	1.00
15	15	12	3	6	3	16	0.94	1	1.25
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
10	11	10	0	1	1	10	1.00	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
35	43	35	0	8	8	54	0.65	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
65	84	62	3	25	22	108	0.60	0	1.05
38	44	38	0	6	6	72	0.53	0	1.00
15	17	13	2	6	4	16	0.94	0	1.15
50	50	41	9	18	9	53	0.94	1	1.22
23	25	23	0	2	2	34	0.68	0	1.00
11	15	11	0	4	4	13	0.85	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
3	5	3	0	2	2	3	1.00	0	1.00
13	18	13	0	5	5	13	1.00	0	1.00
1	2	1	0	1	1	2	0.50	0	1.00
836	1012	811	25	226	201	1063			

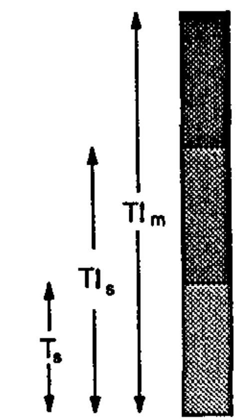


Part Type = 70, # MC = 8, Batch Size <=8, Manufacturing Period = 10 - Shift, Permissible Tool Life = 90%.

ıpplementary Experiment No.41 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
28	30	28	0	2	2	48	0.58	0	1.00
6	8	6	0	2	2	8	0.75	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
24	27	24	0	3	3	31	0.77	0	1.00
17	21	17	0	4	4	28	0.61	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
9	12	9	0	3	3	23	0.39	0	1.00
25	28	25	0	3	3	36	0.69	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
9	11	9	0	2	2	12	0.75	0	1.00
10	12	10	0	2	2	13	0.77	0	1.00
2	3	2	0	1	1	3	0.67	0	1.00
23	28	23	0	5	5	26	0.88	0	1.00
10	11	10	0	1	1	12	0.83	0	1.00
9	11	9	0	2	2	12	0.75	0	1.00
14	16	14	0	2	2	14	1.00	0	1.00
16	22	16	0	6	6	20	0.80	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
10	12	10	0	2	2	24	0.42	0	1.00
9	12	9	0	3	3	16	0.56	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
8	10	8	0	2	2	9	0.89	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
10	12	10	0	2	2	17	0.59	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
6	9	6	0	3	3	8	0.75	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	4	2	1	2	1	3	1.00	0.5	1.50
0	0	0	0	0	0	0	0.00	0	0.00
3	4	3	0	1	1	3	1.00	0	1.00
14	18	14	0	4	4	20	0.70	0	1.00
15	19	15	0	4	4	20	0.75	0	1.00
22	25	22	0	3	3	31	0.71	0	1.00
6	7	6	0	1	1	8	0.75	0	1.00
10	13	10	0	3	3	13	0.77	0	1.00
8	11	8	0	3	3	10	0.80	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
8	10	8	0	2	2	10	0.80	0	1.00
17	25	17	0	8	8	20	0.85	0	1.00
13	18	13	0	5	5	20	0.65	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	6	0.83	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
5	6	5	0	1	1	8	0.63	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
20	24	13	7	11	4	21	0.95	0.64	1.54
3	4	3	0	1	1	3	1.00	0	1.00
16	19	13	3	6	3	16	1.00	0.5	1.23
1	2	1	0	1	1	1	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
8	9	8	0	1	1	10	0.80	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
32	40	32	0	8	8	54	0.59	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
73	85	60	13	25	12	118	0.62	0.52	1.22
39	45	39	0	6	6	72	0.54	0	1.00
16	20	14	2	6	4	16	1.00	0.33	1.14
45	54	36	9	18	9	53	0.85	0.5	1.25
25	27	25	0	2	2	34	0.74	0	1.00
12	16	12	0	4	4	13	0.92	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
3	5	3	0	2	2	3	1.00	0	1.00
12	17	12	0	5	5	13	0.92	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
791	982	756	35	226	191	1073			

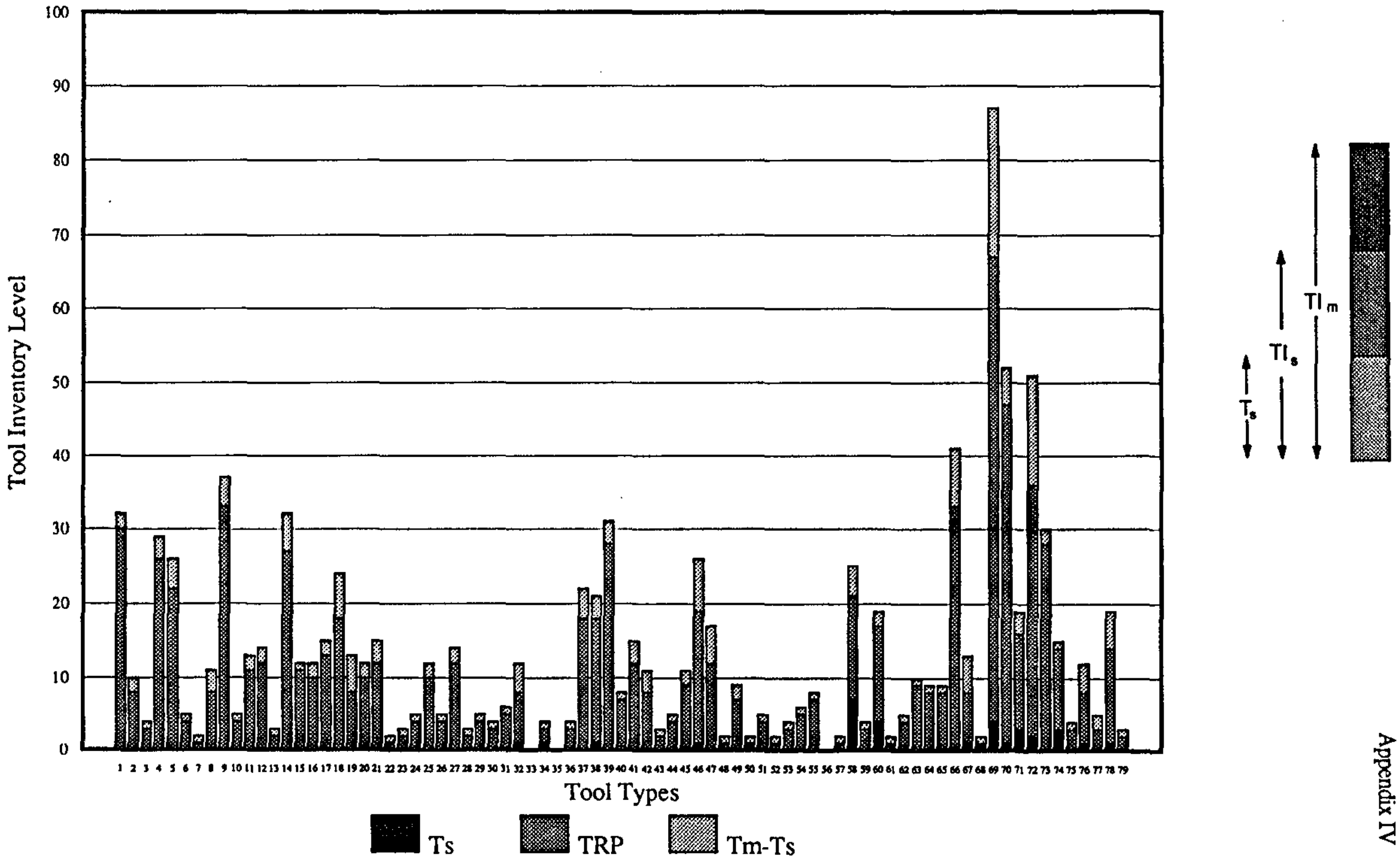




Part Type = 70, # MC =4, Batch Size <=8, Permissible Tool Life = 90%, Manufacturing Period = 10-Shift.

Supplementary Experiment No. 19 - Tool Inventory

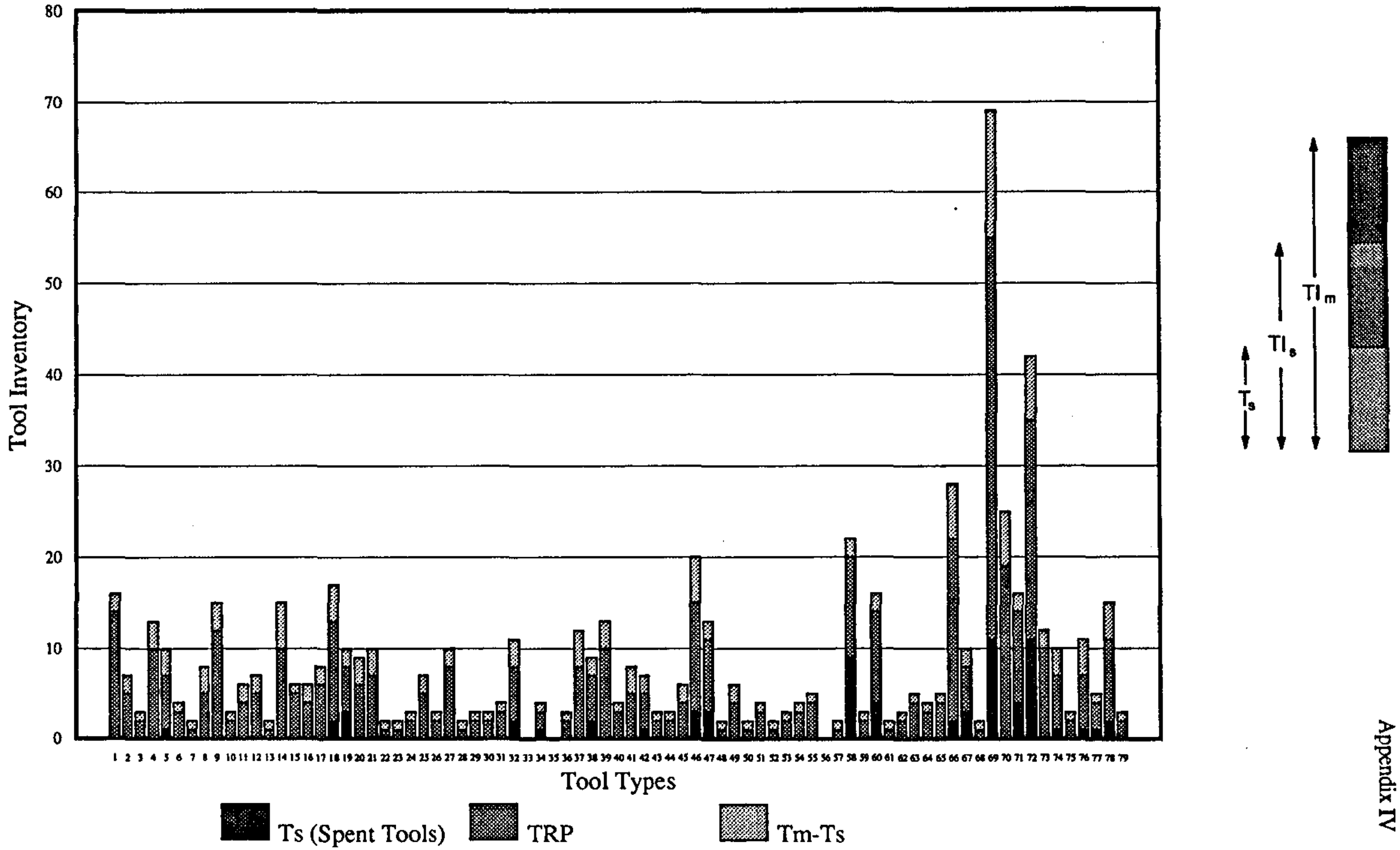
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
30	32	30	0	2	2	48	0.63	0.00	1.00
8	10	8	0	2	2	8	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
26	29	26	0	3	3	31	0.84	0.00	1.00
22	26	22	0	4	4	27	0.81	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
8	11	8	0	3	3	22	0.36	0.00	1.00
33	37	33	0	4	4	37	0.89	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
11	13	11	0	2	2	12	0.92	0.00	1.00
12	14	12	0	2	2	13	0.92	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
27	32	27	0	5	5	27	1.00	0.00	1.00
11	12	11	0	1	1	12	0.92	0.00	1.00
10	12	10	0	2	2	12	0.83	0.00	1.00
13	15	13	0	2	2	14	0.93	0.00	1.00
18	24	18	0	6	6	19	0.95	0.00	1.00
8	13	8	0	5	5	8	1.00	0.00	1.00
10	12	10	0	2	2	23	0.43	0.00	1.00
12	15	12	0	3	3	16	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
10	12	10	0	2	2	10	1.00	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
12	14	12	0	2	2	17	0.71	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
5	6	5	0	1	1	5	1.00	0.00	1.00
8	11	7	1	5	4	9	0.89	0.20	1.14
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
3	4	3	0	1	1	3	1.00	0.00	1.00
18	22	18	0	4	4	20	0.90	0.00	1.00
18	20	17	1	4	3	20	0.90	0.25	1.06
28	31	28	0	3	3	32	0.88	0.00	1.00
7	8	7	0	1	1	8	0.88	0.00	1.00
12	15	12	0	3	3	13	0.92	0.00	1.00
8	11	8	0	3	3	10	0.80	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
9	11	9	0	2	2	10	0.90	0.00	1.00
19	25	18	1	8	7	20	0.95	0.13	1.06
12	17	12	0	5	5	19	0.63	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
7	9	7	0	2	2	7	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
5	6	5	0	1	1	5	1.00	0.00	1.00
7	8	7	0	1	1	8	0.88	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
21	18	14	7	11	4	21	1.00	0.64	1.50
3	4	3	0	1	1	3	1.00	0.00	1.00
17	15	13	4	6	2	17	1.00	0.67	1.31
1	2	1	0	1	1	1	1.00	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
9	10	9	0	1	1	10	0.90	0.00	1.00
8	9	8	0	1	1	8	1.00	0.00	1.00
8	9	8	0	1	1	8	1.00	0.00	1.00
33	41	33	0	8	8	53	0.62	0.00	1.00
8	13	8	0	5	5	8	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
67	83	63	4	24	20	106	0.63	0.17	1.06
47	51	46	1	6	5	71	0.66	0.17	1.02
16	16	13	3	6	3	17	0.94	0.50	1.23
36	49	34	2	17	15	44	0.82	0.12	1.06
28	30	28	0	2	2	34	0.82	0.00	1.00
14	12	11	3	4	1	16	0.88	0.75	1.27
3	4	3	0	1	1	4	0.75	0.00	1.00
8	11	7	1	5	4	8	1.00	0.20	1.14
3	5	3	0	2	2	3	1.00	0.00	1.00
14	18	13	1	6	5	14	1.00	0.17	1.08
2	3	2	0	1	1	2	1.00	0.00	1.00
852	1021	822	30	229	199	1057			



Part Type = 70, # MC =4, Batch Size <=8, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.

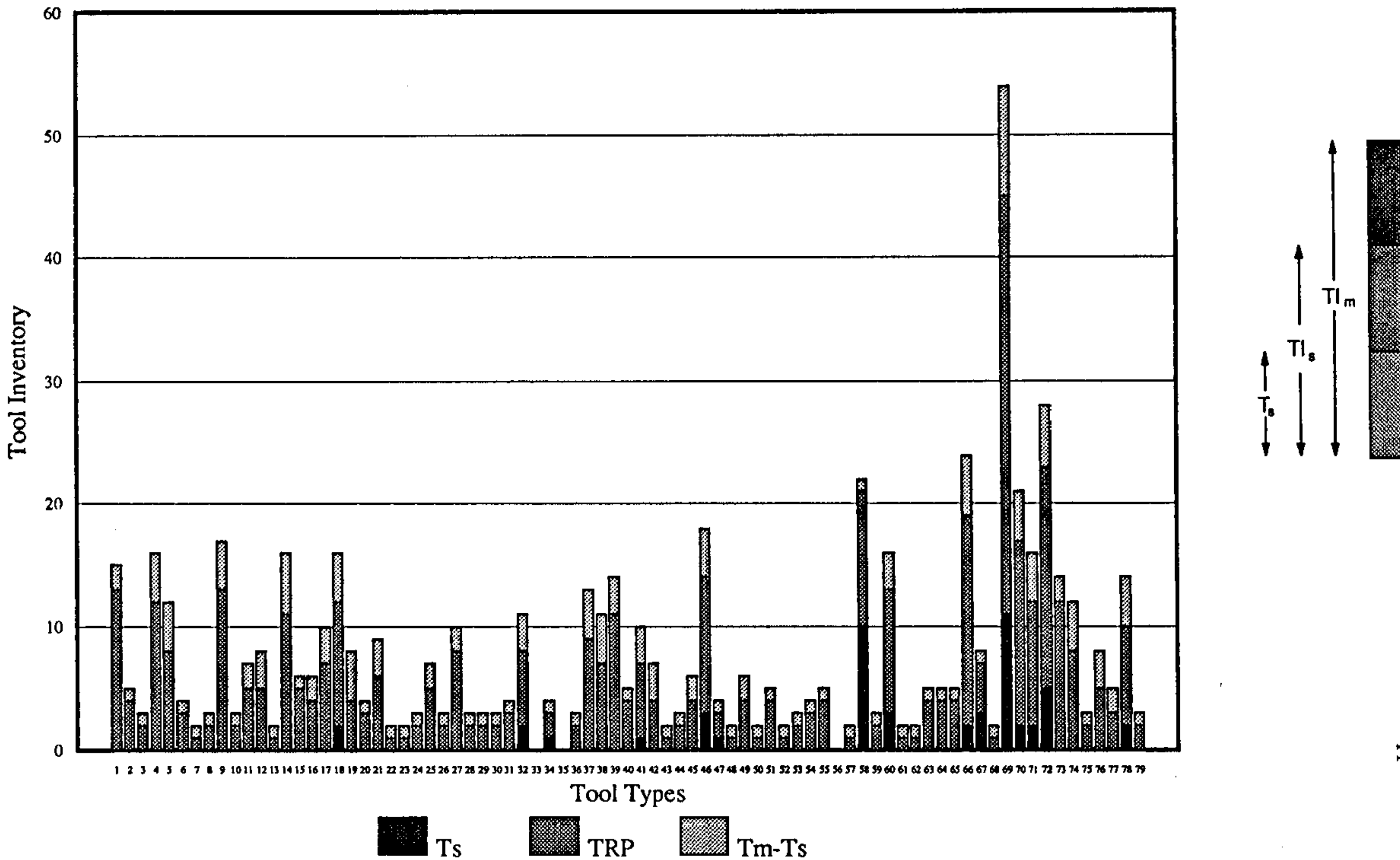
Supplementary Experiment No. 20 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
14	16	14	0	2	2	20	0.70	0.00	1.00
5	7	5	0	2	2	5	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
10	13	10	0	3	3	13	0.77	0.00	1.00
7	9	6	1	4	3	9	0.78	0.25	1.17
3	4	3	0	1	1	3	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
5	8	5	0	3	3	5	1.00	0.00	1.00
12	15	12	0	3	3	17	0.71	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	6	4	0	2	2	5	0.80	0.00	1.00
5	7	5	0	2	2	6	0.83	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
10	15	10	0	5	5	11	0.91	0.00	1.00
5	6	5	0	1	1	6	0.83	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
6	8	6	0	2	2	8	0.75	0.00	1.00
13	15	11	2	6	4	13	1.00	0.33	1.18
8	7	5	3	5	2	8	1.00	0.60	1.60
6	9	6	0	3	3	7	0.86	0.00	1.00
7	10	7	0	3	3	8	0.88	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
5	7	5	0	2	2	5	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
8	10	8	0	2	2	9	0.89	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
8	9	6	2	5	3	8	1.00	0.40	1.33
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	2	1.00	0.00	1.00
8	12	8	0	4	4	9	0.89	0.00	1.00
7	7	5	2	4	2	9	0.78	0.50	1.40
10	13	10	0	3	3	15	0.67	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
5	8	5	0	3	3	6	0.83	0.00	1.00
5	6	4	1	3	2	5	1.00	0.33	1.25
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	6	4	0	2	2	5	0.80	0.00	1.00
15	17	12	3	8	5	15	1.00	0.38	1.25
11	10	8	3	5	2	10	1.10	0.60	1.38
1	2	1	0	1	1	1	1.00	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
20	13	11	9	11	2	20	1.00	0.82	1.82
2	3	2	0	1	1	2	1.00	0.00	1.00
14	12	10	4	6	2	14	1.00	0.67	1.40
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
22	26	20	2	8	6	26	0.85	0.25	1.10
8	7	5	3	5	2	8	1.00	0.60	1.60
1	2	1	0	1	1	1	1.00	0.00	1.00
55	58	44	11	25	14	61	0.90	0.44	1.25
19	25	19	0	6	6	26	0.73	0.00	1.00
14	12	10	4	6	2	14	1.00	0.67	1.40
35	31	24	11	18	7	40	0.88	0.61	1.46
10	12	10	0	2	2	18	0.56	0.00	1.00
7	9	6	1	4	3	9	0.78	0.25	1.17
2	3	2	0	1	1	2	1.00	0.00	1.00
7	10	6	1	5	4	8	0.88	0.20	1.17
4	4	3	1	2	1	4	1.00	0.50	1.33
11	13	9	2	6	4	11	1.00	0.33	1.22
2	3	2	0	1	1	2	1.00	0.00	1.00
509	606	442	67	231	164	581			



Part Type = 70, # MC = 4, Batch Size <=50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.

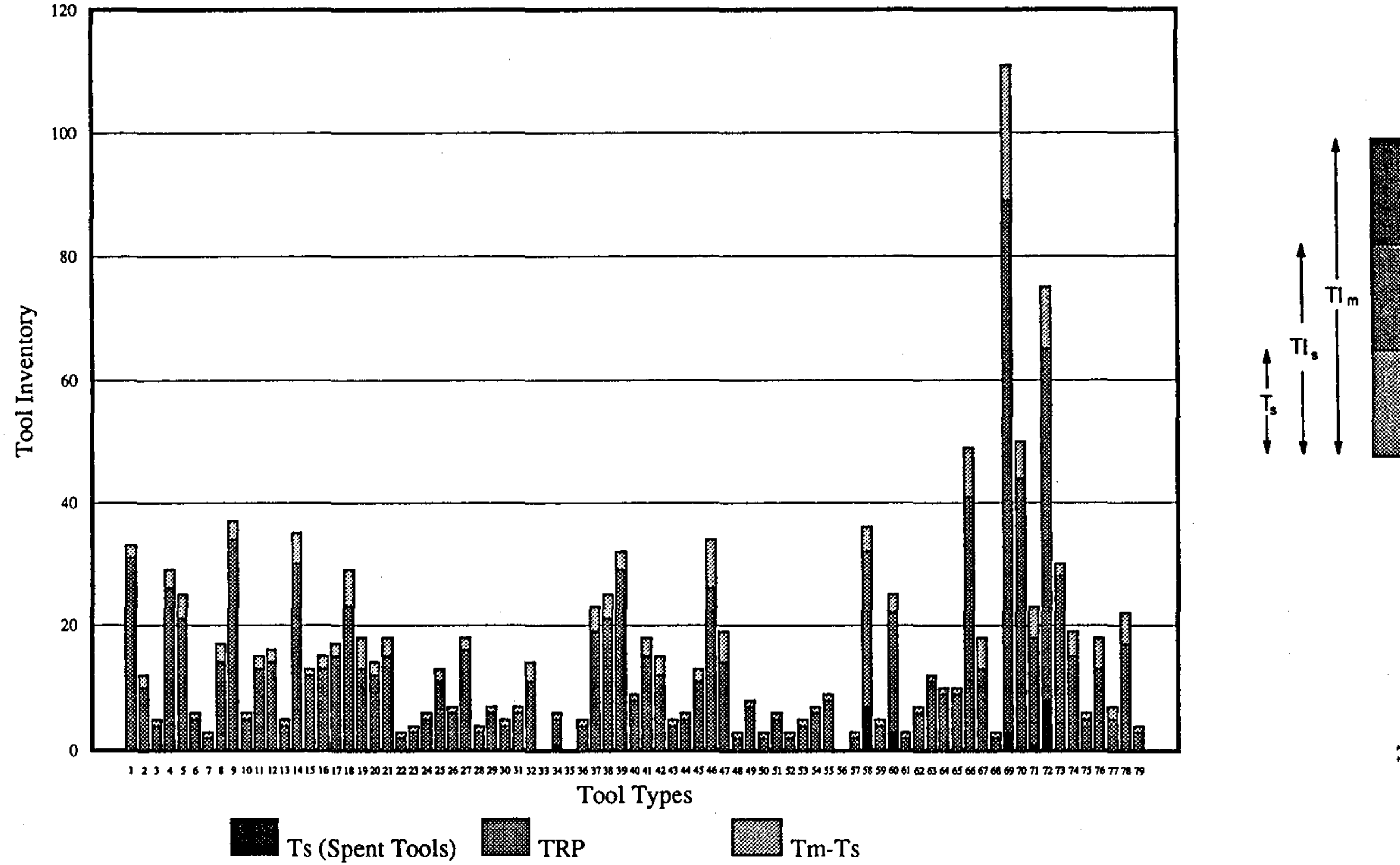
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
13	15	13	0	2	2	19	0.68	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
12	16	12	0	4	4	13	0.92	0.00	1.00
8	12	8	0	4	4	8	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
13	17	13	0	4	4	17	0.76	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
5	7	5	0	2	2	5	1.00	0.00	1.00
5	8	5	0	3	3	6	0.83	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
11	16	11	0	5	5	11	1.00	0.00	1.00
5	6	5	0	1	1	6	0.83	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
7	10	7	0	3	3	8	0.88	0.00	1.00
12	14	10	2	6	4	12	1.00	0.33	1.20
4	8	4	0	4	4	4	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
6	9	6	0	3	3	8	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
5	7	5	0	2	2	5	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
8	10	8	0	2	2	9	0.89	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
8	9	6	2	5	3	8	1.00	0.40	1.33
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	2	1.00	0.00	1.00
9	13	9	0	4	4	9	1.00	0.00	1.00
7	11	7	0	4	4	7	1.00	0.00	1.00
11	14	11	0	3	3	15	0.73	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
7	9	6	1	4	3	7	1.00	0.25	1.17
4	7	4	0	3	3	4	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	6	4	0	2	2	5	0.80	0.00	1.00
14	15	11	3	7	4	14	1.00	0.43	1.27
3	3	2	1	2	1	3	1.00	0.50	1.50
1	2	1	0	1	1	1	1.00	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
21	12	11	10	11	1	21	1.00	0.91	1.91
2	3	2	0	1	1	2	1.00	0.00	1.00
13	13	10	3	6	3	13	1.00	0.50	1.30
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
19	22	17	2	7	5	22	0.86	0.29	1.12
7	5	4	3	4	1	7	1.00	0.75	1.75
1	2	1	0	1	1	1	1.00	0.00	1.00
45	43	34	11	20	9	50	0.90	0.55	1.32
17	19	15	2	6	4	24	0.71	0.33	1.13
12	14	10	2	6	4	12	1.00	0.33	1.20
23	23	18	5	10	5	24	0.96	0.50	1.28
12	14	12	0	2	2	18	0.67	0.00	1.00
8	12	8	0	4	4	8	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
5	8	5	0	3	3	5	1.00	0.00	1.00
3	5	3	0	2	2	3	1.00	0.00	1.00
10	12	8	2	6	4	11	0.91	0.33	1.25
2	3	2	0	1	1	2	1.00	0.00	1.00
467	576	417	50	209	159	516			



Part Type = 70, # MC = 8, Batch Size <=50, Scheduling Rule = SPT, Strategy = Diff.Kitting, Permissible Tool Life =90%

Supplementary Experiment No.91 - Tool Inventory

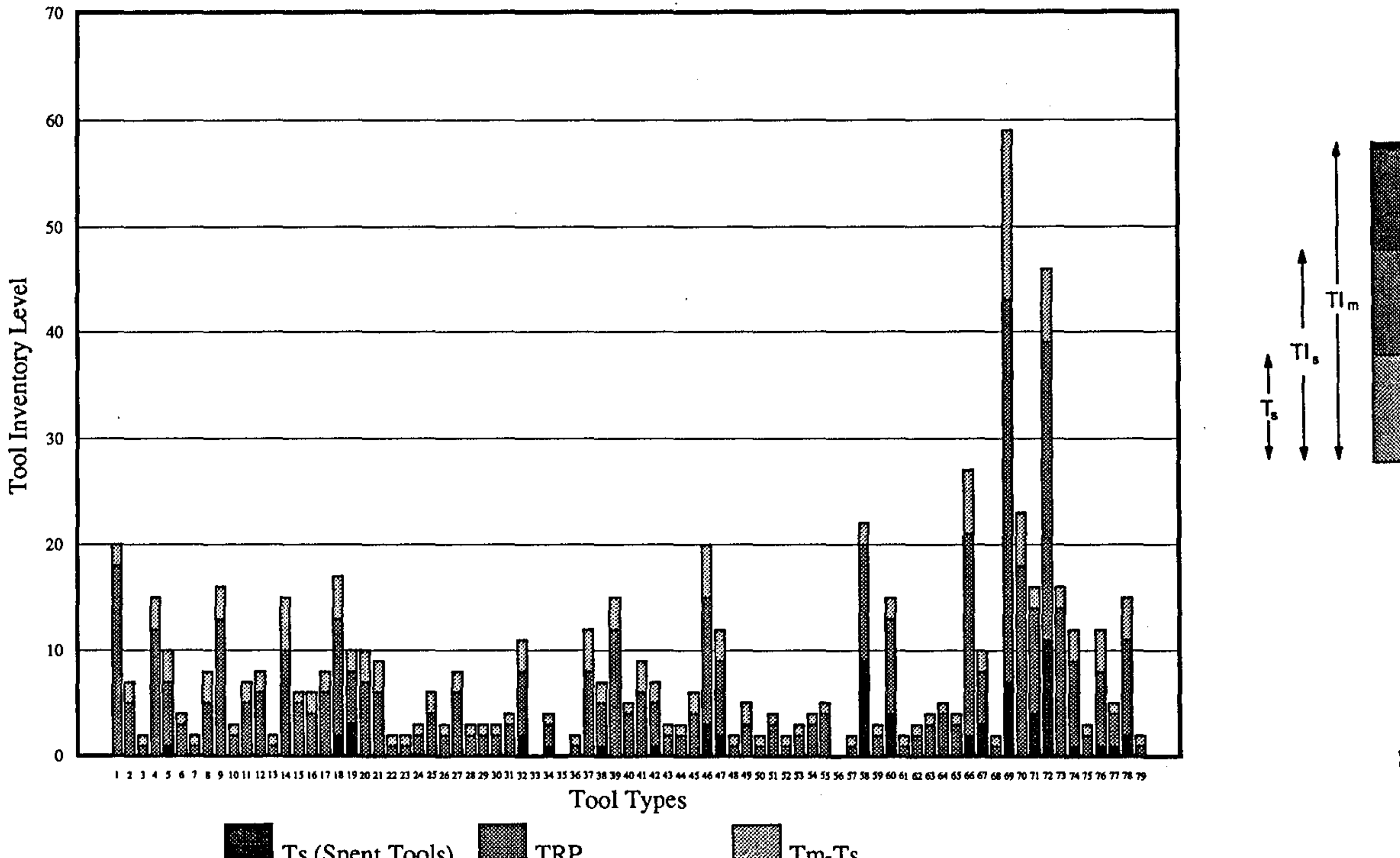
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
29	31	29	0	2	2	48	0.60	0	1.00
8	10	8	0	2	2	8	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
23	26	23	0	3	3	31	0.74	0	1.00
17	21	17	0	4	4	28	0.61	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
11	14	11	0	3	3	23	0.48	0	1.00
31	34	31	0	3	3	36	0.86	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
11	13	11	0	2	2	12	0.92	0	1.00
12	14	12	0	2	2	13	0.92	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
25	30	25	0	5	5	26	0.96	0	1.00
11	12	11	0	1	1	12	0.92	0	1.00
11	13	11	0	2	2	12	0.92	0	1.00
13	15	13	0	2	2	14	0.93	0	1.00
17	23	17	0	6	6	20	0.85	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
10	12	10	0	2	2	24	0.42	0	1.00
12	15	12	0	3	3	16	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
9	11	9	0	2	2	9	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
14	16	14	0	2	2	17	0.82	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
8	11	8	0	3	3	8	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	4	2	1	2	1	3	1.00	0.5	1.50
0	0	0	0	0	0	0	0.00	0	0.00
3	4	3	0	1	1	3	1.00	0	1.00
15	19	15	0	4	4	20	0.75	0	1.00
17	21	17	0	4	4	20	0.85	0	1.00
26	29	26	0	3	3	31	0.84	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
12	15	12	0	3	3	13	0.92	0	1.00
9	12	9	0	3	3	10	0.90	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
9	11	9	0	2	2	10	0.90	0	1.00
18	26	18	0	8	8	20	0.90	0	1.00
9	14	9	0	5	5	20	0.45	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
6	7	6	0	1	1	6	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
21	25	14	7	11	4	21	1.00	0.64	1.50
3	4	3	0	1	1	3	1.00	0	1.00
16	19	13	3	6	3	16	1.00	0.5	1.23
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
10	11	10	0	1	1	10	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
33	41	33	0	8	8	54	0.61	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
64	86	61	3	25	22	108	0.59	0.12	1.05
38	44	38	0	6	6	72	0.53	0	1.00
12	17	11	1	6	5	15	0.80	0.17	1.09
47	57	39	8	18	10	52	0.90	0.44	1.21
26	28	26	0	2	2	34	0.76	0	1.00
11	15	11	0	4	4	13	0.85	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
3	5	3	0	2	2	3	1.00	0	1.00
12	17	12	0	5	5	13	0.92	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
827	1030	804	23	226	203	1061			



Part Type = 70, Batch Size <=8, # MC = 6, Permissible Tool Life = 90%, Manufacturing Period = 10-Shift

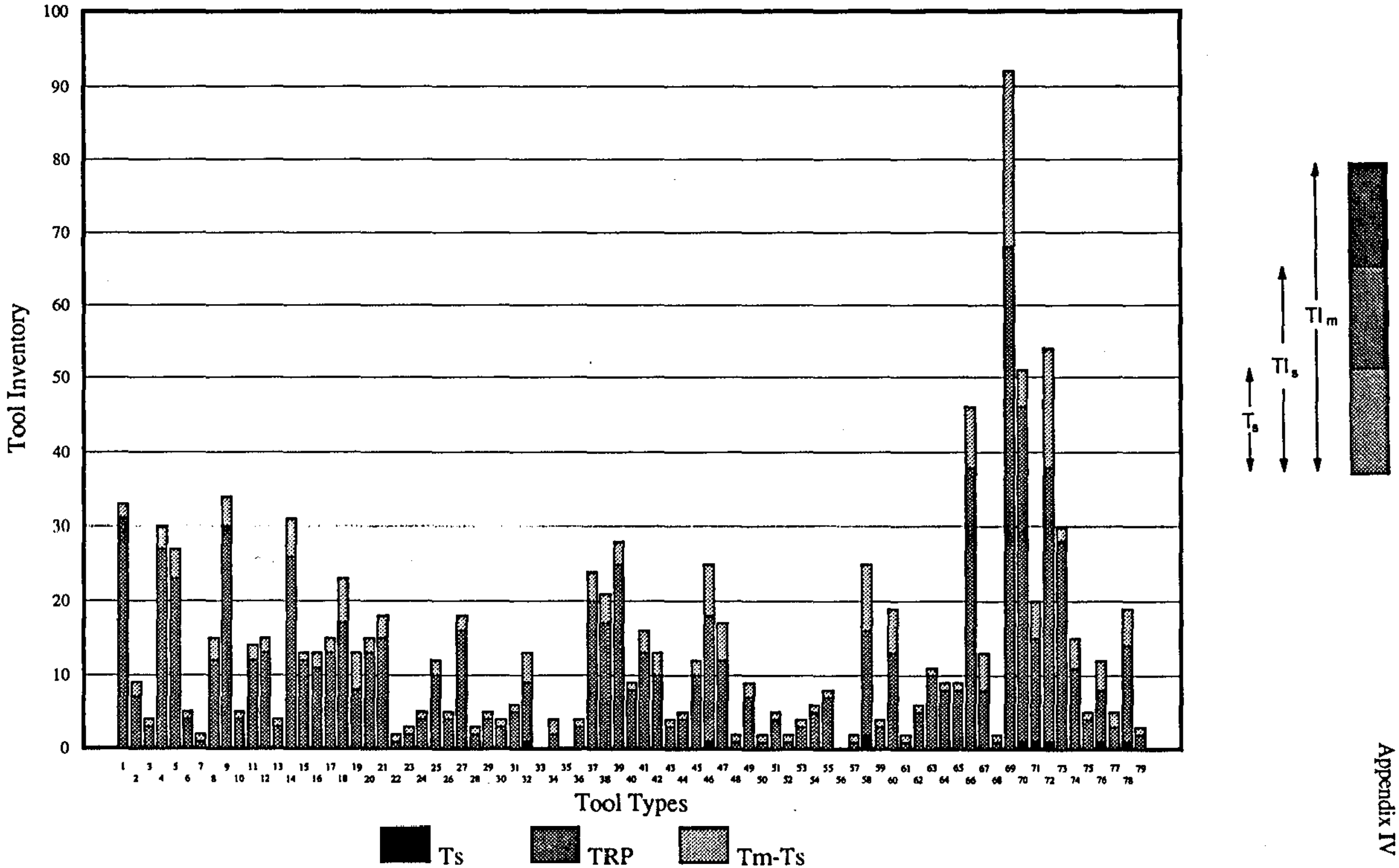
Supplementary Experiment No.93 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
18	20	18	0	2	2	20	0.90	0	1.00
5	7	5	0	2	2	5	1.00	0	1.00
1	2	1	0	1	1	2	0.50	0	1.00
12	15	12	0	3	3	13	0.92	0	1.00
7	10	6	1	4	3	9	0.78	0.25	1.17
3	4	3	0	1	1	3	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
5	8	5	0	3	3	5	1.00	0	1.00
13	16	13	0	3	3	17	0.76	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
5	7	5	0	2	2	5	1.00	0	1.00
6	8	6	0	2	2	6	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
10	15	10	0	5	5	11	0.91	0	1.00
5	6	5	0	1	1	6	0.83	0	1.00
4	6	4	0	2	2	4	1.00	0	1.00
6	8	6	0	2	2	8	0.75	0	1.00
13	17	11	2	6	4	13	1.00	0.33	1.18
8	10	5	3	5	2	8	1.00	0.6	1.60
7	10	7	0	3	3	7	1.00	0	1.00
6	9	6	0	3	3	8	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	6	4	0	2	2	5	0.80	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
6	8	6	0	2	2	9	0.67	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
8	11	6	2	5	3	8	1.00	0.4	1.33
0	0	0	0	0	0	0	0.00	0	0.00
3	4	2	1	2	1	3	1.00	0.5	1.50
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	2	0.50	0	1.00
8	12	8	0	4	4	9	0.89	0	1.00
5	7	4	1	3	2	7	0.71	0.33	1.25
12	15	12	0	3	3	15	0.80	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
6	9	6	0	3	3	6	1.00	0	1.00
5	7	4	1	3	2	5	1.00	0.33	1.25
2	3	2	0	1	1	2	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	6	4	0	2	2	5	0.80	0	1.00
15	20	12	3	8	5	15	1.00	0.375	1.25
9	12	7	2	5	3	9	1.00	0.4	1.29
1	2	1	0	1	1	1	1.00	0	1.00
3	5	3	0	2	2	4	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
20	22	11	9	11	2	20	1.00	0.82	1.82
2	3	2	0	1	1	2	1.00	0	1.00
13	15	9	4	6	2	14	0.93	0.67	1.44
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
3	4	3	0	1	1	5	0.60	0	1.00
21	27	19	2	8	6	26	0.81	0.25	1.11
8	10	5	3	5	2	8	1.00	0.6	1.60
1	2	1	0	1	1	1	1.00	0	1.00
43	59	36	7	23	16	54	0.80	0.30	1.19
18	23	18	0	5	5	26	0.69	0	1.00
14	16	10	4	6	2	14	1.00	0.67	1.40
39	46	28	11	18	7	40	0.98	0.61	1.39
14	16	14	0	2	2	18	0.78	0	1.00
9	12	8	1	4	3	9	1.00	0.25	1.13
2	3	2	0	1	1	2	1.00	0	1.00
8	12	7	1	5	4	8	1.00	0.2	1.14
4	5	3	1	2	1	4	1.00	0.5	1.33
11	15	9	2	6	4	11	1.00	0.33	1.22
1	2	1	0	1	1	2	0.50	0	1.00
507	673	446	61	227	166	571			



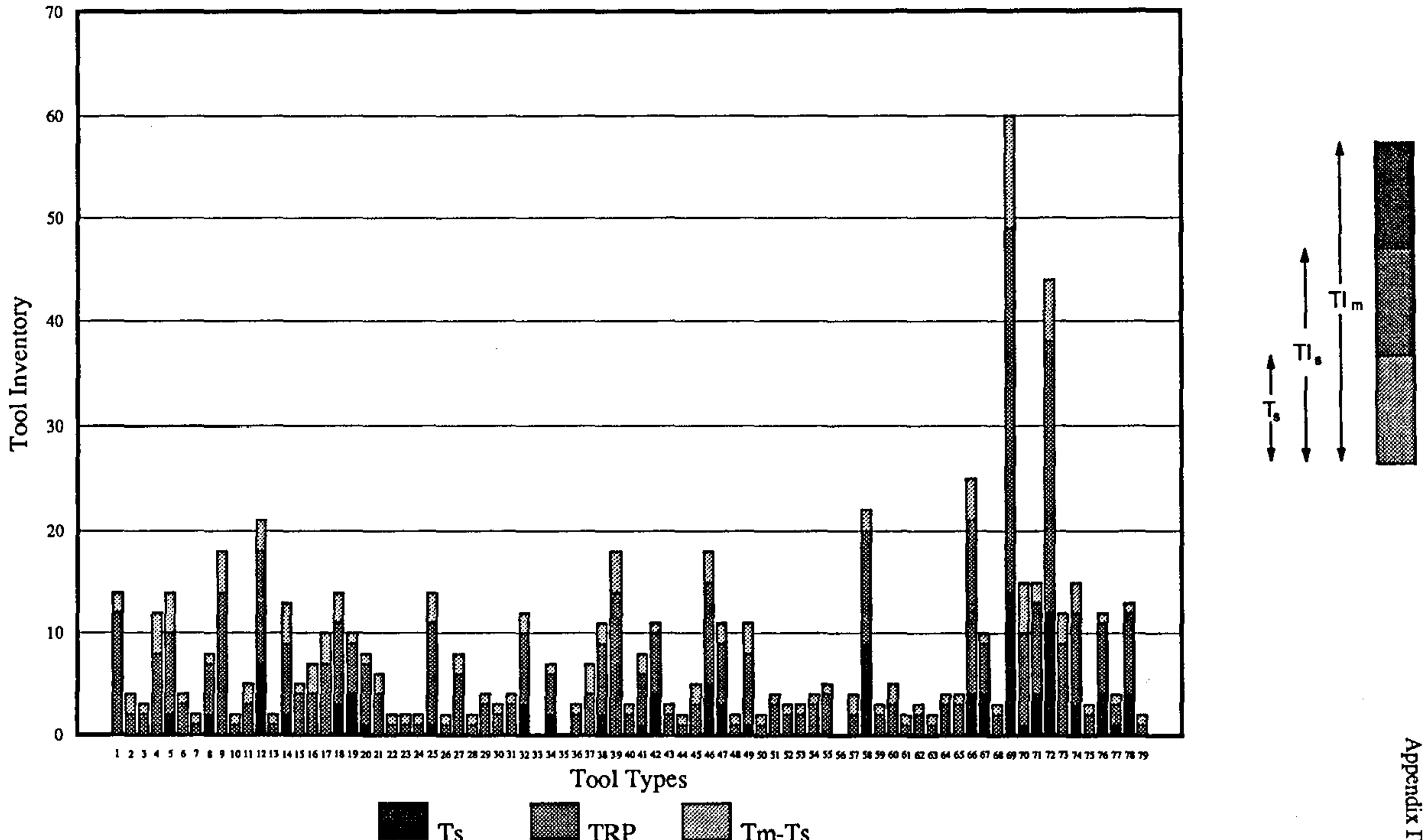
Part Type = 70, # MC = 4, Batch Size <=50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
31	33	31	0	2	2	48	0.65	0	1.00
7	9	7	0	2	2	8	0.88	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
27	30	27	0	3	3	31	0.87	0	1.00
23	27	23	0	4	4	27	0.85	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
12	15	12	0	3	3	22	0.55	0	1.00
30	34	30	0	4	4	37	0.81	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
12	14	12	0	2	2	12	1.00	0	1.00
13	15	13	0	2	2	13	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
26	31	26	0	5	5	27	0.96	0	1.00
12	13	12	0	1	1	12	1.00	0	1.00
11	13	11	0	2	2	12	0.92	0	1.00
13	15	13	0	2	2	14	0.93	0	1.00
17	23	17	0	6	6	19	0.89	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
13	15	13	0	2	2	23	0.57	0	1.00
15	18	15	0	3	3	16	0.94	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
10	12	10	0	2	2	10	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
16	18	16	0	2	2	17	0.94	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
9	12	8	1	5	4	9	1.00	0.2	1.13
0	0	0	0	0	0	0	0.00	0	0.00
2	4	2	0	2	2	2	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	4	3	0	1	1	3	1.00	0	1.00
20	24	20	0	4	4	20	1.00	0	1.00
17	21	17	0	4	4	19	0.89	0	1.00
25	28	25	0	3	3	32	0.78	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
13	16	13	0	3	3	13	1.00	0	1.00
10	13	10	0	3	3	10	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
10	12	10	0	2	2	10	1.00	0	1.00
17	24	17	1	8	7	20	0.85	0.125	1.00
12	17	12	0	5	5	19	0.63	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
7	9	7	0	2	2	7	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
16	23	14	2	11	9	16	1.00	0.18	1.14
3	4	3	0	1	1	3	1.00	0	1.00
13	19	13	0	6	6	13	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
10	11	10	0	1	1	10	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
8	9	8	0	1	1	8	1.00	0	1.00
38	46	38	0	8	8	53	0.72	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
68	92	68	0	24	24	102	0.67	0	1.00
46	50	45	1	6	5	71	0.65	0.17	1.02
15	19	14	1	6	5	15	1.00	0.17	1.07
38	53	37	1	17	16	43	0.88	0.06	1.03
28	30	28	0	2	2	34	0.82	0	1.00
11	15	11	0	4	4	13	0.85	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
8	11	7	1	5	4	8	1.00	0.2	1.14
3	5	3	0	2	2	3	1.00	0	1.00
13	18	13	1	6	5	14	0.93	0.17	1.00
2	3	2	0	1	1	2	1.00	0	1.00
866	1079	859	9	229	220	1036			



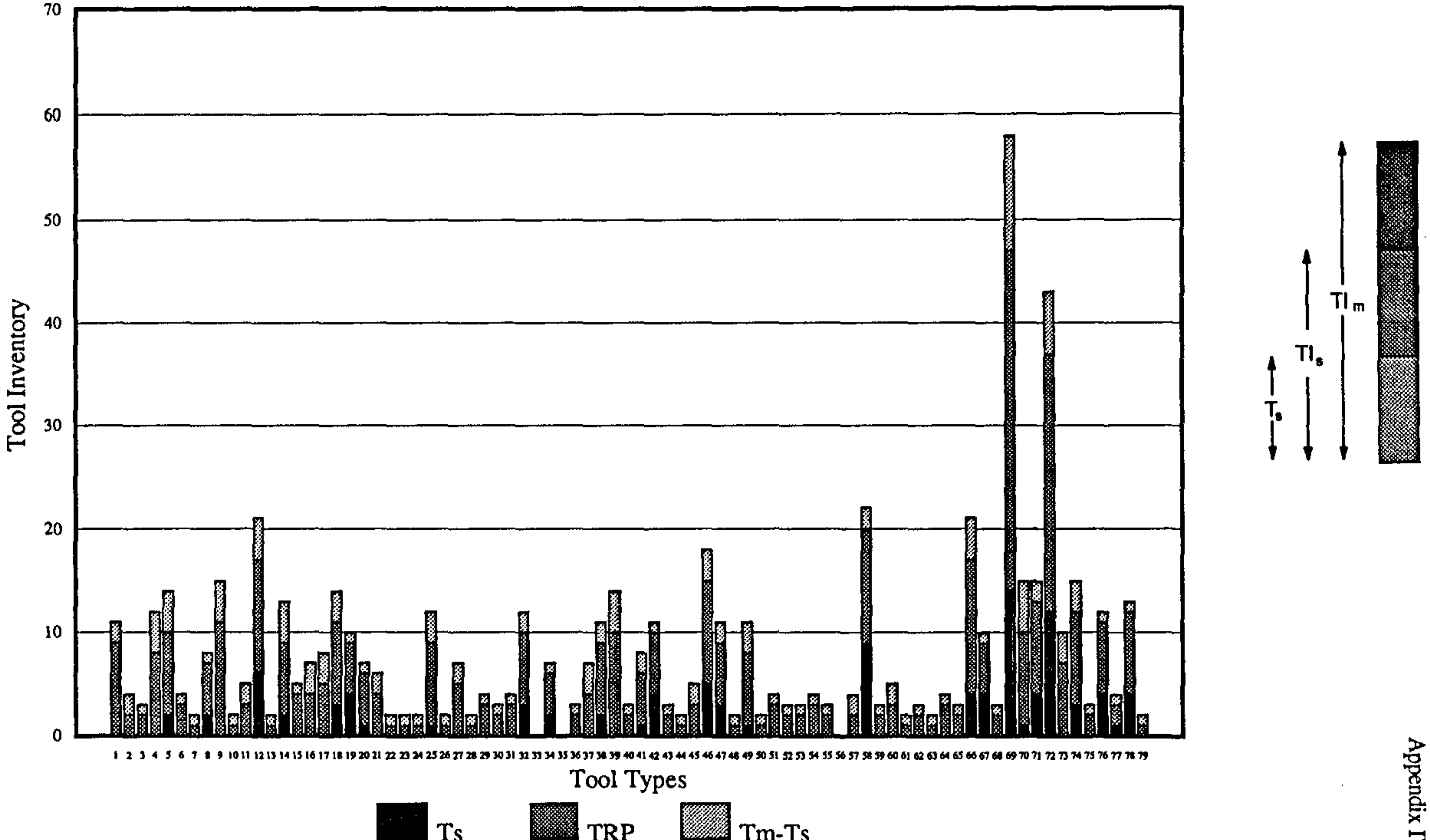
Part Type = 70, Batch Size <=8, # MC = 8, Manufacturing Period = 10-Shift, Permissible Tool Life = 90%.

Tls	Tlm	TRP	Ts	Tm	(Tm-Ts)	(Tls)fk	Tls/(Tls)fk	Ts/Tm	Tls/TRP
12	14	12	0	2	2	48	0.25	0.00	1.00
2	4	2	0	2	2	8	0.25	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
8	12	8	0	4	4	31	0.26	0.00	1.00
10	12	8	2	6	4	29	0.34	0.33	1.25
3	4	3	0	1	1	4	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
7	6	5	2	3	1	24	0.29	0.67	1.40
14	18	14	0	4	4	37	0.38	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	12	0.25	0.00	1.00
18	14	11	7	10	3	20	0.90	0.70	1.64
1	2	1	0	1	1	3	0.33	0.00	1.00
9	11	7	2	6	4	29	0.31	0.33	1.29
4	5	4	0	1	1	12	0.33	0.00	1.00
4	7	4	0	3	3	12	0.33	0.00	1.00
7	10	7	0	3	3	14	0.50	0.00	1.00
11	11	8	3	6	3	22	0.50	0.50	1.38
9	6	5	4	5	1	12	0.75	0.80	1.80
7	7	6	1	2	1	24	0.29	0.50	1.17
4	6	4	0	2	2	16	0.25	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
11	13	10	1	4	3	11	1.00	0.25	1.10
1	2	1	0	1	1	5	0.20	0.00	1.00
6	8	6	0	2	2	17	0.35	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
10	9	7	3	5	2	11	0.91	0.60	1.43
0	0	0	0	0	0	0	0.00	0.00	0.00
6	5	4	2	3	1	4	1.50	0.67	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	3	0.67	0.00	1.00
4	7	4	0	3	3	20	0.20	0.00	1.00
9	9	7	2	4	2	21	0.43	0.50	1.29
14	18	14	0	4	4	32	0.44	0.00	1.00
2	3	2	0	1	1	8	0.25	0.00	1.00
6	7	5	1	3	2	14	0.43	0.33	1.20
10	7	6	4	5	1	14	0.71	0.80	1.67
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	10	0.30	0.00	1.00
15	13	10	5	8	3	24	0.63	0.63	1.50
9	8	6	3	5	2	22	0.41	0.60	1.50
1	2	1	0	1	1	1	1.00	0.00	1.00
8	10	7	1	4	3	8	1.00	0.25	1.14
1	2	1	0	1	1	1	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
4	5	4	0	1	1	8	0.50	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
2	4	2	0	2	2	1	2.00	0.00	1.00
20	13	11	9	11	2	23	0.87	0.82	1.82
2	3	2	0	1	1	3	0.67	0.00	1.00
3	5	3	0	2	2	13	0.23	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	5	0.40	0.00	1.00
1	2	1	0	1	1	10	0.10	0.00	1.00
3	4	3	0	1	1	8	0.38	0.00	1.00
3	4	3	0	1	1	8	0.38	0.00	1.00
21	21	17	4	8	4	57	0.37	0.50	1.24
9	6	5	4	5	1	12	0.75	0.80	1.80
2	3	2	0	1	1	1	2.00	0.00	1.00
49	46	35	14	25	11	116	0.42	0.56	1.40
10	14	9	1	6	5	71	0.14	0.17	1.11
13	11	9	4	6	2	18	0.72	0.67	1.44
38	32	26	12	18	6	54	0.70	0.67	1.46
9	12	9	0	3	3	34	0.26	0.00	1.00
12	12	9	3	6	3	16	0.75	0.50	1.33
2	3	2	0	1	1	4	0.50	0.00	1.00
11	8	7	4	5	1	11	1.00	0.80	1.57
3	3	2	1	2	1	4	0.75	0.50	1.50
12	9	8	4	5	1	17	0.71	0.80	1.50
1	2	1	0	1	1	2	0.50	0.00	1.00
513	557	410	103	250	147	1130			



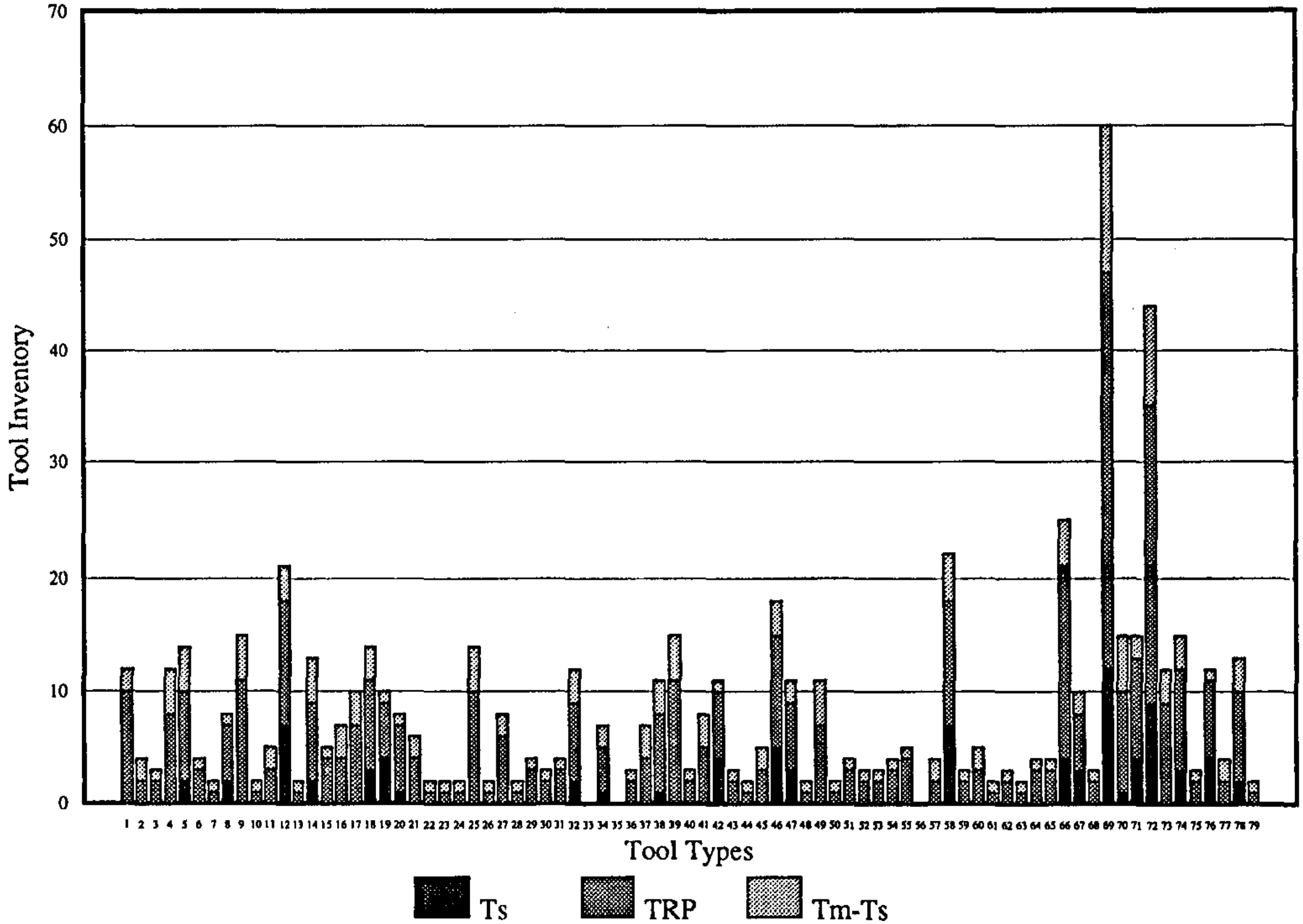
Part Types = 70, Batch Size <= 8, # MC = 4, Strategy = Differential Clustering, Permissible Tool Life = 90%
Manufacturing period = 10-shift,

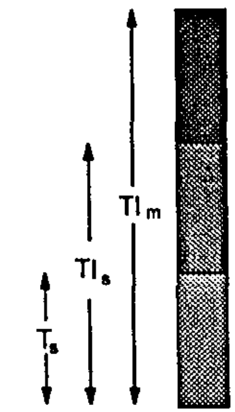
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
9	11	9	0	2	2	48	0.19	0.00	1.00
2	4	2	0	2	2	8	0.25	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
8	12	8	0	4	4	31	0.26	0.00	1.00
10	12	8	2	6	4	29	0.34	0.33	1.25
3	4	3	0	1	1	4	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
7	6	5	2	3	1	24	0.29	0.67	1.40
11	15	11	0	4	4	37	0.30	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	12	0.25	0.00	1.00
17	15	11	6	10	4	19	0.89	0.60	1.55
1	2	1	0	1	1	3	0.33	0.00	1.00
9	11	7	2	6	4	29	0.31	0.33	1.29
4	5	4	0	1	1	12	0.33	0.00	1.00
4	7	4	0	3	3	12	0.33	0.00	1.00
5	8	5	0	3	3	14	0.36	0.00	1.00
11	11	8	3	6	3	22	0.50	0.50	1.38
9	6	5	4	5	1	12	0.75	0.80	1.80
6	6	5	1	2	1	24	0.25	0.50	1.20
4	6	4	0	2	2	16	0.25	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
9	11	8	1	4	3	11	0.82	0.25	1.13
1	2	1	0	1	1	5	0.20	0.00	1.00
5	7	5	0	2	2	17	0.29	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
10	9	7	3	5	2	11	0.91	0.60	1.43
0	0	0	0	0	0	0	0.00	0.00	0.00
6	5	4	2	3	1	4	1.50	0.67	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	3	0.67	0.00	1.00
4	7	4	0	3	3	20	0.20	0.00	1.00
9	9	7	2	4	2	21	0.43	0.50	1.29
10	14	10	0	4	4	32	0.31	0.00	1.00
2	3	2	0	1	1	8	0.25	0.00	1.00
6	7	5	1	3	2	14	0.43	0.33	1.20
10	7	6	4	5	1	14	0.71	0.80	1.67
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	10	0.30	0.00	1.00
15	13	10	5	8	3	24	0.63	0.63	1.50
9	8	6	3	5	2	22	0.41	0.60	1.50
1	2	1	0	1	1	1	1.00	0.00	1.00
8	10	7	1	4	3	8	1.00	0.25	1.14
1	2	1	0	1	1	1	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
2	3	2	0	1	1	8	0.25	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
2	4	2	0	2	2	1	2.00	0.00	1.00
20	13	11	9	11	2	23	0.87	0.82	1.82
2	3	2	0	1	1	3	0.67	0.00	1.00
3	5	3	0	2	2	13	0.23	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	5	0.40	0.00	1.00
1	2	1	0	1	1	10	0.10	0.00	1.00
3	4	3	0	1	1	8	0.38	0.00	1.00
2	3	2	0	1	1	8	0.25	0.00	1.00
17	17	13	4	8	4	57	0.30	0.50	1.31
9	6	5	4	5	1	12	0.75	0.80	1.80
2	3	2	0	1	1	1	2.00	0.00	1.00
47	44	33	14	25	11	116	0.41	0.56	1.42
10	14	9	1	6	5	71	0.14	0.17	1.11
13	11	9	4	6	2	18	0.72	0.67	1.44
37	31	25	12	18	6	54	0.69	0.67	1.48
7	10	7	0	3	3	34	0.21	0.00	1.00
12	12	9	3	6	3	16	0.75	0.50	1.33
2	3	2	0	1	1	4	0.50	0.00	1.00
11	8	7	4	5	1	11	1.00	0.80	1.57
3	3	2	1	2	1	4	0.75	0.50	1.50
12	9	8	4	5	1	17	0.71	0.80	1.50
1	2	1	0	1	1	2	0.50	0.00	1.00
484	530	382	102	250	148	1129			



Part Types = 70, Batch Size <= 8, # MC = 6, Strategy = Differential Clustering, Permissible Tool Life = 90%
Manufacturing period = 10-shift,

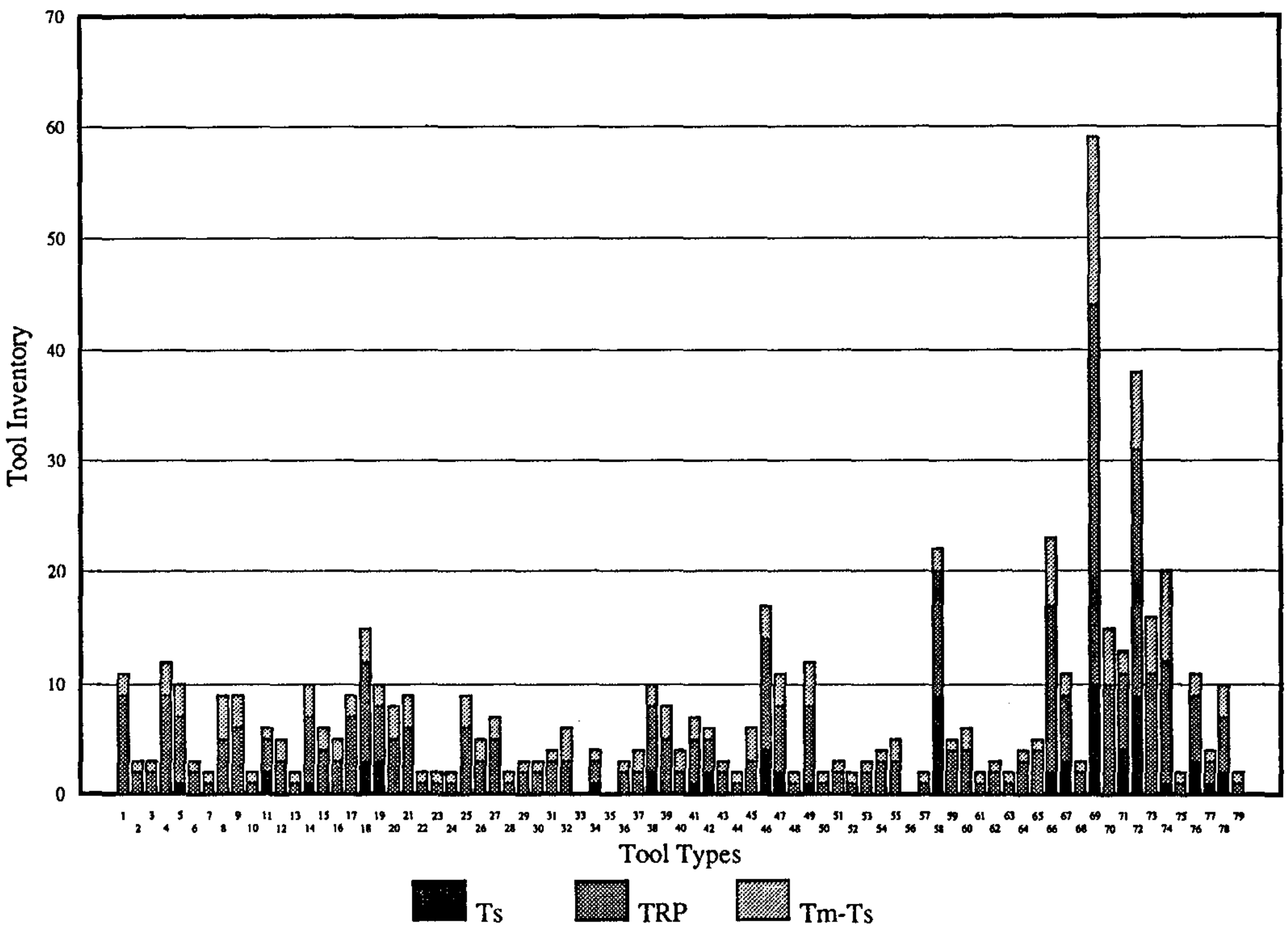
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
10	12	10	0	2	2	48	0.21	0.00	1.00
2	4	2	0	2	2	8	0.25	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
8	12	8	0	4	4	31	0.26	0.00	1.00
10	12	8	2	6	4	29	0.34	0.33	1.25
3	4	3	0	1	1	4	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
7	6	5	2	3	1	24	0.29	0.67	1.40
11	15	11	0	4	4	37	0.30	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	12	0.25	0.00	1.00
18	14	11	7	10	3	20	0.90	0.70	1.64
1	2	1	0	1	1	3	0.33	0.00	1.00
9	11	7	2	6	4	29	0.31	0.33	1.29
4	5	4	0	1	1	12	0.33	0.00	1.00
4	7	4	0	3	3	12	0.33	0.00	1.00
7	10	7	0	3	3	14	0.50	0.00	1.00
11	11	8	3	6	3	22	0.50	0.50	1.38
9	6	5	4	5	1	12	0.75	0.80	1.80
7	7	6	1	2	1	24	0.29	0.50	1.17
4	6	4	0	2	2	16	0.25	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
10	14	10	0	4	4	10	1.00	0.00	1.00
1	2	1	0	1	1	5	0.20	0.00	1.00
6	8	6	0	2	2	17	0.35	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
9	10	7	2	5	3	10	0.90	0.40	1.29
0	0	0	0	0	0	0	0.00	0.00	0.00
5	6	4	1	3	2	3	1.67	0.33	1.25
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	3	0.67	0.00	1.00
4	7	4	0	3	3	20	0.20	0.00	1.00
8	10	7	1	4	3	20	0.40	0.25	1.14
11	15	11	0	4	4	32	0.34	0.00	1.00
2	3	2	0	1	1	8	0.25	0.00	1.00
5	8	5	0	3	3	13	0.38	0.00	1.00
10	7	6	4	5	1	14	0.71	0.80	1.67
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	4	0.25	0.00	1.00
3	5	3	0	2	2	10	0.30	0.00	1.00
15	13	10	5	8	3	24	0.63	0.63	1.50
9	8	6	3	5	2	22	0.41	0.60	1.50
1	2	1	0	1	1	1	1.00	0.00	1.00
7	11	7	0	4	4	7	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
3	4	3	0	1	1	5	0.60	0.00	1.00
4	5	4	0	1	1	8	0.50	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
2	4	2	0	2	2	1	2.00	0.00	1.00
18	15	11	7	11	4	21	0.86	0.64	1.64
2	3	2	0	1	1	3	0.67	0.00	1.00
3	5	3	0	2	2	13	0.23	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	5	0.40	0.00	1.00
1	2	1	0	1	1	10	0.10	0.00	1.00
3	4	3	0	1	1	8	0.38	0.00	1.00
3	4	3	0	1	1	8	0.38	0.00	1.00
21	21	17	4	8	4	57	0.37	0.50	1.24
8	7	5	3	5	2	11	0.73	0.60	1.60
2	3	2	0	1	1	1	2.00	0.00	1.00
47	48	35	12	25	13	114	0.41	0.48	1.34
10	14	9	1	6	5	71	0.14	0.17	1.11
13	11	9	4	6	2	18	0.72	0.67	1.44
35	35	26	9	18	9	51	0.69	0.50	1.35
9	12	9	0	3	3	34	0.26	0.00	1.00
12	12	9	3	6	3	16	0.75	0.50	1.33
2	3	2	0	1	1	4	0.50	0.00	1.00
11	8	7	4	5	1	11	1.00	0.80	1.57
2	4	2	0	2	2	3	0.67	0.00	1.00
10	11	8	2	5	3	15	0.67	0.40	1.25
1	2	1	0	1	1	2	0.50	0.00	1.00
488	566	402	86	250	164	1113			

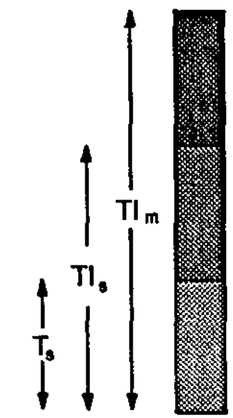




Part Types = 70, Batch Size <= 8, # MC = 8, Strategy = Differential Clustering, Permissible Tool Life = 90%
Manufacturing period = 10-shift,

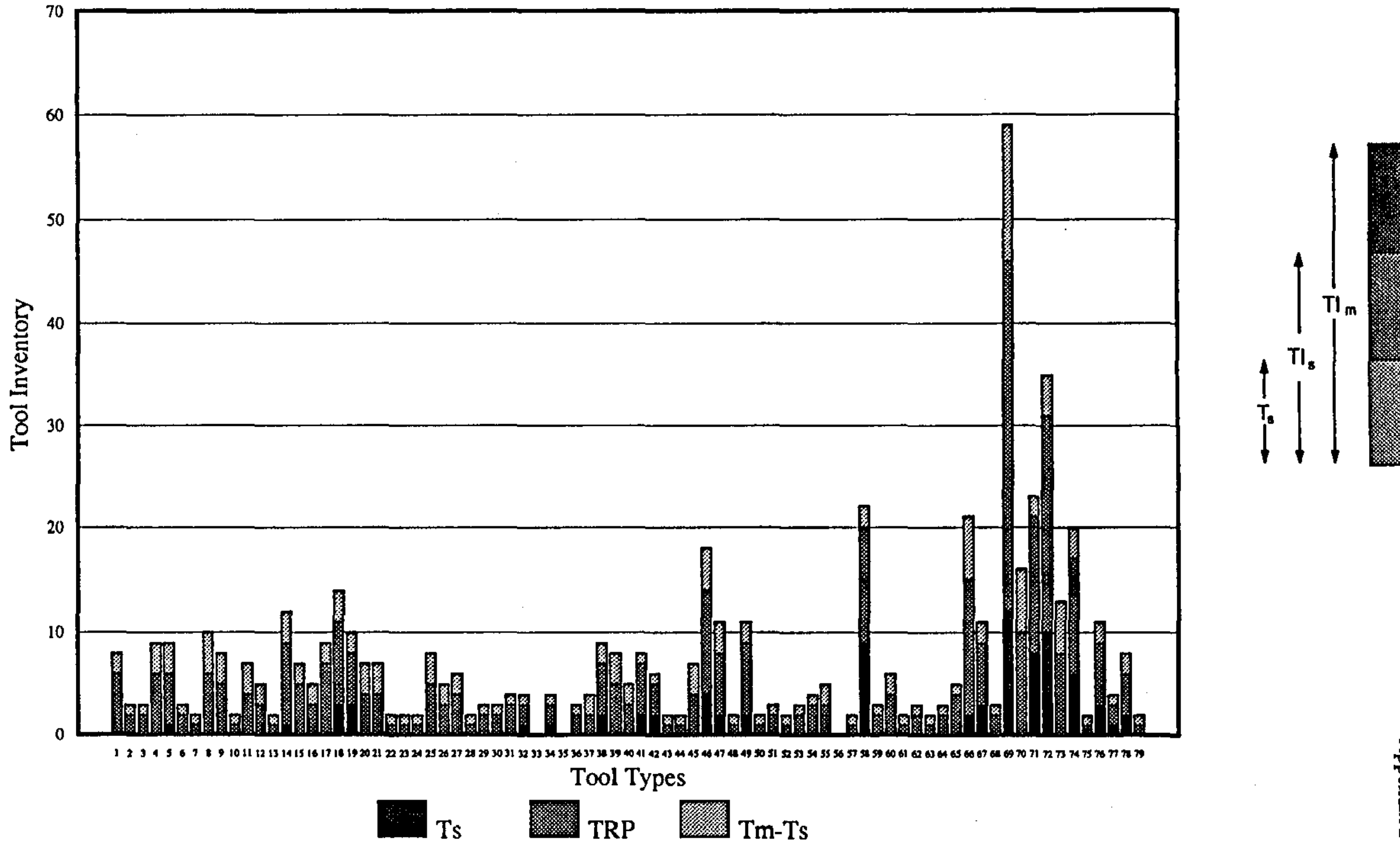
TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
11	9	0	2	2	48	0.19	0	1
3	2	0	1	1	8	0.25	0	1
3	2	0	1	1	3	0.67	0	1
12	9	0	3	3	31	0.29	0	1
9	6	1	4	3	28	0.25	0.25	1.1667
3	2	0	1	1	4	0.50	0	1
2	1	0	1	1	1	1.00	0	1
9	5	0	4	4	22	0.23	0	1
9	6	0	3	3	37	0.16	0	1
2	1	0	1	1	4	0.25	0	1
4	3	2	3	1	14	0.36	0.6667	1.6667
5	3	0	2	2	13	0.23	0	1
2	1	0	1	1	3	0.33	0	1
9	6	1	4	3	28	0.25	0.25	1.1667
6	4	0	2	2	12	0.33	0	1
5	3	0	2	2	12	0.25	0	1
9	7	0	2	2	14	0.50	0	1
12	9	3	6	3	22	0.55	0.5	1.3333
7	5	3	5	2	11	0.73	0.6	1.6
8	5	0	3	3	23	0.22	0	1
9	6	0	3	3	16	0.38	0	1
2	1	0	1	1	1	1.00	0	1
2	1	0	1	1	2	0.50	0	1
2	1	0	1	1	4	0.25	0	1
9	6	0	3	3	10	0.60	0	1
5	3	0	2	2	5	0.60	0	1
7	5	0	2	2	17	0.29	0	1
2	1	0	1	1	2	0.50	0	1
3	2	0	1	1	5	0.40	0	1
3	2	0	1	1	3	0.67	0	1
4	3	0	1	1	5	0.60	0	1
6	3	0	3	3	8	0.38	0	1
0	0	0	0	0	0	0.00	0	0
3	2	1	2	1	3	1.00	0.5	1.5
0	0	0	0	0	0	0.00	0	0
3	2	0	1	1	3	0.67	0	1
4	2	0	2	2	20	0.10	0	1
8	6	2	4	2	21	0.38	0.5	1.3333
8	5	0	3	3	32	0.16	0	1
4	2	0	2	2	8	0.25	0	1
6	4	1	3	2	14	0.36	0.33	1.25
4	3	2	3	1	12	0.42	0.67	1.6667
3	2	0	1	1	3	0.67	0	1
2	1	0	1	1	4	0.25	0	1
6	3	0	3	3	10	0.30	0	1
13	10	4	7	3	23	0.61	0.57	1.4
9	6	2	5	3	21	0.38	0.4	1.3333
2	1	0	1	1	1	1.00	0	1
11	7	1	5	4	8	1.00	0.2	1.1429
2	1	0	1	1	1	1.00	0	1
3	2	0	1	1	4	0.50	0	1
2	1	0	1	1	1	1.00	0	1
3	2	0	1	1	3	0.67	0	1
4	3	0	1	1	5	0.60	0	1
5	3	0	2	2	8	0.38	0	1
0	0	0	0	0	0	0.00	0	0
2	1	0	1	1	1	1.00	0	1
13	11	9	11	2	23	0.87	0.82	1.8182
5	4	0	1	1	3	1.33	0	1
6	4	0	2	2	13	0.31	0	1
2	1	0	1	1	1	1.00	0	1
3	2	0	1	1	5	0.40	0	1
2	1	0	1	1	10	0.10	0	1
4	3	0	1	1	8	0.38	0	1
5	4	0	1	1	8	0.50	0	1
21	15	2	8	6	55	0.31	0.25	1.1333
8	6	3	5	2	11	0.82	0.6	1.5
3	2	0	1	1	1	2.00	0	1
49	34	10	25	15	112	0.39	0.4	1.2941
15	10	0	5	5	70	0.14	0	1
9	7	4	6	2	18	0.61	0.6667	1.5714
29	22	9	16	7	51	0.61	0.5625	1.4091
16	11	0	5	5	34	0.32	0	1
19	11	1	9	8	14	0.86	0.1111	1.0909
2	1	0	1	1	4	0.25	0	1
8	6	3	5	2	10	0.90	0.6	1.5
3	2	1	2	1	4	0.75	0.5	1.5
8	5	2	5	3	15	0.47	0.4	1.4
2	1	0	1	1	2	0.50	0	1
523	355	67	235	168	1094			





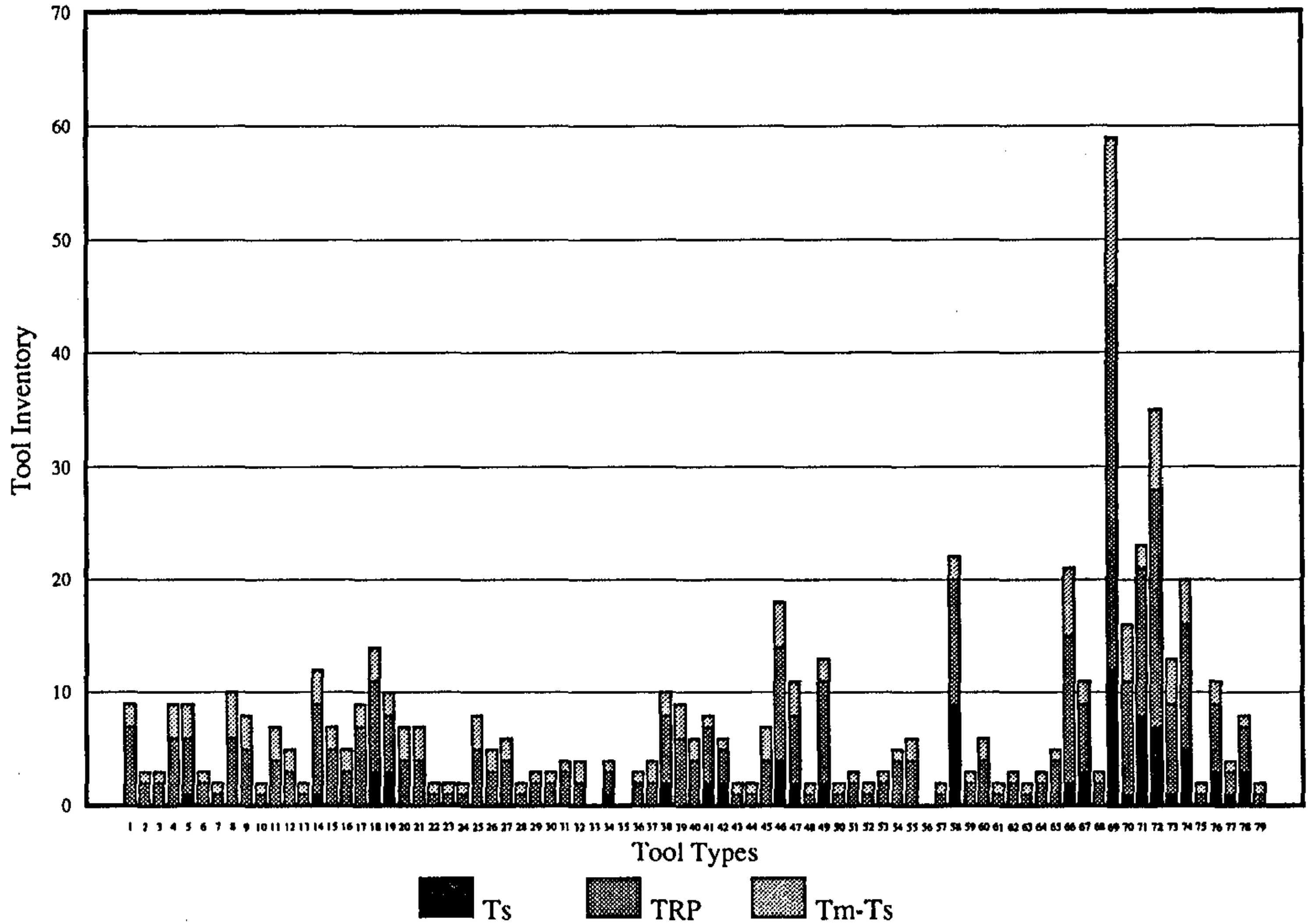
Part Type = 70, # MC = 8, Batch Size <=50, Permissible Tool Life = 90%, Strategy = Differential Clustering.
Manufacturing Period = 10-Shift.

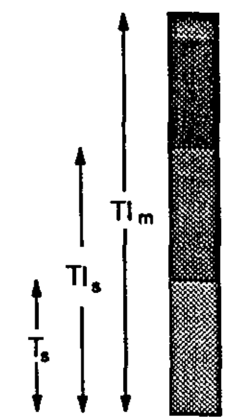
TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
6	8	6	0	2	2	20	0.30	0.00	1.00
2	3	2	0	1	1	5	0.40	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
6	9	6	0	3	3	13	0.46	0.00	1.00
6	8	5	1	4	3	9	0.67	0.25	1.20
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
6	10	6	0	4	4	5	1.20	0.00	1.00
5	8	5	0	3	3	17	0.29	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
4	7	4	0	3	3	5	0.80	0.00	1.00
3	5	3	0	2	2	6	0.50	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
9	11	8	1	4	3	12	0.75	0.25	1.13
5	7	5	0	2	2	6	0.83	0.00	1.00
3	5	3	0	2	2	4	0.75	0.00	1.00
7	9	7	0	2	2	8	0.88	0.00	1.00
11	11	8	3	6	3	14	0.79	0.50	1.38
8	7	5	3	5	2	8	1.00	0.60	1.60
4	7	4	0	3	3	7	0.57	0.00	1.00
4	7	4	0	3	3	8	0.50	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
5	8	5	0	3	3	5	1.00	0.00	1.00
3	5	3	0	2	2	2	1.50	0.00	1.00
4	6	4	0	2	2	9	0.44	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
3	3	2	1	2	1	7	0.43	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	4	2	0	2	2	9	0.22	0.00	1.00
7	7	5	2	4	2	9	0.78	0.50	1.40
5	8	5	0	3	3	15	0.33	0.00	1.00
3	5	3	0	2	2	4	0.75	0.00	1.00
7	6	5	2	3	1	8	0.88	0.67	1.40
5	4	3	2	3	1	6	0.83	0.67	1.67
1	2	1	0	1	1	2	0.50	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
4	7	4	0	3	3	5	0.80	0.00	1.00
14	14	10	4	8	4	16	0.88	0.50	1.40
8	9	6	2	5	3	9	0.89	0.40	1.33
1	2	1	0	1	1	1	1.00	0.00	1.00
9	9	7	2	4	2	19	0.47	0.50	1.29
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
3	5	3	0	2	2	3	1.00	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
20	13	11	9	11	2	30	0.67	0.82	1.82
2	3	2	0	1	1	1	2.00	0.00	1.00
4	6	4	0	2	2	6	0.67	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
15	19	13	2	8	6	19	0.79	0.25	1.15
9	8	6	3	5	2	14	0.64	0.60	1.50
2	3	2	0	1	1	1	2.00	0.00	1.00
46	47	34	12	25	13	56	0.82	0.48	1.35
10	16	10	0	6	6	6	1.67	0.00	1.00
21	15	13	8	10	2	29	0.72	0.80	1.62
31	25	21	10	14	4	39	0.79	0.71	1.48
8	13	8	0	5	5	11	0.73	0.00	1.00
17	14	11	6	9	3	24	0.71	0.67	1.55
1	2	1	0	1	1	1	1.00	0.00	1.00
9	8	6	3	5	2	14	0.64	0.60	1.50
3	3	2	1	2	1	4	0.75	0.50	1.50
6	6	4	2	4	2	10	0.60	0.50	1.50
1	2	1	0	1	1	1	1.00	0.00	1.00
422	498	342	80	236	156	587			



Part Type = 70, Batch Size <= 50, # MC = 4, # Jobs =73, Strategy = Differential Clustering, Permissible Tool Life = 90%.
Manufacturing Period = 10-Shift.

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
7	9	7	0	2	2	20	0.35	0.00	1.00
2	3	2	0	1	1	5	0.40	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
6	9	6	0	3	3	13	0.46	0.00	1.00
6	8	5	1	4	3	9	0.67	0.25	1.20
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
6	10	6	0	4	4	5	1.20	0.00	1.00
5	8	5	0	3	3	17	0.29	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
4	7	4	0	3	3	5	0.80	0.00	1.00
3	5	3	0	2	2	6	0.50	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
9	11	8	1	4	3	12	0.75	0.25	1.13
5	7	5	0	2	2	6	0.83	0.00	1.00
3	5	3	0	2	2	4	0.75	0.00	1.00
7	9	7	0	2	2	8	0.88	0.00	1.00
11	11	8	3	6	3	14	0.79	0.50	1.38
8	7	5	3	5	2	8	1.00	0.60	1.60
4	7	4	0	3	3	7	0.57	0.00	1.00
4	7	4	0	3	3	8	0.50	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
5	8	5	0	3	3	5	1.00	0.00	1.00
3	5	3	0	2	2	2	1.50	0.00	1.00
4	6	4	0	2	2	9	0.44	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	4	3	0	1	1	3	1.00	0.00	1.00
2	4	2	0	2	2	6	0.33	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	4	2	0	2	2	9	0.22	0.00	1.00
8	8	6	2	4	2	9	0.89	0.50	1.33
6	9	6	0	3	3	15	0.40	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
7	6	5	2	3	1	8	0.88	0.67	1.40
5	4	3	2	3	1	6	0.83	0.67	1.67
1	2	1	0	1	1	2	0.50	0.00	1.00
1	2	1	0	1	1	2	0.50	0.00	1.00
4	7	4	0	3	3	5	0.80	0.00	1.00
14	14	10	4	8	4	16	0.88	0.50	1.40
8	9	6	2	5	3	9	0.89	0.40	1.33
1	2	1	0	1	1	1	1.00	0.00	1.00
11	11	9	2	4	2	19	0.58	0.50	1.22
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
4	5	4	0	1	1	3	1.33	0.00	1.00
4	6	4	0	2	2	3	1.33	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
20	13	11	9	11	2	30	0.67	0.82	1.82
2	3	2	0	1	1	1	2.00	0.00	1.00
4	6	4	0	2	2	6	0.67	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	1	2.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
15	19	13	2	8	6	19	0.79	0.25	1.15
9	8	6	3	5	2	14	0.64	0.60	1.50
2	3	2	0	1	1	1	2.00	0.00	1.00
46	47	34	12	25	13	56	0.82	0.48	1.35
11	15	10	1	6	5	7	1.57	0.17	1.10
21	15	13	8	10	2	29	0.72	0.80	1.62
28	28	21	7	14	7	36	0.78	0.50	1.33
9	12	8	1	5	4	12	0.75	0.20	1.13
16	15	11	5	9	4	23	0.70	0.56	1.45
1	2	1	0	1	1	1	1.00	0.00	1.00
9	8	6	3	5	2	14	0.64	0.60	1.50
3	3	2	1	2	1	4	0.75	0.50	1.50
7	5	4	3	4	1	11	0.64	0.75	1.75
1	2	1	0	1	1	1	1.00	0.00	1.00
428	508	350	78	236	158	585			

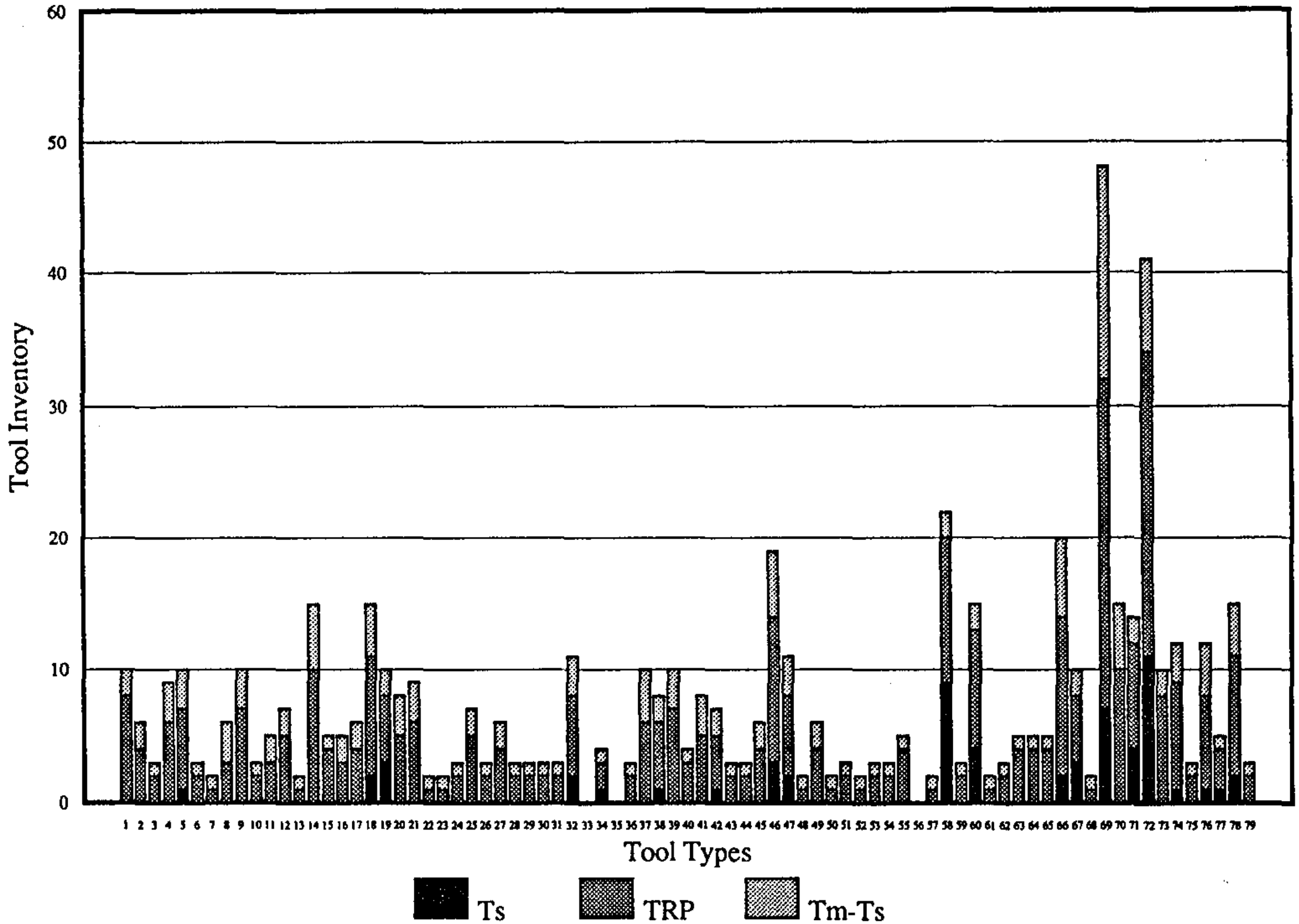


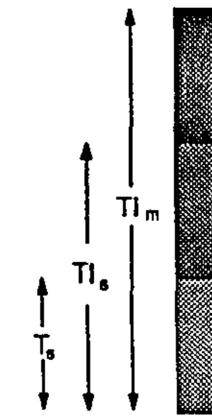


Part Type = 70, Batch Size <= 50, # MC = 6, # Jobs =73, Strategy = Differential Clustering, Permissible Tool Life = 90%.
Manufacturing Period = 10-Shift.

Hybrid Approach Experiment No. 9 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
8	10	8	0	2	2	20	0.40	0.00	1.00
4	6	4	0	2	2	5	0.80	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
6	9	6	0	3	3	13	0.46	0.00	1.00
7	9	6	1	4	3	9	0.78	0.25	1.17
2	3	2	0	1	1	3	0.67	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
3	6	3	0	3	3	5	0.60	0.00	1.00
7	10	7	0	3	3	17	0.41	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
3	5	3	0	2	2	5	0.60	0.00	1.00
5	7	5	0	2	2	6	0.83	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
10	15	10	0	5	5	11	0.91	0.00	1.00
4	5	4	0	1	1	6	0.67	0.00	1.00
3	5	3	0	2	2	4	0.75	0.00	1.00
4	6	4	0	2	2	8	0.50	0.00	1.00
11	13	9	2	6	4	13	0.85	0.33	1.22
8	7	5	3	5	2	8	1.00	0.60	1.60
5	8	5	0	3	3	7	0.71	0.00	1.00
6	9	6	0	3	3	8	0.75	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
5	7	5	0	2	2	5	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	6	4	0	2	2	9	0.44	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
8	9	6	2	5	3	8	1.00	0.40	1.33
0	0	0	0	0	0	0	0.00	0.00	0.00
3	3	2	1	2	1	3	1.00	0.50	1.50
0	0	0	0	0	0	0	0.00	0.00	0.00
2	3	2	0	1	1	2	1.00	0.00	1.00
6	10	6	0	4	4	9	0.67	0.00	1.00
6	7	5	1	3	2	7	0.86	0.33	1.20
7	10	7	0	3	3	15	0.47	0.00	1.00
3	4	3	0	1	1	4	0.75	0.00	1.00
5	8	5	0	3	3	6	0.83	0.00	1.00
5	6	4	1	3	2	5	1.00	0.33	1.25
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	6	4	0	2	2	5	0.80	0.00	1.00
14	16	11	3	8	5	15	0.93	0.38	1.27
8	9	6	2	5	3	9	0.89	0.40	1.33
1	2	1	0	1	1	1	1.00	0.00	1.00
4	6	4	0	2	2	4	1.00	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	4	0.50	0.00	1.00
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
2	3	2	0	1	1	3	0.67	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
0	0	0	0	0	0	0	0.00	0.00	0.00
1	2	1	0	1	1	1	1.00	0.00	1.00
20	13	11	9	11	2	20	1.00	0.82	1.82
2	3	2	0	1	1	2	1.00	0.00	1.00
13	11	9	4	6	2	14	0.93	0.67	1.44
1	2	1	0	1	1	1	1.00	0.00	1.00
2	3	2	0	1	1	2	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
4	5	4	0	1	1	4	1.00	0.00	1.00
4	5	4	0	1	1	5	0.80	0.00	1.00
14	18	12	2	8	6	26	0.54	0.25	1.17
8	7	5	3	5	2	8	1.00	0.60	1.60
1	2	1	0	1	1	1	1.00	0.00	1.00
32	41	25	7	23	16	54	0.59	0.30	1.28
10	15	10	0	5	5	26	0.38	0.00	1.00
12	10	8	4	6	2	14	0.86	0.67	1.50
34	30	23	11	18	7	40	0.85	0.61	1.48
8	10	8	0	2	2	18	0.44	0.00	1.00
9	11	8	1	4	3	9	1.00	0.25	1.13
2	3	2	0	1	1	2	1.00	0.00	1.00
8	11	7	1	5	4	8	1.00	0.20	1.14
4	4	3	1	2	1	4	1.00	0.50	1.33
11	13	9	2	6	4	11	1.00	0.33	1.22
2	3	2	0	1	1	2	1.00	0.00	1.00
423	528	362	61	227	166	571			

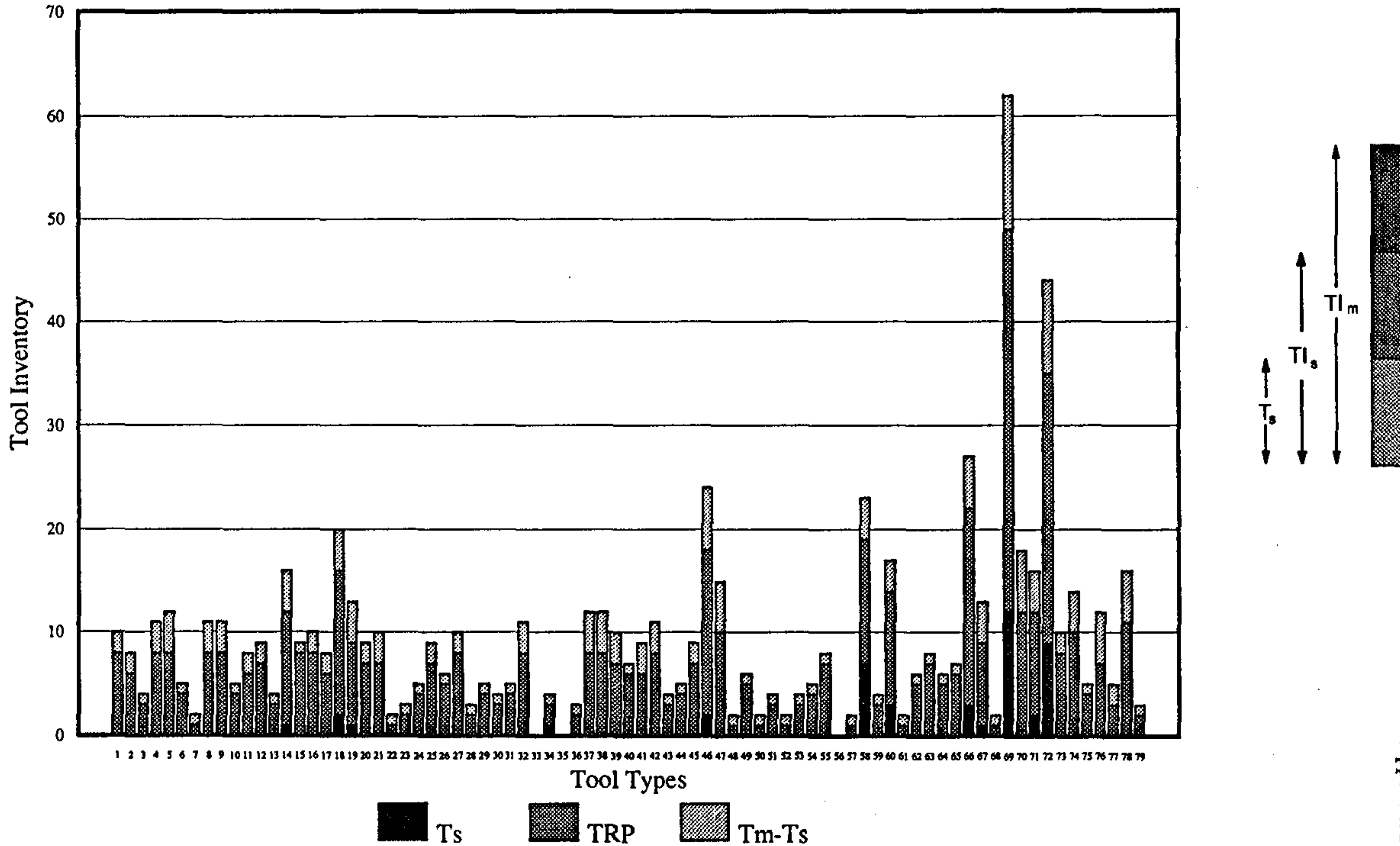




Family III, Large Batch (<=50) 8 MC Experiment. Hybrid Single Tools Kitting Strategy, Manufacturing period = 10-Shift.
The part scheduling rule is EDD.

Hybrid Approach Experiment No. 10 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
8	10	8	0	2	2	48	0.17	0	1.00
6	8	6	0	2	2	8	0.75	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
8	11	8	0	3	3	31	0.26	0	1.00
8	12	8	0	4	4	28	0.29	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
8	11	8	0	3	3	23	0.35	0	1.00
8	11	8	0	3	3	36	0.22	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
6	8	6	0	2	2	12	0.50	0	1.00
7	9	7	0	2	2	13	0.54	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
11	15	11	1	5	4	27	0.41	0.2	1.00
8	9	8	0	1	1	12	0.67	0	1.00
8	10	8	0	2	2	12	0.67	0	1.00
6	8	6	0	2	2	14	0.43	0	1.00
14	18	14	2	6	4	22	0.64	0.33	1.00
8	12	8	1	5	4	9	0.89	0.2	1.00
7	9	7	0	2	2	24	0.29	0	1.00
7	10	7	0	3	3	16	0.44	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
7	9	7	0	2	2	9	0.78	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
8	10	8	0	2	2	17	0.47	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
8	11	8	0	3	3	8	1.00	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	3	2	1	2	1	3	1.00	0.5	1.50
0	0	0	0	0	0	0	0.00	0	0.00
2	3	2	0	1	1	3	0.67	0	1.00
8	12	8	0	4	4	20	0.40	0	1.00
8	12	8	0	4	4	20	0.40	0	1.00
7	10	7	0	3	3	31	0.23	0	1.00
6	7	6	0	1	1	8	0.75	0	1.00
6	9	6	0	3	3	13	0.46	0	1.00
8	11	8	0	3	3	10	0.80	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
7	9	7	0	2	2	10	0.70	0	1.00
16	22	16	2	8	6	22	0.73	0.25	1.00
10	15	10	0	5	5	20	0.50	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	6	0.83	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
7	8	7	0	1	1	8	0.88	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
19	16	12	7	11	4	21	0.90	0.64	1.58
3	4	3	0	1	1	3	1.00	0	1.00
14	14	11	3	6	3	16	0.88	0.5	1.27
1	2	1	0	1	1	1	1.00	0	1.00
5	6	5	0	1	1	5	1.00	0	1.00
7	8	7	0	1	1	10	0.70	0	1.00
5	6	5	0	1	1	8	0.63	0	1.00
6	7	6	0	1	1	8	0.75	0	1.00
19	24	19	3	8	5	57	0.33	0.375	1.00
8	12	8	1	5	4	9	0.89	0.2	1.00
1	2	1	0	1	1	1	1.00	0	1.00
40	50	37	12	25	13	117	0.34	0.48	1.08
12	18	12	0	6	6	72	0.17	0	1.00
12	14	10	2	6	4	16	0.75	0.33	1.20
35	35	26	9	18	9	53	0.66	0.5	1.35
8	10	8	0	2	2	34	0.24	0	1.00
10	14	10	0	4	4	13	0.77	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
7	12	7	0	5	5	8	0.88	0	1.00
3	5	3	0	2	2	3	1.00	0	1.00
11	16	11	0	5	5	13	0.85	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
537	694	512	44	226	182	1082			

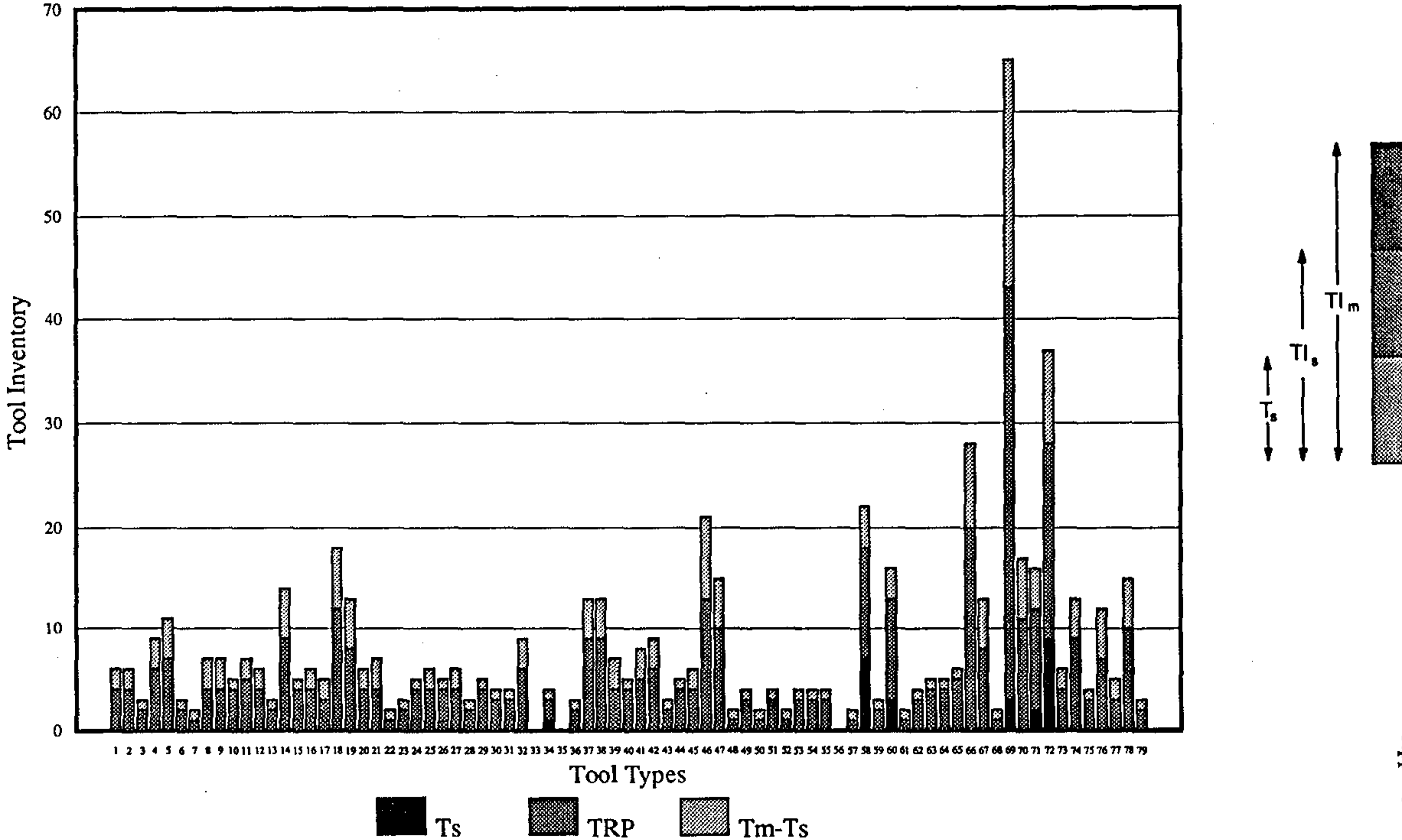


Family III, Small Batch (<=8) 8 MC Experiment. The Manufacturing Period is 10-Shift.
The part scheduling rule is EDD. Hybrid Single Tools Kitting Strategy

Hybrid Approach Experiment No.19 - Tool Inventory

TIs	TIm	TRP	Ts	Tm	(Tm-Ts)	(TIs)fk	TIs/(TIs)fk	Ts/Tm	TIs/TRP
4	6	4	0	2	2	48	0.08	0	1.00
4	6	4	0	2	2	8	0.50	0	1.00
2	3	2	0	1	1	3	0.67	0	1.00
6	9	6	0	3	3	31	0.19	0	1.00
7	11	7	0	4	4	28	0.25	0	1.00
2	3	2	0	1	1	4	0.50	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
4	7	4	0	3	3	23	0.17	0	1.00
4	7	4	0	3	3	36	0.11	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
5	7	5	0	2	2	12	0.42	0	1.00
4	6	4	0	2	2	13	0.31	0	1.00
2	3	2	0	1	1	3	0.67	0	1.00
9	14	9	0	5	5	26	0.35	0	1.00
4	5	4	0	1	1	12	0.33	0	1.00
4	6	4	0	2	2	12	0.33	0	1.00
3	5	3	0	2	2	14	0.21	0	1.00
12	18	12	0	6	6	20	0.60	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
4	6	4	0	2	2	24	0.17	0	1.00
4	7	4	0	3	3	16	0.25	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
4	6	4	0	2	2	9	0.44	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
4	6	4	0	2	2	17	0.24	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
4	5	4	0	1	1	5	0.80	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
3	4	3	0	1	1	5	0.60	0	1.00
6	9	6	0	3	3	8	0.75	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
3	3	2	1	2	1	3	1.00	0.5	1.50
0	0	0	0	0	0	0	0.00	0	0.00
2	3	2	0	1	1	3	0.67	0	1.00
9	13	9	0	4	4	20	0.45	0	1.00
9	13	9	0	4	4	20	0.45	0	1.00
4	7	4	0	3	3	31	0.13	0	1.00
4	5	4	0	1	1	8	0.50	0	1.00
5	8	5	0	3	3	13	0.38	0	1.00
6	9	6	0	3	3	10	0.60	0	1.00
2	3	2	0	1	1	3	0.67	0	1.00
4	5	4	0	1	1	4	1.00	0	1.00
4	6	4	0	2	2	10	0.40	0	1.00
13	21	13	0	8	8	20	0.65	0	1.00
10	15	10	0	5	5	20	0.50	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	6	0.50	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	3	1.00	0	1.00
3	4	3	0	1	1	5	0.60	0	1.00
3	4	3	0	1	1	8	0.38	0	1.00
0	0	0	0	0	0	0	0.00	0	0.00
1	2	1	0	1	1	1	1.00	0	1.00
18	15	11	7	11	4	21	0.86	0.64	1.64
2	3	2	0	1	1	3	0.67	0	1.00
13	13	10	3	6	3	16	0.81	0.5	1.30
1	2	1	0	1	1	1	1.00	0	1.00
3	4	3	0	1	1	5	0.60	0	1.00
4	5	4	0	1	1	10	0.40	0	1.00
4	5	4	0	1	1	8	0.50	0	1.00
5	6	5	0	1	1	8	0.63	0	1.00
20	28	20	0	8	8	54	0.37	0	1.00
8	13	8	0	5	5	8	1.00	0	1.00
1	2	1	0	1	1	1	1.00	0	1.00
43	62	40	3	25	22	108	0.40	0.12	1.08
11	17	11	0	6	6	72	0.15	0	1.00
12	14	10	2	6	4	16	0.75	0.33	1.20
28	28	19	9	18	9	53	0.53	0.5	1.47
4	6	4	0	2	2	34	0.12	0	1.00
9	13	9	0	4	4	13	0.69	0	1.00
3	4	3	0	1	1	4	0.75	0	1.00
7	12	7	0	5	5	8	0.88	0	1.00
3	5	3	0	2	2	3	1.00	0	1.00
10	15	10	0	5	5	13	0.77	0	1.00
2	3	2	0	1	1	2	1.00	0	1.00
439	615	414	25	226	201	1063			

The Hybrid Approach Experiment No.19 - Tool Inventory



Family III, Small Batch (<=8) 4 MC Experiment. The Manufacturing period is 10-Shift. The Permissible Tool Life is 90%.
The part scheduling rule is EDD. Hybrid Single Tools Kitting

Individual Machine Utilization Performance

Tables

(Complementary to Chapter 18)

Ref. No.	Average MC Utilization	Machine Utilization (%)								Comment
		1	2	3	4	5	6	7	8	
W68	98	98	98	95						F1-4 SPT
W17	95	98	90	93	95					F1-4 SPT
W69	92	95	97	95	84	85	86			F1-4 SPT
W70	90	94	77	81	97	82	97	83	90	F1-4 SPT
W71	91	99	89	85						F1-50 SPT
W22	87	99	72	94	79					F1-50 SPT
W72	70	78	61	52	75	51	97			F1-50 SPT
W73	65	69	86	66	40	61	42	51	98	F1-50 SPT
W78	95	99	94	91						F1-50 SPT
W18	95	92	99	94	92					F2-8 SPT
W79	72	68	99	81	68	55	56			F2-8 SPT
W83	93	96	97	89	99	89	87	92	91	F2-8 SPT
W80	97	93	99	99						F2-50 SPT
W21	94	95	90	87	98					F2-50 SPT
W81	93	98	82	94	92	93	90			F2-50 SPT
W82	75	82	66	70	57	81	61	81	98	F2-50 SPT
W94	96	94	93	99						F3-8 SPT
W19	96	99	92	96	97					F3-8 SPT
W95	89	84	93	87	86	99	84			F3-8 SPT
W96	87	81	91	98	83	95	83	79	79	F3-8 SPT
W97	95	87	96	99						F3-50 SPT
W20	95	99	93	91	93					F3-50 SPT
W23	95	93	92	99	94	99	96			F3-50 SPT
W98	86	75	72	93	83	99	86	94	87	F3-50 SPT

Ref. No.	Average MC Utilization	Machine Utilization (%)								Comment
		1	2	3	4	5	6	7	8	
W62	97	98	98	93						F1-4 EDD
W1	92	98	90	90	87					F1-4 EDD
W63	96	99	99	93	92	98	97			F1-4 EDD
W64	92	97	82	84	84	96	95	88	94	F1-4 EDD
W67	92	82	93	98						F1-50 EDD
W66	88	72	98	95	83					F1-50 EDD
W4	88	94	97	61	86	94	82			F1-50 EDD
W65	72	66	95	75	68	72	70	51	55	F1-50 EDD
W74	95	89	97	99						F2-8 EDD
W2	97	99	97	98	92					F2-8 EDD
T24	89	94	98	93	64	86	93			F2-8 EDD
W75	90	97	98	96	94	96	77	75	75	F2-8 EDD
W76	91	88	99	84						F2-50 EDD
W5	95	92	92	98	95					F2-50 EDD
W84	78	99	71	71	69	71	83			F2-50 EDD
W77	72	64	72	78	66	62	62	98	68	F2-50 EDD
W90	96	99	92	97						F3-8 EDD
W41	93	79	99	96	95					F3-8 EDD
W91	95	98	99	92	85	96	97			F3-8 EDD
W25	91	92	98	88	79	85	90	94	94	F3-8 EDD
W92	97	99	99	93						F3-50 EDD
W93	95	91	99	98	88					F3-50 EDD
W6	96	98	92	92	96	94	99			F3-50 EDD
W7	87	87	79	76	80	99	93	91	84	F3-50 EDD
W47	91	92	98	88	80	88	93	97	97	F3-8 EDD (4 + 4)
W49	90	91	98	89	85	81	89	98	93	F3-50 EDD (4 + 4)

Ref. No.	Average MC Utilization	Machine Utilization (%)								Comment
		1	2	3	4	5	6	7	8	
C1	93	89	91	99	90					F1-4 FC
C7	95	85	96	97	95	92	90			F1-4 FC
C8	77	88	76	98	74	71	74	73	68	F1-4 FC
C13	92	89	91	99	90					F1-4 DC
C19	95	85	96	97	95	92	90			F1-4 DC
C20	77	88	76	98	74	71	74	73	68	F1-4 DC
C38	81	99	66	66	93					F1-50 DC
C37	85	87	79	78	79	98	98			F1-50 DC
C34	70	99	75	76	76	37	73	31	90	F1-50 DC
C33	70	99	75	76	76	37	73	31	90	F1-50 FC
C43	48	36	11	59	24	50	83	99	63	F1-PROCESS DC
C44	81	71	98	69	97	97	63	86	58	F1-62 DC
C45	81	98	77	76	83	76	74	90	66	F1-25 DC
C27	85	87	78	96	87	73	79	76	85	F1-10 FC
C29	85	87	78	96	87	73	79	76	85	F1-10 DC
C28	91	81	85	82	92	97	84			F1-10 DC
C3	89	99	76	97	82					F2-8 FC
C15	89	99	76	97	82					F2-8 DC
C9	82	65	91	78	75	99	80			F2-8 FC
C21	82	65	91	78	75	99	80			F2-8 DC
C10	78	70	72	84	97	67	69	67	75	F2-8 FC
C22	78	70	72	84	97	67	69	67	75	F2-8 DC
C39	93	88	94	91	99					F2-50 FC
C40	88	83	83	84	93	98	85			F2-50 DC
C36	85	84	85	85	82	98	84	87	80	F2-50 DC
C35	85	84	85	85	82	98	84	87	80	F2-50 FC
C30	73	74	75	98	66	66	76	53	68	F2-10 FC
C31	73	74	75	98	66	66	76	53	68	F2-10 DC
C46	85	88	97	85	89	82	80	79	79	F2-PROCESS DC
C47	92	84	95	94	96	84	83	98	93	F2-62 DC
C48	83	77	80	73	89	88	74	98	74	F2-25 DC

Ref. No.	Average MC Utilization	Machine Utilization (%)								Comment
		1	2	3	4	5	6	7	8	
C5	92	88	99	90	88					F3-8 FC
C11	87	98	94	85	77	83	85			F3-8 FC
C12	83	88	92	90	82	76	71	79	81	F3-8 FC
C17	92	88	99	90	88					F3-8 DC
C23	87	98	94	85	77	83	85			F3-8 DC
C24	83	88	92	90	82	76	71	79	81	F3-8 DC
C41	93	88	97	98	94					F3-50 DC
C42	89	87	85	80	98	87	88			F3-50 DC
C25	78	99	75	66	75	60	72	74	91	F3-50 DC
C26	78	99	75	66	75	60	72	74	91	F3-50 FC
C49	74	71	88	51	98	66	61	68	74	F3-PROCESS DC
C50	89	92	95	89	81	66	86	98	88	F3-62 DC
C51	95	91	98	92	91	90	95	92	97	F3-25 DC
C52	90	81	87	85	98	97	94	82	84	F3-10 DC
C53	77	99	75	66	75	60	72	74	91	F3-50 DC 4+4

Ref. No.	Average MC Utilization	Machine Utilization (%)								Comment
		1	2	3	4	5	6	7	8	
H1	95	99	94	94	89					F1-4 EDD
H5	84	78	89	88	80					F1-50 EDD
H2	95	92	93	95	99					F2-8 EDD
H6	96	94	97	95	98					F2-50 EDD
H3	96	92	93	95	99					F3-8 EDD
H4	89	85	85	98	90					F3-50 EDD
H7	88	78	96	77	89	99	95			F3-50 EDD
H8	88	78	96	77	89	99	95			F2-50 EDD
H10	91	93	99	88	80	85	91	95	95	F3-8 EDD
H9	85	85	98	83	79	71	88	90	83	F3-50 EDD
H11	93	97	89	92	94					F1-4 SPT
H16	90	97	93	91	82					F1-50 SPT
H12	96	95	95	99	96					F2-8 SPT
H15	90	95	80	98	89					F2-50 SPT
H14	92	84	84	99	99					F3-50 SPT
H17	85	80	78	81	98	82	98			F3-50 SPT
H18	86	96	76	90	85	81	87	82	97	F3-50 SPT
H19	97	99	95	97	96					F3-8 EDD
H20	85	85	77	83	79	84	88	98	83	F3-50 EDD 4+4
H21	95	92	98	98	89					F3-50 EDD
H22	92	93	99	88	80	89	95	98	98	F3-8 EDD (4+4)
H13	87	75	73	84	91	98	91			F3-50 EDD
H23	89	90	84	84	98	86	91			F3-50 EDD

Appendix V

Knowledge-Based Systems

(Complementary to Chapter 6, 8 and 9)

Appendix V
Knowledge Based Systems

V.1 Introduction

This appendix explains the theory and logic of knowledge based systems briefly and the software package used to create the knowledge based tool management design modules.

V.2. Definition of Knowledge Based Systems and KES

There are many formal definitions of Artificial Intelligence (AI). The following definitions have been made by different experts:

"Artificial intelligence is that field of computer science concerned with designing intelligent computer systems; that is a computer system that exhibits the characteristics we associate with intelligence in human behaviour [7].

" AI is the field that aims to understand how computers can be made to exhibit intelligence" [5].

" AI is the science of making machines do things that would require intelligence if done by men" [5] [11].

"AI is the branch of computer science that uses computers to reproduce behaviour usually associated with human intelligence." [10].

Thus the techniques and theoretical results from the field of AI offer a new and exiting technology for solving problem in manufacturing systems.

AI based applications must be integrated with existing manufacturing systems and practices. Much of the current interest in the area of AI applications to manufacturing has been focussed on shop floor automation. One of the significant branch of AI, expert systems, produce intelligent behaviour by operating on the knowledge of a human expert in a well defined application domain. The ability to operate on this knowledge gives the expert system the capability to perform its task at a skill level usually associated with the expert. Because knowledge is the key ingredient in an expert system, such systems are often called knowledge based systems [14].

The Knowledge Engineering System (KES) is an environment and support tool for implementing interactive expert systems. The purpose of the KES developed expert system is to enable users to make decisions related to knowledge-intensive problems as if they had access to a human expert. KES accepts English-like definitions into the knowledge base and converts them into a form suitable for combination without requiring a knowledge of either programming or AI techniques. KES is domain independent, that is, it is not restricted to any knowledge area because the software system and knowledge are strictly separated. This separation allows the development of a variety of knowledge bases which can be utilised by the system to produce operational expert systems. KES has three methods of representing knowledge and making inferences: production rules, statistical pattern classification and hypothesise-and-test. Linear discriminant functions are provided with each inference mechanism [9].

V.3 Design of Knowledge Based Systems

Knowledge based systems, otherwise known as expert systems are computer programs that provide "expert quality" solutions to problems in a specific domain. Since the methodology used is far different from that in conventional programming, knowledge based systems needs a special attention and approach. Generally, the knowledge is extracted from human experts in the domain and an attempt is made to emulate their methodology and performance. The differences between as well as the advantages and disadvantages of expert systems and conventional programs are given in many references including [5], Waterman [15].

An expert system is organised in a way that separates the knowledge which is used to solve the problem domain from the knowledge used to run the program. This collection of domain knowledge is named the knowledge-base and the knowledge which applies the knowledge base to known facts in order to draw conclusions is known as an inference engine, [15] and [8], Figure V.1 shows the architecture of a typical expert system, and its elements are described below.

- **User Interface:** which is used to support the interaction between the expert system and the user as well as give access to the program.

- **Working memory:** which is a dynamic database representing the current stage of the expert system which is being changed either through the user interface or by transition from one stage to another automatically.

- **Knowledge-base:** which is the collection of acts and heuristics that makes up an expert's knowledge. It is represented using a number of ways. The more widely used techniques are rule-based, semantic nets and frame-based methods [7]. The rule-based technique has been used to build the tool management strategy selection module.

- **Inference Engine:** that applies the knowledge to the solution of the actual problem manipulating the knowledge base. It executes the program, controls the order of questions, interprets the given answers and draws conclusion from the known and found knowledge.

- **Explanation facility:** The explanation facility provides two main services. First, it explains to the user why a particular question is asked to make the questions more understandable. The second service is to explain the reasoning behind the conclusions that have been reached.

- **Knowledge Acquisition:** This part enables the knowledge to be entered into the knowledge-base. Using this facility, it is possible to add, change or remove the rule(s) in the knowledge base.

An exploratory development cycle for a rule-based expert system is depicted in Figure V.2 [8].

V.4. Acquiring the Knowledge

When an expert system is built, one of the most important tasks is to acquire the knowledge which forms the core of the knowledge-base. The domain expert provides the knowledge of the problem area. The domain expert is generally someone who has considerable experience in the domain area and understands the nature of the problem as well as the solution techniques. Knowledge, however, may be acquired form many sources, such as, textbooks, reports, case studies, empirical data, personal experience and domain experts.

Much of the tool management strategy selection data has been produced by the tool requirements planning module (see chapter 7) and is transferred via the database or communication file. The working mechanism of the tool issue strategies have been formulated by either observing industry practice of tool management systems or in a different form by the researchers.

The criteria used to make the decision in strategy selection have been chosen by gained personal experience and observed through extensive discussion with the tool management system research group in the laboratory. The detail structure of tool management strategy selection is given in Chapter 8. The data base maintains records involving large volumes of data and represent entities, facts and relationships. Thus, knowledge about the domain may be implicitly represented by the structure of databases [9]. However, rules represent the conditional relationships between stored data and valuable data gathered and more can be inferred by using the rules, so that as a result of knowing more about the problem, more accurate conclusions are hopefully achieved.

In the knowledge acquisition for tool management strategy selection two main sources have been used adopting the approaches such as the knowledge from the tool requirements planning module as well as tool management experts and extracting and deducing the knowledge from published tool management system research papers, theses and other literatures. Various stages of the development of the rules and the relationships between rules as well as development of the decision tree, the wide experience of the research supervisor is one of the many expert advices.

V.5. Representing the Knowledge

In order to solve a problem or make a decision it is necessary to know enough about the problem domain as well as formulate the solution technique(s) used explicitly. At this stage interpretation of the knowledge about the domain and structure of the knowledge representation plays a critical role in expert systems. There are two main aims in representing the knowledge that must be met. First, knowledge should be described in a form appropriate to the expert - the knowledge should be understandable to the expert either verifying, organising, classifying or relating to each other. Second, knowledge should be in the form such that the machine is able to process it. Detail and the advantages of the forms of knowledge representation may be found in the literature [1], [2], [5] and [6].

Since expert systems are related to solving problems, based on how a human expert approaches a task, knowledge about the problem should be explicitly represented in the knowledge base. Therefore, the knowledge base should have all the methods the expert uses to tackle a problem. These methods may include computer programs rules of thumb, theories, logic. When the knowledge is explicitly represented, all the relations and facts stated and the data provided the expert system are able to compute a solution, draw a conclusion or find a way to reach a decision.

V.5.1. Knowledge Representation in KES

KES (Knowledge Engineering System) is a tool kit that has three shells, namely PS (Production Systems), HT (Hypothesize Tests), and BAYES (statistical reasoning). PS has been used to develop the tool management strategy selection module. PS shell uses production rules to represent knowledge. It is particularly well-suited to tool management strategy selection where the domain knowledge is readily translatable to if-then rules.

The format of a rule in PS is:

if
  antecedent
then
  consequent
endif.

An antecedent is a condition expressed in the form of a logical comparison which may be true or false. It is possible to connect multiple antecedent conditions with "AND" and "OR" logical operators to create compound conditions. A consequent contains KES commands and contributes to the value of an attribute.

PS can have up to ten non-mandatory sections, each of which contains and/or manipulates domain knowledge. These sections when used have to follow a fixed order as follows:

1. Constants, 2. Texts, 3. Patterns, 4. Types, 5. Attributes, 6. Classes, 7. Externals, 8. Rules, 9. Demons, 10. Actions.

A knowledge base can be developed using the compulsory sections which are attributes, rules or demons and actions and it is only sections that were intended for use. The KES reference manuals can be referred to for further explanation of the detail of the usage of these KES sections in building knowledge bases.

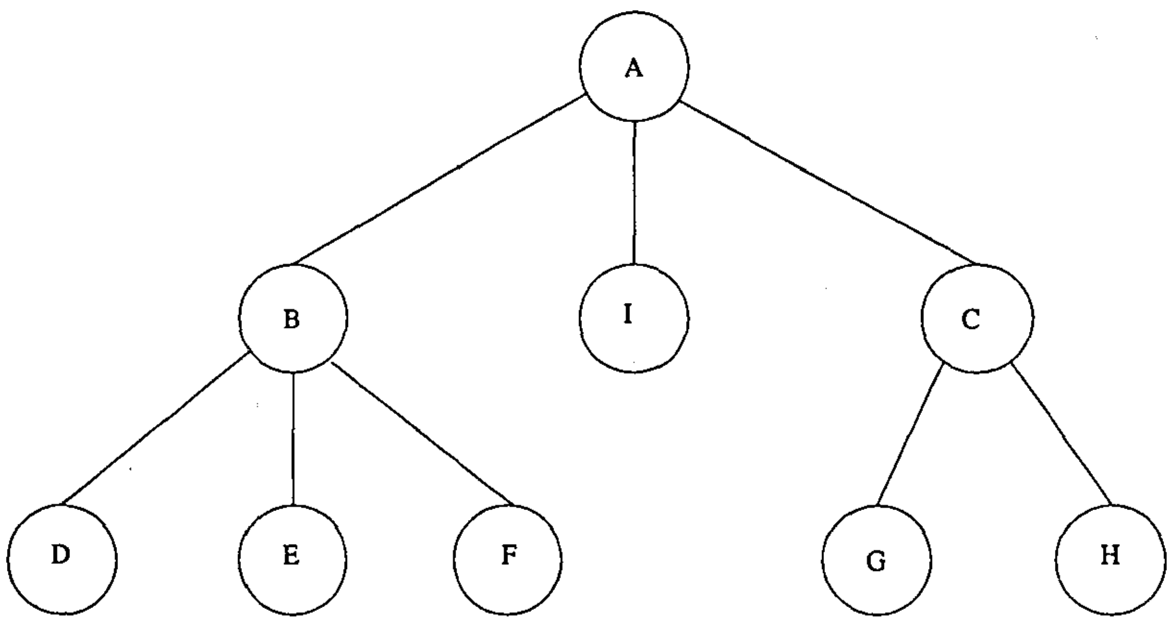
V.5.2. The Inference Engine

The inference engine controls the use of knowledge in the knowledge base, decides how to apply the rules to infer new knowledge and functions the way an expert does when solving problems and making decisions [14]. It acts as an interpreter for the knowledge base. There is no generic approach which suits all applications.

The inference engine used must be appropriate to the application. The knowledge base author needs to select the appropriate inference engine. If the inference engine does not support the appropriate reasoning processes, its use can be a mistake and worse than starting from nothing [8]. KES provides three inference engines, these are production systems (PS), which has been used to create this expert system, hypothesize and test (HT) and statistical reasoning (BAYES).

All three KES inference engines use a similar, goal-driven approach (backward chaining) in making inferences. In addition to goal-driven inferencing, KES also provides an event-driven inferencing (forward chaining) through the use of demons.

In a backward chaining inference, the goal is initially placed in working memory. The system matches rule conclusions with the goal, selecting one rule and placing its premises in the working memory. The process continues with these premises becoming the new goals to match. This hierarchy is a conceptual way of relating attributes in a domain.



The hierarchy expresses the dependencies between the attributes, that is, it identifies which attributes can be used to infer the values of others. The hierarchy contains three inferences attributes: A,B and C. The system's ultimate goal is to obtain and display a value for A. To obtain A, the expert system must first establish the value of B. The expert system establishes these values by setting a subgoal for itself. It decides to first obtain B, then return to the task of determining a value for A. This process is referred to as depth-first backward chaining. As the system proceeds to obtain a value for B, it discovers that it needs to know the values of other attributes first (D,E and F). The system reecognises these as input attributes and automatically asks the end user (or other source such as values read from an external data file) for their values as needed, since these values cannot be inferred from any other attributes. A similar process occurs with the value for C. Finally, knowing the value of B and C, the system completes the initial obtain command and assign a value to A.

More detail knowledge can be obtained from the KES Knowledge-base author manual.

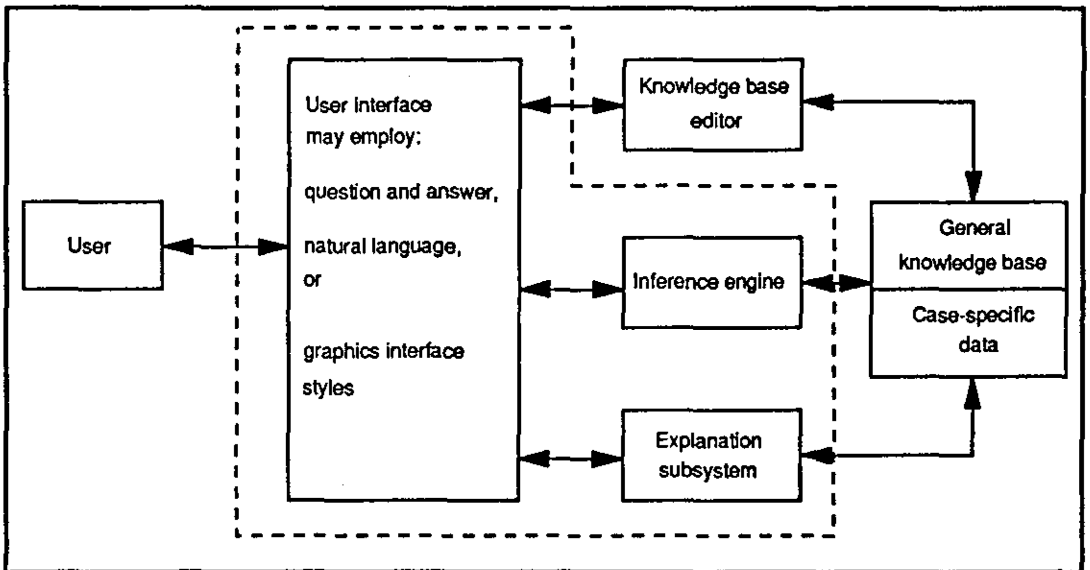


Figure V.1	Architecture of a typical expert system	(Ref. Appedices ref.8)	LUT - FMS Research Group

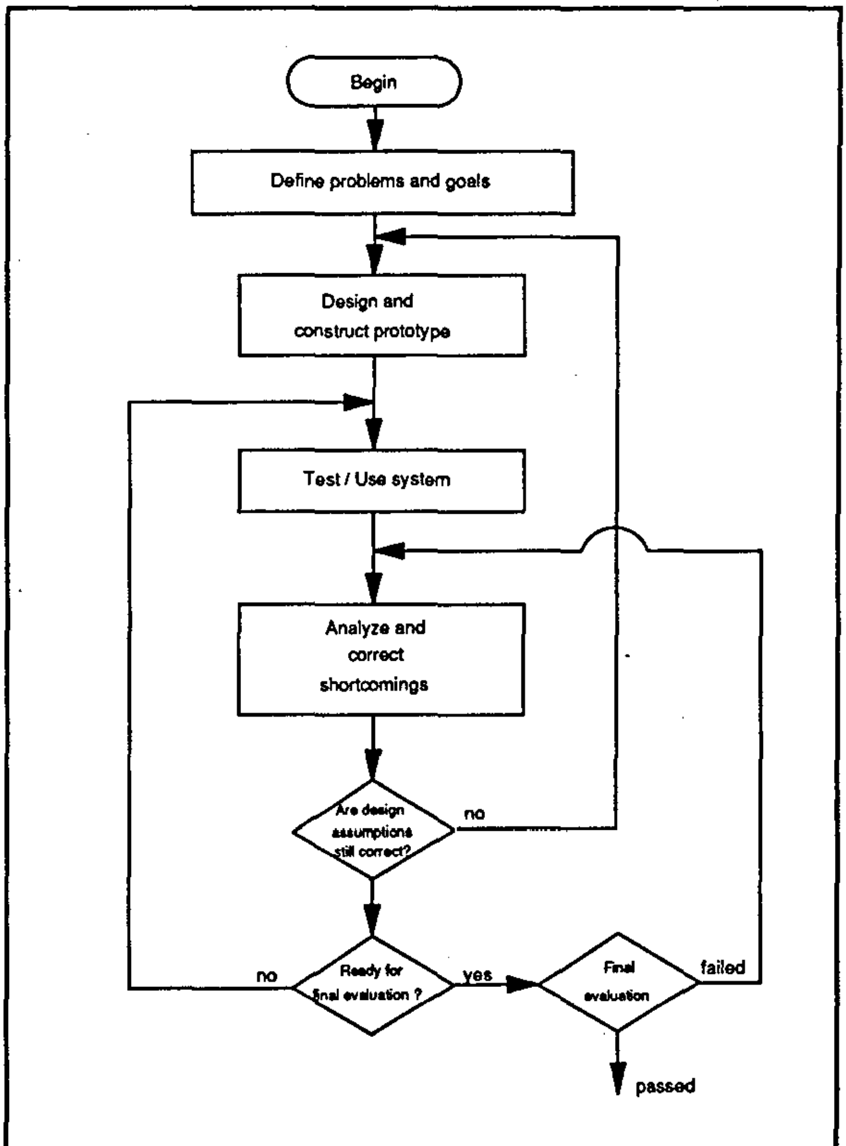


Figure V.2	Exploratory development cycle for rule-based expert systems. (Ref. Appedices ref.8)	LUT - FMS Research Group

Appendix V

Knowledge-Based TMS Strategy Selection Outputs

(Complementary to Chapter 8)

What would you like to do ?

1. Job Scheduling System
2. Tool Management Decision Support System
3. Tool Management Interrogation System
4. Quit

=? 2

What would you like to do ?

1. View global system results for the kitting strategy
2. View global system results for the differential kitting strategy
3. View global system results for the single tools strategy
4. View global system results for the dynamic cluster analysis strategy
5. View global system results for the hybrid single tools strategy
6. View job data
7. View station data
8. Diagnose the system orientation
9. Justify the system orientation
10. Tool Issue Strategy Selection
11. Leave this menu

=? 1

************* CELL KITTING STRATEGY TABLE ***************

Av. Machine Utilisation = 87.324997

Kitting Starategy Number of captive Tools = 152

Kitting Starategy Captive Tooling Cost = 67.5

Number of Machines = 4

Number of Jobs = 17

Tool Movements = 17

Kitting Strategy Throughput Time on MC #1 = 1071.86

Kitting Strategy Throughput Time on MC #2 = 1657

Kitting Strategy Throughput Time on MC #3 = 1374

Kitting Strategy Throughput Time on MC #4 = 1041

Type 'c' to continue or 's' to stop.

2. View global system results for the differential kitting strategy

****
CELL DIFFERANTIAL KITTING STRATEGY TABLE
****
Average Machine Utilisation = 87.324997

Differential Kitting Strategy Number of Captive Tools = 142

Differential Kitting Strategy Captive Tooling Cost = 0

Number of Machines =4

Number of Jobs =17

Differntial Kitting Tool Movements = 17

Differential Kitting Strategy Throughput Time on MC #1 = 1071.86

Differential Kitting Strategy Throughput Time on MC #2 = 1657

Differential Kitting Strategy Throughput Time on MC #3 = 1374

Differential Kitting Strategy Throughput Time on MC #4 = 1041

Type 'c' to continue or 's' to stop.

3. View global system results for the single tools strategy

****
***** SINGLE TOOLS STRATEGY TABLE
****

Average Machine Utilisation = 87.324997

Single Tools Strategy Number of Captive Tools = 142

Single Tools Strategy Captive Tooling Cost = 13

Number of Machines =4

Number of Jobs =17

Single Tools Tool Movements = 17

Single Tools Strategy Throughput Time on MC #1 = 1071.86

Single Tools Strategy Throughput Time on MC #2 = 1657

Single Tools Strategy Throughput Time on MC #3 = 1374

Single Tools Strategy Throughput Time on MC #4 = 1041

Type 'c' to continue or 's' to stop.

4. View global system results for the dynamic cluster analysis strategy

****
DYNAMIC CLUSTER ANALYSIS STRATEGY TABLE
****

Average Machine Utilisation = 91.379547

Cluster Analysis Strategy Number of Captive Tools = 110

Cluster Analysis Strategy Captive Tooling Cost = 0

Number of Machines =4

Number of Jobs =11

Cluster Analysis Tool Movements = 11

Number of Cluster Sets = 11

Dynamic Differential Clustering Throughput Time on MC #1 = 920.29999

Dynamic Differential Clustering Throughput Time on MC #2 = 1321

Dynamic Differential Clustering Throughput Time on MC #3 = 841

Dynamic Differential Clustering Throughput Time on MC #4 = 939

Type 'c' to continue or 's' to stop.

5. View global system results for the hybrid single tools strategy

****
** HYBRID SINGLE TOOLS STRATEGY TABLE
****

Average Machine Utilisation = 87.324997

Hybrid Single Tools Strategy Number of Captive Tools = 127

Hybrid Single Tools Strategy Captive Tooling Cost = 0

Number of Machines =4

Number of Jobs =17

Hybrid Single Tools Tool Movements = 17

Hybrid Single Tools Strategy Throughput Time =5142.8203

Hybrid Single Tools Strategy Lead Time =5142.8203

Type 'c' to continue or 's' to stop.

8. Diagnose the system orientation

****
The system strategy is workpiece oriented strategy <1.00>

****
Type 'c' to continue or 's' to stop.

9. Justify the system orientation

****
For the system orientation workpiece oriented strategy <1.00> the justification is :
****

The value of system strategy = workpiece oriented strategy <1.00>.

This is due to the following knowledge sources:
rule: strategy rule1 is selecting the strategy orientation

Would you like to see the supporting knowledge sources and demons? (y/n)

Name: strategy rule1 is selecting the strategy orientation
Kind of entity: Production Rule

\---

****
*** SYSTEM STRATEGY RULE ***
****
\System Strategy Rule decides the TMS Strategy wheteher Workpiece-Oriented or
Tool-Oriented
\---

strategy rule1 is selecting the strategy orientation:

\This rule basicly helps the users to decide what type of strategy they apply to
\their system. Main criteria applicable are compared and has given. These may not
\always acceptable criteria to every manufacturing system

```
if
     machine support_1 = true and
     machine support_2 = false and
     system_type = true and
     tool availability = true and
     system problems_1 = false and
     system problems_2 = false and
     machine visit = false
  then
     reassert system strategy = workpiece oriented strategy.

  endif

  {explanation:"Workpiece oriented approach considers the case where the
          machines ",
       "are supported with tools related to the actual orders, i.e ",
       "manufacturing system is said to be demand-driven ",
       "A tool rationalisation algorithm is applied to reduce dupplication",
       "of the tools not only within the primary tool store, but also within ",
       "the overall manufacturing system."}.
```

To see an explanation of a rule, type: display attach explanation of a rule name.

Type 'c' to continue or 's' to stop.

10. Tool Issue Strategy Selection

What would you like to do ?

1. Best strategy for overall system
2. Best strategy for the manufacturing cell
3. Best strategy for the manufacturing workstation
4. Justify the selected strategy
5. Exit

=? 1

What is the most essential priority for you ?

1. tool inventory
2. machine utilization
3. throughput time
4. tool movement
5. captive tool size

=? 1

```
*****************************************************************************
 The best strategy is hybrid kitting
*****************************************************************************
```

Type 'c' to continue or 's' to stop.

2. Best strategy for the manufacturing cell

****
The best strategy for the manufacturing cell is hybrid kitting

****
Type 'c' to continue or 's' to stop.

3. Best strategy for the manufacturing workstation

****
Sorry, The best strategy for the workstation has not been determined yet.
****

Type 'c' to continue or 's' to stop.

4. Justify the selected strategy

****
For the selected strategy hybrid kitting the justification is :
****

The value of best strategy = "hybrid kitting".

This is due to the following knowledge sources:
rule: Strategy_rule2 selects the best strategy for overall system

Would you like to see the supporting knowledge sources and demons? (y/n)

Name: Strategy_rule2 selects the best strategy for overall system
Kind of entity: Production Rule

\--

```
Strategy_rule2 selects the best strategy for overall system:

SR:strategy,  ST:strategy

  if
    ST # SR and
    system strategy = workpiece oriented strategy  or
    system strategy = tool oriented strategy and
    user priority = tool inventory and
    SR>tool inventory lt ST>tool inventory and
    SR>captive tool size lt ST>captive tool size

  then
    reassert best strategy = SR.

  endif.
```

To see an explanation of a rule, type: display attach explanation
of a rule name.

Type 'c' to continue or 's' to stop.

****

For the selected strategy hybrid kitting the justification is :

The value of cell strategy = "hybrid kitting".

This is due to the following knowledge sources:
rule: Cell strategy_rule2 selects the best strategy for the related cell configuration

Would you like to see the supporting knowledge sources and demons? (y/n) y

Name: Cell strategy_rule2 selects the best strategy for the related cell configuration

Kind of entity: Production Rule

\--

```
 Cell strategy_rule2 selects the best strategy for the related cell
 configuration:

 SR:strategy, ST:strategy

     if
        ST#SR and
        ST>strategy name # "none" and
        SR>strategy name # "none" and
        SR>tool inventory le ST>tool inventory and
        SR>average mc utilization ge ST>average mc utilization or
        SR>cell throughput time le ST>cell throughput time and
        SR>cell tool movement lt ST>cell tool movement or
        SR>cell captive tool size lt ST>cell captive tool size
     then
        reassert cell strategy = SR.

     endif.
```

To see an explanation of a rule, type: display attach explanation of a rule name.

Type 'c' to continue or 's' to stop.

****

Sorry, best strategy for the workstation has not been determined yet.
It is not possible to justify the selected stratey at the moment

****

Type 'c' to continue or 's' to stop.

Appendix VI

TMS Interrogation System Outputs

(Complementary to Chapter 9)

What would you like to do ?

1. Job Scheduling System
2. Tool Management Decision Support System
3. Tool Management Interrogation System
4. Quit

=? 3

What would like to do ?

1. System Performance Analysis
2. System Operation Problems and_Fault Detection
3. Exit

=? 1

What would you like to do ?

1. Manufacturing Workstation Utilization
2. CTS Utilization
3. STS Utilization
4. PTS Utilization
5. Tool Utilization
6. Transporter Utilization
7. Throughput_and Lead Time Report
8. Exit

=? 1

************ STATION UTILIZATION TABLE **************

```
Station       : dummy
Group         :
Jobs Done     : 0
Utilisation   : 0
Worked        : 0

Station       : stations1
Group         : 1
Jobs Done     : 3
Utilisation   : 73.254166
Worked        : 1054.86

Station       : stations2
Group         : 1
Jobs Done     : 6
Utilisation   : 98.085278
Worked        : 1479.08

Station       : stations3
Group         : 1
Jobs Done     : 4
Utilisation   : 92.85833
Worked        : 1337.1599

Station       : stations4
Group         : 1
Jobs Done     : 4
```

Utilisation : 70.334724
Worked : 1012.82

Total Machining time for Station 1: 987.40002

Total Machining time for Station 2: 1479

Total Machining time for Station 3: 1250

Total Machining time for Station 4: 926

Type 'c' to continue or 's' to stop.

2. CTS Utilization

****
Total tools have been taken from CTS in Kitting Strategy are : 152

Total sister tools used from CTS in Kitting Strategy are : 21

Total worn tools during the operations in Kitting Strategy are : 21

****

Total tools have been taken from CTS in Differential Kitting Strategy are : 142

Total sister tools used from CTS in Differential Kitting Strategy are : 21

Total worn tools during the operations in Differentail Kitting Strategy are : 21

****
Total tools have been taken from CTS in Single Tools Strategy are : 142

Total sister tools used from CTS in Single Tools Strategy are : 21

Total worn tools during the operations in Single Tools Strategy are : 21

****
Total tools have been taken from CTS in Dynamic Cluster Analysis are : 110

Total sister tools used from CTS in Dynamic Cluster Analysis are : 16

Total worn tools during the operations in Dyanmic Cluster Analysis are : 16

****
Total tools have been taken from CTS in Hybrid Single Tools Strategy are : 127

Total sister tools used from CTS in Hybrid Single Tools Strategy are : 21

Total worn tools during the operations in Hybrid Single Tools Strategy are : 21

****

Type 'c' to continue or 's' to stop.

3. STS Utilization

Total used tool in STS1 is : 152

Total used tool in STS2 is : 0

Total number of worn tools in STS1 are : 21

Total number of worn tools in STS2 are : 0

Total number of sister tools used in STS1 are : 21

Type 'c' to continue or 's' to stop.

4. PTS Utilization

****

Total tools have been loaded and unloaded on PTS1 in Kitting strategy are : 26

Total sister tools used on PTS1 in Kitting Strategy are : 2

Total worn tools during the operations on PTS1 in Kitting Strategy are : 2

****

Total tools have been loaded and unloaded on PTS2 in Kitting strategy are : 63

Total sister tools used on PTS2 in Kitting Strategy are : 13

Total worn tools during the operations on PTS2 in Kitting Strategy are : 13

****

Total tools have been loaded and unloaded on PTS3 in Kitting strategy are : 31

Total sister tools used on PTS3 in Kitting Strategy are : 4

Total worn tools during the operations on PTS3 in Kitting Strategy are : 4

****

Total tools have been loaded and unloaded on PTS4 in Kitting strategy are : 32

Total sister tools used on PTS4 in Kitting Strategy are : 2

Total worn tools during the operations on PTS4 in Kitting Strategy are : 2

****

Total tools have been loaded and unloaded on PTS1 in Diff. Kitting strategy are: 24

Total sister tools used on PTS1 in Diff. Kitting Strategy are : 2

Total worn tools during the operations on PTS1 in Diff. Kitting Strategy are : 2

****

Total tools have been loaded and unloaded on PTS2 in Diff. Kitting strategy are : 58

Total sister tools used on PTS2 in Diff. Kitting Strategy are : 13

Total worn tools during the operations on PTS2 in Diff. Kitting Strategy are :13

****

Total tools have been loaded and unloaded on PTS3 in Diff. Kitting strategy are : 30

Total sister tools used on PTS3 in Diff. Kitting Strategy are : 4

Total worn tools during the operations on PTS3 in Diff. Kitting Strategy are : 4

****

Total tools have been loaded and unloaded on PTS4 in Diff. Kitting strategy are : 30

Total sister tools used on PTS4 in Diff. Kitting Strategy are : 2

Total worn tools during the operations on PTS4 in Diff. Kitting Strategy are : 2

****

Total tools have been loaded and unloaded on PTS1 in Single Tools Strategy are: 24

Total sister tools used on PTS1 in Single Tools Strategy are :2

Total worn tools during the operations on PTS1 in Single Tools Strategy are :2

****

Total tools have been loaded and unloaded on PTS2 in Single Tools Strategy are: 58

Total sister tools used on PTS2 in Single Tools Strategy are :13

Total worn tools during the operations on PTS2 in Single Tools Strategy are :13

****

Total tools have been loaded and unloaded on PTS3 in Single Tools Strategy are: 30

Total sister tools used on PTS3 in Single Tools Strategy are :4

Total worn tools during the operations on PTS3 in Single Tools Strategy are : 4

****

Total tools have been loaded and unloaded on PTS4 in Single Tools strategy are: 30

Total sister tools used on PTS4 in Single Tools Strategy are : 2

Total worn tools during the operations on PTS4 in Single Tools Strategy are : 2

****

Total tools have been loaded and unloaded on PTS1 in Dynamic Cluster Analysis are : 0

Total sister tools used on PTS1 in Dynamic Cluster Analysis are :0

Total worn tools during the operations on PTS1 in Dynamic Cluster Analysis are : 0

****

Total tools have been loaded and unloaded on PTS2 in Dynamic Cluster Analysis are : 0

Total sister tools used on PTS2 in Dynamic Cluster Analysis are :0

Total worn tools during the operations on PTS2 in Dynamic Cluster Analysis are: 0

****

Total tools have been loaded and unloaded on PTS3 in Dynamic Cluster Analysis are : 0

Total sister tools used on PTS3 in Dynamic Cluster Analysis are :0

Total worn tools during the operations on PTS3 in Dynamic Cluster Analysis are : 0

****

Total tools have been loaded and unloaded on PTS4 in Dynamic Cluster Analysis are :0

Total sister tools used on PTS4 in Dynamic Cluster Analysis are :0

Total worn tools during the operations on PTS4 in Dynamic Cluster Analysis are: 0

****

Total tools have been loaded and unloaded on PTS1 in Hybrid Single Tools Strategy are : 22

Total sister tools used on PTS1 in Hybrid Single Tools Strategy are : 2

Total worn tools during the operations on PTS1 in Hybrid Single Tools Strategy are : 2

****

Total tools have been loaded and unloaded on PTS2 in Hybrid Single Tools Strategy are : 46

Total sister tools used on PTS2 in Hybrid Single Tools Strategy are : 13

Total worn tools during the operations on PTS2 in Hybrid Single Tools Strategy are : 13

****

Total tools have been loaded and unloaded on PTS3 in Hybrid Single Tools Strategy are : 30

Total sister tools used on PTS3 in Hybrid Single Tools Strategy are :4

Total worn tools during the operations on PTS3 in Hybrid Single Tools Strategy are :4

****

Total tools have been loaded and unloaded on PTS4 in Hybrid Single Tools strategy are :29

Total sister tools used on PTS4 in Hybrid Single Tools Strategy are :2

Total worn tools during the operations on PTS4 in Hybrid Single Tools Strategy are :2

****

Type 'c' to continue or 's' to stop.

5. Tool Utilization

****

Total tools are used in case of using Kitting Strategy is :152

Kitting Strategy Tooling Cost is :67.5

Total sister tools used in Kitting strategy are : 21

Total worn tools in Kitting strategy are : 21

****

Total tools are used in case of using Diff. Kitting strategy is :142

Differential Kitting Strategy tooling cost :0

Total sister tools used in Diff Kitt Strategy are :19

Total worn tools used in Diff Kitting Strategy :19

****

Total tools are used in case of using Single Tools Strategy is :142

Single Tools strategy tooling cost is :13

Total sister tools used in Single Tools Strategy :19

Total number of worn tools in Single Tools Strategy :19

****

Total tools are used in case of using Hybrid Single Tools Strategy is :127

Hybrid Single Tools Strategy tooling cost is :13

Total sister tools used in Hybrid Single Tools Strategy :19

Total number of worn tools in Hybrid Single Tools Strategy :19

****

Total tools are used in case of using Dynamic Cluster Analysis is :110

Cluster Analysis tooling cost :0

Total sister tools used in Dynamic Cluster Analysis :16

Total number of worn tool size in Dynamic Cluster Analysis :16

****

Type 'c' to continue or 's' to stop.

6. Transporter Utilization

****

Transporter is used 0.0013898 of the Manufacturing Period

Number of times Transporter visited to the Cell in Kitt Strategy is :23

Number of times Transporter visited to the Cell in Diff Kitt Str is : 20

Number of times Transporter visited to the Cell in Hybrid Single Tools Str is :20

Number of times Transporter visited the Cell in Dynamic Cluster Analysis is : 16

Type 'c' to continue or 's' to stop.

****

Throughput Time is : 1625.08

Suggestable Due Date is : 1625.08

****

Type 'c' to continue or 's' to stop.

What would like to do ?

1. System Performance Analysis
2. System Operation Problems and_Fault Detection
3. Exit

=? 2

What would you like to do ?

1. Manufacturing cell problem
2. Manufacturing workstation problem
3. Tool store problem
4. Tooling problem
5. Justify the manufacturing problem
6. Justify the tooling problem
7. Justify the mc problem
8. Justify the tool store problem
9. Provide the solution
10. Justify the solution
11. Exit

=? 1

****
****
The Flexible Manufacturing Cell Problem is tool load_unload too long <1.00>
****
****

Type 'c' to continue or 's' to stop.

2. Manufacturing workstation problem

What is the acceptable tool setup time for the station ?
(Enter a number)
=? 2.5

What is the acceptable PTS index time for this station ?
(Enter a number)
=? 0.5

****
****
The Flexible Manufacturing Workststion Problem is machine utilisation is low<1.00>
****
****

Type 'c' to continue or 's' to stop.

3. Tool store problem

****
*
The Flexible Manufacturing Cell under this Configuration has no Tool Store Problem
****
*

Type 'c' to continue or 's' to stop.

4. Tooling problem

What amount of_tools should be available for future production ?
(Enter a number)
=? 30

What size is the company tool inventory ?
(Enter a number)
=? 200

What amount of_tools should be available for future production ?
(Enter a number)
=? 30

What size is the company tool inventory ?
(Enter a number)
=? 200

critical tool level
(Enter a number)
=? 20

current critical tool size
(Enter a number)
=? 20

current sister tool size
(Enter a number)
=? 20

Has any tool broken during the machining operation ?
1. true
2. false
=? 2

****
****
The Tooling Problem is tool has worn <1.00>
****
****

Type 'c' to continue or 's' to stop.

5. Justify the manufacturing problem

****
****
For the Manufacturing Problem tool load_unload too long <1.00> the justification is :
****
****

The value of manufacturing problem = tool load_unload too long <1.00>.

This is due to the following knowledge sources:

rule: manufacturing cell problem rule17

Would you like to see the supporting knowledge sources and demons? (y/n) y

Name: manufacturing cell problem rule17
Kind of entity: Production Rule

\\---

manufacturing cell problem rule17:

if
maximum tl ld_unld time gt acceptable tl ld_unld time
then
reassert manufacturing problem = tool load_unload too long.

endif.

To see an explanation of a rule, type: display attach explanation of a rule name.

Type 'c' to continue or 's' to stop.

8. Justify the tool store problem

****
*****
Any Manufacturing problem has not been determined at the moment.
****
*****

Type 'c' to continue or 's' to stop.

9. Provide the solution

****
****
For the Flexible Manufacturing Cell Problem A suggested solution is :
****
****

reduce part setup time <0.25>
use the alternative job sequence <0.20>
use the alternative job route <0.20>
reduce part load_unload time <0.10>
reduce the tool setup time <0.10>
reduce tool load_unload time <0.05>
reduce station tool setup time <0.05>
increase the load_unload mechanism efficiency <0.05>

Type 'c' to continue or 's' to stop.

****
****
For the Tool Problem A suggested solution is :
****
****

use a new tool<0.5>

sister_tools_needed<0.5>

10. Justify the solution

****
****

For the Manufacturing Problem reduce part setup time <0.25>, use the alternative job sequence <0.20>, use the alternative job route <0.20>, reduce part load_unload time <0.10>, reduce the tool setup time <0.10>, reduce tool load_unload time <0.05>, reduce station tool setup time <0.05> and increase the load_unload mechanism efficiency <0.05> the justification is :

****
****

The value of remedy = reduce part setup time <0.25>
  & use the alternative job sequence <0.20>
  & use the alternative job route <0.20>
  & reduce part load_unload time <0.10> & reduce the tool setup time <0.10>
  & reduce tool load_unload time <0.05>
  & reduce station tool setup time <0.05>
  & increase the load_unload mechanism efficiency <0.05>.

This is due to the following knowledge sources:

rule: machine utilisation is low problem solution

Would you like to see the supporting knowledge sources and demons? (y/n) y

Name: machine utilisation is low problem solution
Kind of entity: Production Rule

\---

```
 machine utilisation is low problem solution:

 if
   mc problem = machine utilisation is low
 then

   reassert remedy = reduce part load_unload time<0.1>|
              reduce tool load_unload time<0.05>|
              reduce part setup time<0.25>|
              reduce the tool setup time<0.1>|
              reduce station tool setup time<0.05>|
              increase the load_unload mechanism efficiency<0.05>|
              use the alternative job sequence<0.2>|
              use the alternative job route<0.2>.

              endif.
```

To see an explanation of a rule, type: display attach explanation of a rule name.

Type 'c' to continue or 's' to stop.

****
****

For the Tooling Problem use a new tool<0.5>sister_tools_needed<0.5> the justification is:

```
\*************************************************************************

  The value of remedy = use a new tool<0.5>|sister_tools_needed<0.5>

  This is due to following knowledge sources:

  rule:worn tool problem solution

  Would you like to see  the supporting knowledge sources and demons? (y/n) y

  Name:tool has worn problem solution
  Kind of entity:Production Rule

\---------------------------------------------------------------------------


    worn tool problem solution:

   if
tooling problem = tool has worn
   then
      reassert remedy = use a new
tool<0.5>|sister_tools_needed<0.5>.


   endif.

 To see an explanation of a rule, type:display attach explanation
of a rule name.

 Type 'c' to continue or 's' to stop.


What would you like to do ?

   1. Job Scheduling System
   2. Tool Management Decision Support System
   3. Tool Management Interrogation System
   4. Quit
=? 4

Type 'n' for another case or 's' to stop

Ready for command: s

KES - Copyright 1990, Software Architecture & Engineering, Inc.
```

Appendix VII

Design of Workpiece Oriented Strategies - The Taguchi Method

(Complementary to Chapter 7 & 13)

Appendix VII
Design of Workpiece Oriented Strategies - The Taguchi Method

VII.1 Introduction

For the design of the computational experiments a well known design method, The Taguchi Method has been used. This appendix presents the Taguchi method and the factors and the variables of factors involved in the experiments.

VII.2 Overview of The Taguchi Method

The Taguchi method offers a new powerful design methodology. First, it is a disciplined way of developing a product or investigating complex problems. Second, it provides a cost effective investigation of available alternatives. The technique is applied in four steps as shown in [12], Figure VII.1.

1- Brainstorming the design parameters primarily important

2- Design and conduct the experiment

3- Analyse the results to determine the optimum conditions

4- Run confirmatory test(s) using the optimum conditions.

Brainstorming is the pre-design effort used to understand problem structure, characteristics, elements, limitations and reasons as well as to understand the design effort and objectives. Many possible factors are believed to affect the design and to reflect each of the factors and minimize the uncontrollable factors, it is strongly recommended to give full thought to the problem. This will make clear the next step and will reduce the risk that would be faced. Although there are no strict guide-lines it is suggested that the first step is to understand problem broadly and to know the capabilities and limitations. (Reference to Chapter 12)

The Taguchi method is designed according to some strict rules. A set of orthogonal arrays (OA) are used to design experiments. In many situations, a standard OA is modified to suit a particular experiment requiring factors of mixed levels. The process of experiment design includes selecting the suitable OA, assigning the factors to the appropriate columns and determining the conditions for the individual experiments. When noise factors are included in the experiments, the condition of the noise factors for each individual experiment is also determined. In the next phase, analysis of variance(ANOVA) is performed on the result. ANOVA study identifies the relative influence of the factors in discrete terms.

Although the Taguchi method suggests a reasonable number of design experiments in comparison to the number of factorial experiment, it does not guarantee optimum or useful design experiments.

VII.3 Design Factors

The following design factors listed are those of influence the tool management system design.

A: Number of Machines

B: Part Scheduling Rules

C: Tool Issue Strategies

D: Part Batch Size

E: Size of Job List

F: Manufacturing Period Length

G: Permissible Tool Life

H: Machine Magazine Capacity

VII.4 Level of Variables

The level of variables have been determined as mixed quantitative and qualitative. The qualitative variables later are transformed into quantitative values. In order to transform qualitative values into quantitative values, there is no strict rule and this process mostly depends on experience and common practice which is evident in manufacturing industry.

A: Number of Machines: 3 to 8 machines are laid out in six level variables that are evident in most modern manufacturing facility examples such as Kolb and Yamazaki manufacturing cells.

B: Part Scheduling Rules: Four different part scheduling rules are practiced and laid out in four variables.

C: Tool Issue Strategies : Three workpiece-oriented strategies, full kitting, differential kitting and single tools kitting are considered and laid out in three variables.

D: Part Batch Size : Two qualitative values are assigned. These are small batch and large batch sizes. Considering manufacturing practice, a small batch is allowed up to 8 components and the large batch is allowed up to 50 components.

E: Size of Job List: Three qualitative values are assigned, these are short list, medium list and long list. 15 part types are in the short list, 40 part types in medium list and 70 part types in long list are considered as the quantitative values.

F: Manufacturing Period : Three different manufacturing period, short, medium and long are considered. Short term as one shift, medium term as three-shift and long term as ten-shift are accepted as the manufacturing period length.

G: Permissible Tool Life : Three different levels of permissible tool life have been practiced, these are: 90%, 75% and 50% as evident in manufacturing industry.

H: Machine Magazine Capacity: Two different machine capacities are considered which are evident in most modern workstations. These are 60-tool capacity and 120-tool capacity.

VII.5 Orthogonal Arrays:

Eight main factors with different levels of variables ranging from two to six levels, have a total 18 degree-of-freedom (DOF) and the nearest suitable orthogonal array (OA) which contains 2-level variables is used to determine the individual experiment parameter (main factor) combinations. However, this OA is not matched to our design of experiment problem and it is necessary to modify the original OA to convert it into a suitable OA which should contain $L_{18}(6^1 \times 4^1 \times 3^4 \times 2^2)$ OA to suit our problem. The original OA matrix and the modified OA matrix are presented in Table VII.1 and VII.2 respectively.

VII.6 Test of Experiments

32 experiments have been conducted, each of which has different factor combinations. Although the Taguchi method reduces the great number of factorial combinations to a reasonable number of experiments, later most of the experiments are considered as unhelpful to the analysis

and conclusions. Therefore, some additional experiments are created by the author apart from the Taguchi method suggested experiments but inspired by the Taguchi method. The new experiments are designed in a similar way to the ones the Taguchi method suggested.

VII.7 Statistical Analysis of Test Results

Although the Taguchi method suggests two steps to analyse the experimental results, since most of the Taguchi suggested experiments are dismissed due to an unhelpful combination of parameters, the statistical analysis of the test results lost its importance and has been omitted.

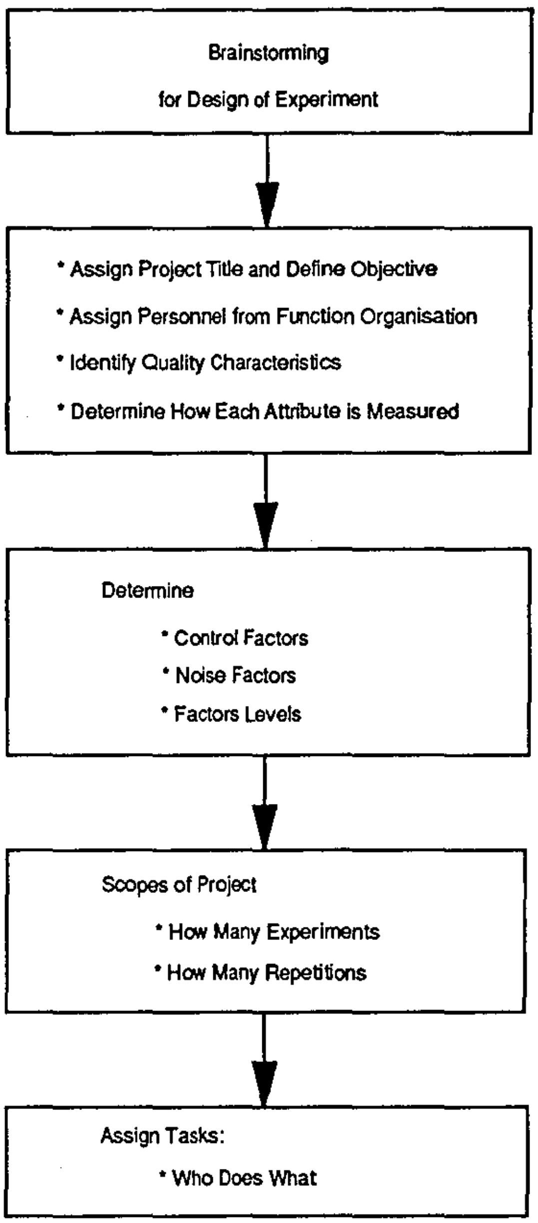


Figure VII.1 Agenda for a brainstorming session in Taguchi Method

L_{32} (2^{31}) Orthogonal Array

Expt.	Column																														
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
4	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1
5	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
6	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1
7	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
8	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2
9	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
10	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1
11	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
12	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2
13	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
14	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2
15	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
16	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	2	2	1	1	1	1	2	2	1	1	2	2	2	2	1	1
17	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
18	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1
19	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
20	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2
21	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
22	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2
23	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
24	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	1	2	1	2	2	1	2	1
25	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
26	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2
27	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
28	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1
29	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
30	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1
31	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1
32	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	2	1	1	2	1	2	2	1	1	2	2	1	2	1	1	2

Table VII.1 32-Column Orthogonal Array Table

Modified Orthogonal Array

Expt. No.	Column 1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2
3	1	2	1	2	1	1	1	1
4	1	2	1	2	1	1	1	2
5	2	4	1	1	1	1	1	1
6	2	4	1	1	1	1	1	2
7	2	2	1	2	1	1	1	1
8	2	2	1	2	1	1	1	2
9	2	4	2	2	1	1	1	2
10	2	4	2	2	1	1	1	1
11	2	2	3	1	1	1	1	2
12	2	2	3	1	1	1	1	1
13	3	1	2	2	1	2	1	2
14	3	1	2	2	1	1	1	1
15	3	2	3	1	1	3	1	2
16	3	2	3	1	1	3	1	1
17	3	2	3	2	2	3	2	1
18	3	2	3	2	2	3	3	2
19	3	2	2	1	3	2	2	1
20	3	2	2	1	3	2	3	2
21	4	3	3	2	3	3	2	1
22	4	3	3	2	3	3	3	2
23	4	3	2	1	2	2	2	1
24	4	3	2	1	1	2	3	2
25	5	3	1	1	2	3	2	2
26	5	3	1	1	2	3	3	1
27	5	3	2	2	3	2	2	2
28	5	3	2	3	3	2	3	1
29	6	2	1	1	3	2	2	2
30	6	2	1	1	3	2	3	1
31	6	2	2	2	2	3	2	1
32	6	2	2	2	2	3	3	1

Table VII.2 Modified Orthogonal Array

Appendix VIII
Hybrid Approach Output

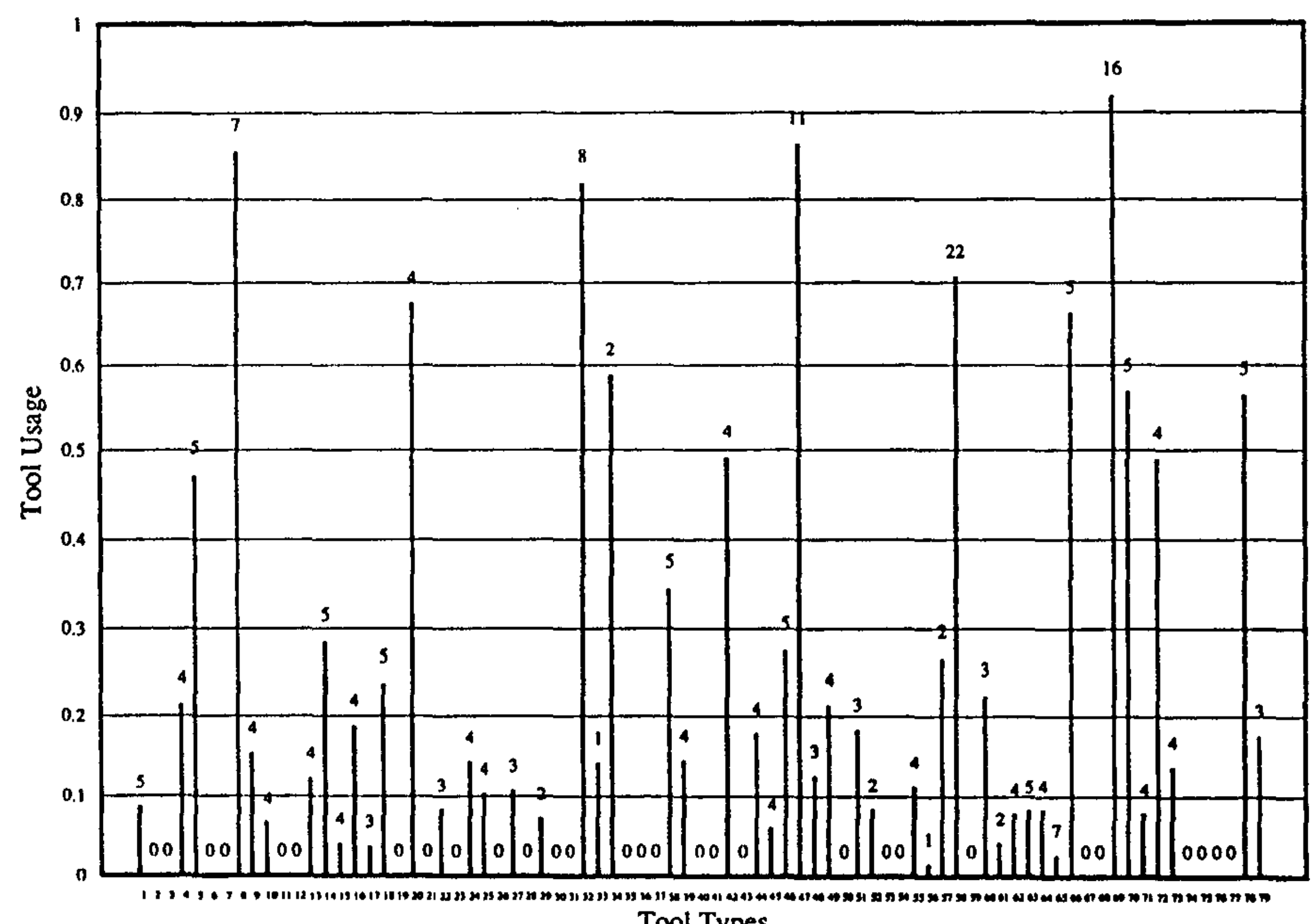
(Complementary to Chapter 7 & 17)

The Hybrid Approach Experiment No: 1

Throughput Time :	1483.75	Avr.Transport.Util.(%):	10.736
Avr. MC Util.(%):	95.149		

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No.ofSpent Tools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
5	0.43	4.57	0	1	24	5	0.09
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	0.86	3.14	0	1	12	4	0.21
5	2.37	2.63	0	3	27	5	0.47
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	3.42	0.58	3	4	31	7	0.86
4	0.62	3.38	0	1	11	4	0.15
4	0.26	3.74	0	1	8	4	0.07
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	0.49	3.51	0	1	5	4	0.12
5	1.43	3.57	0	2	16	5	0.29
4	0.16	3.84	0	1	4	4	0.04
4	0.75	3.25	0	1	11	4	0.19
3	0.11	2.89	0	1	4	3	0.04
5	1.19	3.81	0	2	12	5	0.24
0	0.00	0.00	0	0	0	0	0.00
4	2.70	1.30	0	3	42	4	0.68
0	0.00	0.00	0	0	0	0	0.00
3	0.25	2.75	0	1	3	3	0.08
0	0.00	0.00	0	0	0	0	0.00
4	0.57	3.43	0	1	8	4	0.14
4	0.42	3.58	0	1	4	4	0.10
0	0.00	0.00	0	0	0	0	0.00
3	0.32	2.68	0	1	7	3	0.11
0	0.00	0.00	0	0	0	0	0.00
2	0.14	1.86	0	1	2	2	0.07
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
6	4.92	1.08	2	5	11	8	0.82
1	0.14	0.86	0	1	1	1	0.14
2	1.18	0.82	0	2	2	2	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
5	1.73	3.27	0	2	16	5	0.35
4	0.58	3.42	0	1	11	4	0.15
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	1.97	2.03	0	2	11	4	0.49
0	0.00	0.00	0	0	0	0	0.00
4	0.72	3.28	0	1	8	4	0.18
4	0.24	3.76	0	1	4	4	0.06
5	1.38	3.62	0	2	12	5	0.28
8	6.91	1.09	3	7	35	11	0.86
3	0.38	2.62	0	1	3	3	0.13
4	0.85	3.15	0	1	4	4	0.21
0	0.00	0.00	0	0	0	0	0.00
3	0.55	2.45	0	1	4	3	0.18
2	0.17	1.83	0	1	2	2	0.08
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	0.45	3.55	0	1	11	4	0.11
1	0.01	0.99	0	1	1	1	0.01
2	0.53	1.47	0	1	2	2	0.27
15	10.61	4.39	7	11	15	22	0.71
0	0.00	0.00	0	0	0	0	0.00
3	0.67	2.33	0	1	4	3	0.22
2	0.08	1.92	0	1	2	2	0.04
4	0.32	3.68	0	1	5	4	0.08
5	0.41	4.59	0	1	19	5	0.08
4	0.33	3.67	0	1	8	4	0.08
7	0.18	6.82	0	1	8	7	0.03
5	3.32	1.68	0	4	56	5	0.66
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
12	11.03	0.97	4	12	75	16	0.92
4	2.28	1.72	1	3	51	5	0.57
4	0.31	3.69	0	1	4	4	0.08
4	1.96	2.04	0	2	16	4	0.49
4	0.55	3.45	0	1	27	4	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	2.26	1.74	1	3	6	5	0.57
3	0.53	2.47	0	1	4	3	0.18
213	74	139	21	102	669	234	



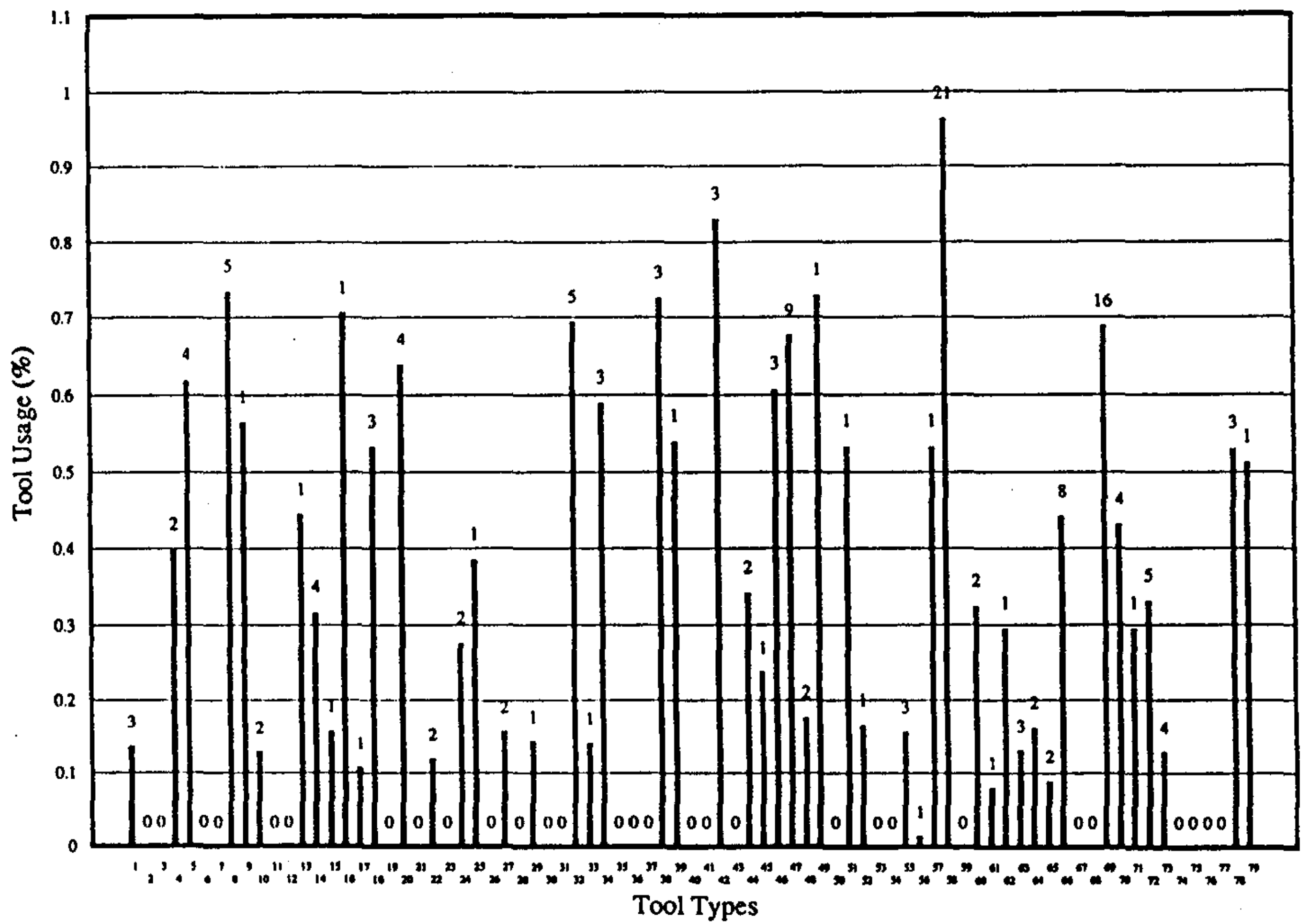
Family I, (15 parts), # MC = 4, Batch Size <=4, Manufacturing Period = 3-Shift, Permissible Tool Life = 90%.
Part Scheduling Rule = EDD, Magazine Capacity 60-Tool. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool tool typ

The Hybrid Approach Experiment No. 5

Throughput Time :	1306.7	Avr.Transport.Util.(%):	2.923
Avr. MC Util.(%):	84.161		

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
3	0.41	2.59	0	1	3	3	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.80	1.20	0	1	2	2	0.40
3	1.85	1.15	1	2	4	4	0.62
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	2.20	0.80	2	3	3	5	0.73
1	0.56	0.44	0	1	3	1	0.56
2	0.26	1.74	0	1	2	2	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.44	0.56	0	1	1	1	0.44
4	1.27	2.73	0	2	4	4	0.32
1	0.16	0.84	0	1	1	1	0.16
1	0.71	0.29	0	1	1	1	0.71
1	0.11	0.89	0	1	2	1	0.11
2	1.07	0.93	1	2	2	3	0.53
0	0.00	0.00	0	0	0	0	0.00
3	1.91	1.09	1	2	6	4	0.64
0	0.00	0.00	0	0	0	0	0.00
2	0.24	1.76	0	1	2	2	0.12
0	0.00	0.00	0	0	0	0	0.00
2	0.55	1.45	0	1	2	2	0.28
1	0.39	0.61	0	1	1	1	0.39
0	0.00	0.00	0	0	0	0	0.00
2	0.32	1.68	0	1	4	2	0.16
0	0.00	0.00	0	0	0	0	0.00
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
4	2.78	1.22	1	3	4	5	0.69
1	0.14	0.86	0	1	1	1	0.14
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	1.45	0.55	1	2	3	3	0.73
1	0.54	0.46	0	1	3	1	0.54
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	1.66	0.34	1	2	2	3	0.83
0	0.00	0.00	0	0	0	0	0.00
2	0.68	1.32	0	1	2	2	0.34
1	0.24	0.76	0	1	1	1	0.24
2	1.21	0.79	1	2	2	3	0.61
6	4.06	1.94	3	5	6	9	0.68
2	0.35	1.65	0	1	2	2	0.18
1	0.73	0.27	0	1	1	1	0.73
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	2	1	0.53
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.47	2.53	0	1	3	3	0.16
1	0.01	0.99	0	1	1	1	0.01
1	0.53	0.47	0	1	1	1	0.53
11	10.61	0.39	10	11	11	21	0.96
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.33
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
3	0.40	2.60	0	1	4	3	0.13
2	0.33	1.67	0	1	2	2	0.16
2	0.18	1.82	0	1	3	2	0.09
8	3.53	4.47	0	4	11	8	0.44
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
11	7.57	3.43	5	8	13	16	0.69
4	1.72	2.28	0	2	6	4	0.43
1	0.30	0.70	0	1	1	1	0.30
5	1.66	3.34	0	2	5	5	0.33
4	0.52	3.48	0	1	6	4	0.13
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	1.59	1.41	0	2	3	3	0.53
1	0.51	0.49	0	1	2	1	0.51
127	60	67	28	89	152	155	



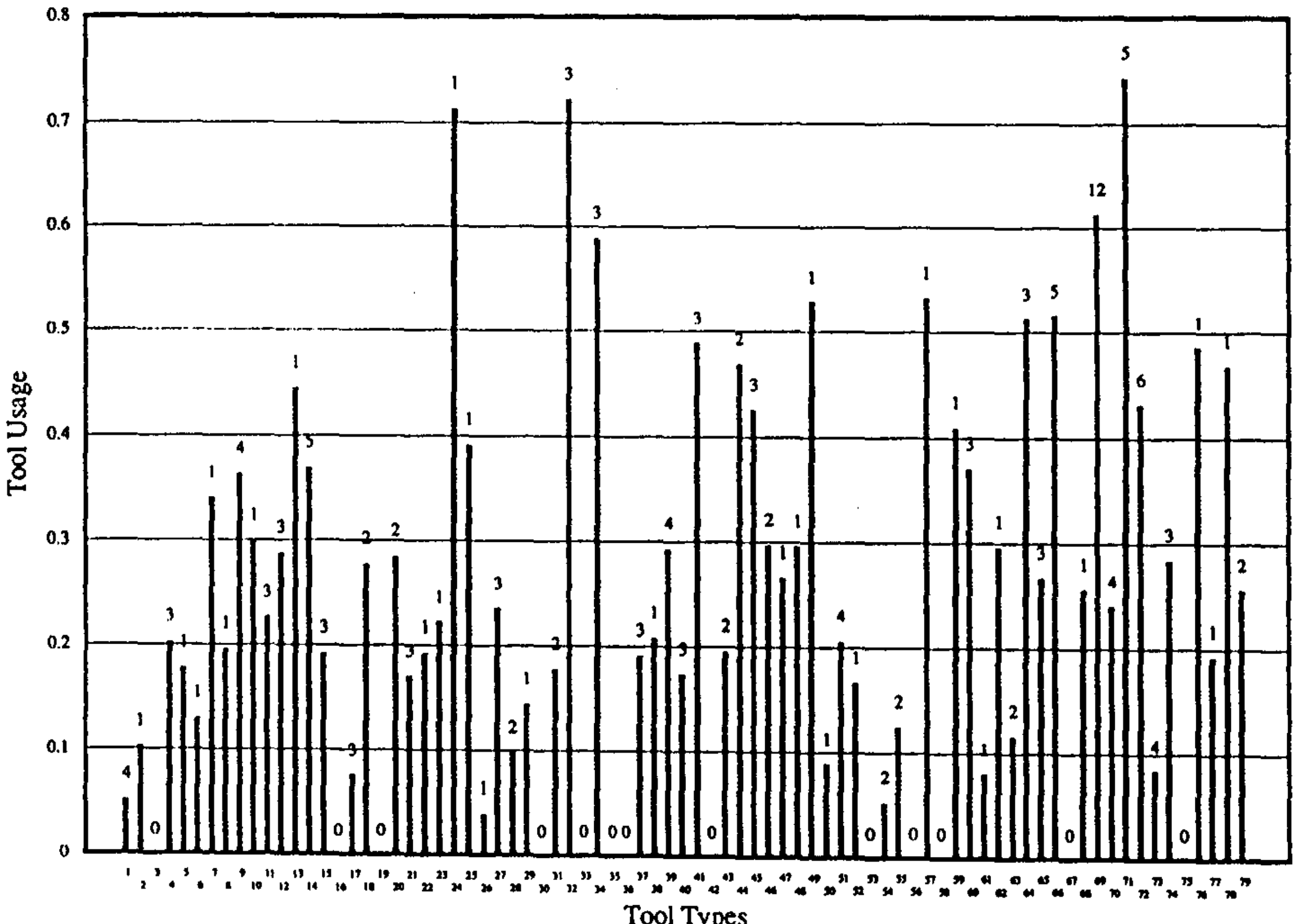
Family I, Large Batch (<=50), 4 MC Experiment, The Manufacturing Period is 3-Shift
The part scheduling rule is EDD. The numbers above the tool usage percentage indicate the tool inventory level of that particular tool type.

The Hybrid Approach Experiment No. 15

Throughput Time :	1448	Avr. Transport Util.(%):	3.709
Avr. MC Util.(%):	90.780		

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
4	0.21	3.79	0	1	6	4	0.05
1	0.10	0.90	0	1	1	1	0.10
0	0.00	0.00	0	0	0	0	0.00
3	0.61	2.39	0	1	5	3	0.20
1	0.18	0.82	0	1	1	1	0.18
1	0.13	0.87	0	1	2	1	0.13
1	0.34	0.66	0	1	1	1	0.34
1	0.20	0.80	0	1	1	1	0.20
4	1.45	2.55	0	2	9	4	0.36
1	0.30	0.70	0	1	2	1	0.30
3	0.68	2.32	0	1	3	3	0.23
3	0.87	2.13	0	1	3	3	0.29
1	0.44	0.56	0	1	1	1	0.44
5	1.85	3.15	0	2	5	5	0.37
3	0.58	2.42	0	1	4	3	0.19
0	0.00	0.00	0	0	0	0	0.00
3	0.23	2.77	0	1	3	3	0.08
2	0.56	1.44	0	1	2	2	0.28
0	0.00	0.00	0	0	0	0	0.00
2	0.57	1.43	0	1	3	2	0.29
3	0.51	2.49	0	1	4	3	0.17
1	0.19	0.81	0	1	1	1	0.19
1	0.22	0.78	0	1	1	1	0.22
1	0.71	0.29	0	1	2	1	0.71
1	0.39	0.61	0	1	2	1	0.39
1	0.04	0.96	0	1	1	1	0.04
3	0.71	2.29	0	1	5	3	0.24
2	0.20	1.80	0	1	2	2	0.10
1	0.14	0.86	0	1	1	1	0.14
0	0.00	0.00	0	0	0	0	0.00
2	0.36	1.64	0	1	2	2	0.18
2	1.44	0.56	1	2	2	3	0.72
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
3	0.57	2.43	0	1	3	3	0.19
1	0.21	0.79	0	1	1	1	0.21
4	1.17	2.83	0	2	8	4	0.29
3	0.52	2.48	0	1	3	3	0.17
3	1.47	1.53	0	2	3	3	0.49
0	0.00	0.00	0	0	0	0	0.00
2	0.39	1.61	0	1	2	2	0.20
2	0.94	1.06	0	1	2	2	0.47
3	1.27	1.73	0	2	4	3	0.42
2	0.59	1.41	0	1	2	2	0.30
1	0.27	0.73	0	1	1	1	0.27
1	0.30	0.70	0	1	1	1	0.30
1	0.53	0.47	0	1	2	1	0.53
1	0.09	0.91	0	1	1	1	0.09
4	0.82	3.18	0	1	4	4	0.21
1	0.17	0.83	0	1	1	1	0.17
0	0.00	0.00	0	0	0	0	0.00
2	0.11	1.89	0	1	2	2	0.05
2	0.25	1.75	0	1	2	2	0.13
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
0	0.00	0.00	0	0	0	0	0.00
1	0.41	0.59	0	1	1	1	0.41
3	1.11	1.89	0	2	3	3	0.37
1	0.08	0.92	0	1	1	1	0.08
1	0.30	0.70	0	1	1	1	0.30
2	0.23	1.77	0	1	3	2	0.12
2	1.03	0.97	1	2	4	3	0.51
3	0.80	2.20	0	1	5	3	0.27
4	2.07	1.93	1	3	11	5	0.52
0	0.00	0.00	0	0	0	0	0.00
1	0.26	0.74	0	1	1	1	0.26
9	5.52	3.48	3	6	14	12	0.61
4	0.96	3.04	0	1	9	4	0.24
3	2.23	0.77	2	3	3	5	0.74
5	2.16	2.84	1	3	7	6	0.43
4	0.34	3.66	0	1	6	4	0.08
3	0.85	2.15	0	1	3	3	0.28
0	0.00	0.00	0	0	0	0	0.00
1	0.49	0.51	0	1	1	1	0.49
1	0.19	0.81	0	1	1	1	0.19
1	0.47	0.53	0	1	1	1	0.47
2	0.51	1.49	0	1	2	2	0.26
147	46	101	10	86	197	157	



Family B, Large Batch (<=50) 4 MC Experiment. The manufacturing period is 3-Shift. The Permissible Tool life is 90%.
The part scheduling rule is SPT. The number above the tool life utilization indicate the tool inventory level of that particular tool type.

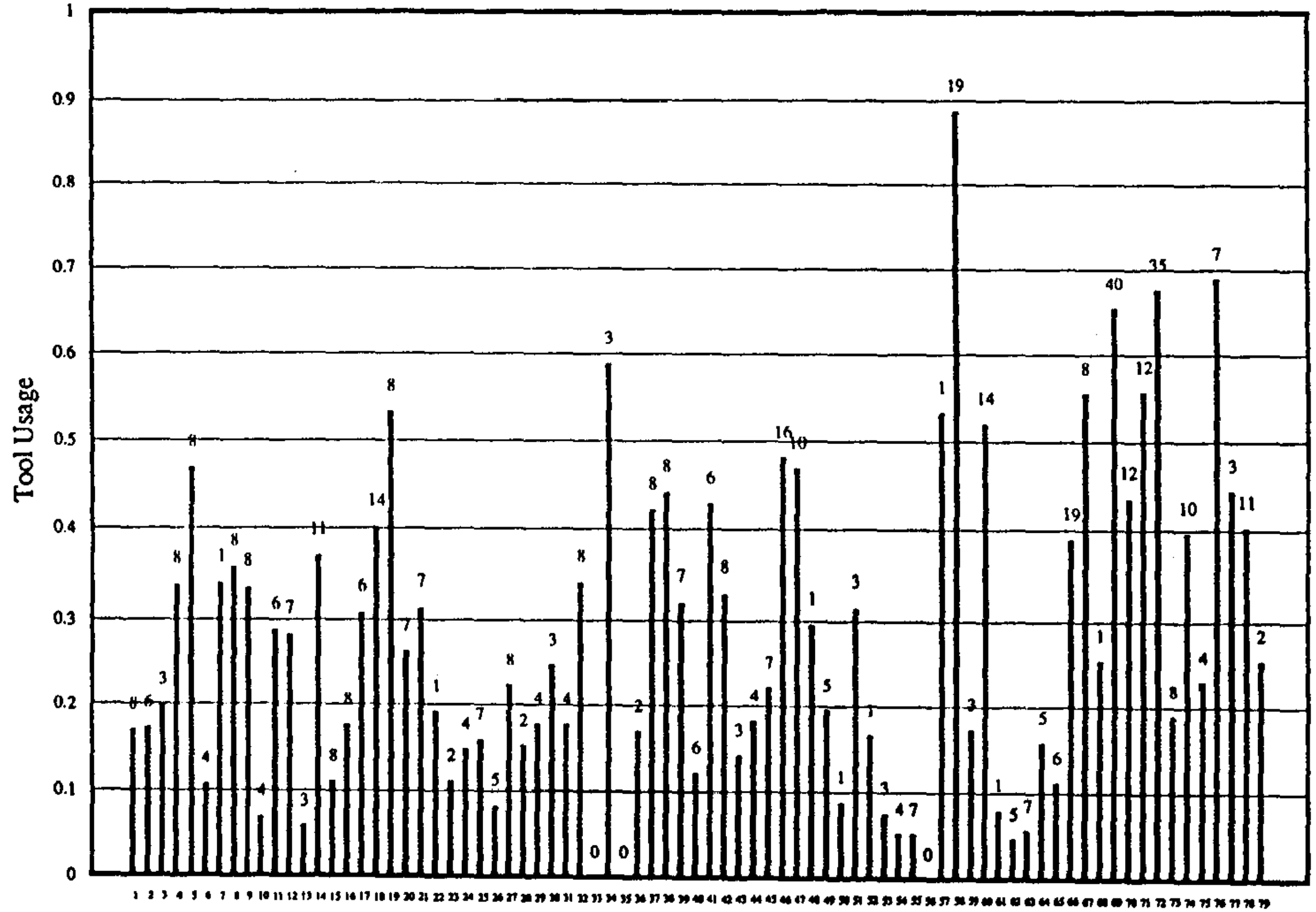
The Hybrid Approach Experiment No. 10

Throughput Time : 2470.85 Avr. Transport.Util.(%): 12.769

Avr. MC Util.(%): 91.531

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
8	1.36	6.64	0	2	48	8	0.17
6	1.04	4.96	0	2	8	6	0.17
3	0.60	2.40	0	1	3	3	0.20
8	2.71	5.29	0	3	31	8	0.34
8	3.75	4.25	0	4	28	8	0.47
4	0.43	3.57	0	1	4	4	0.11
1	0.34	0.66	0	1	1	1	0.34
8	2.86	5.14	0	3	23	8	0.36
8	2.68	5.32	0	3	36	8	0.34
4	0.28	3.72	0	1	4	4	0.07
6	1.73	4.27	0	2	12	6	0.29
7	1.99	5.01	0	2	13	7	0.28
3	0.18	2.82	0	1	3	3	0.06
11	4.07	6.93	1	5	26	11	0.37
8	0.89	7.11	0	1	12	8	0.11
8	1.41	6.59	0	2	12	8	0.18
6	1.85	4.15	0	2	14	6	0.31
14	5.63	8.37	2	6	20	14	0.40
8	4.27	3.73	1	5	8	8	0.53
7	1.85	5.15	0	2	24	7	0.26
7	2.19	4.81	0	3	16	7	0.31
1	0.19	0.81	0	1	1	1	0.19
2	0.22	1.78	0	1	2	2	0.11
4	0.59	3.41	0	1	4	4	0.15
7	1.12	5.88	0	2	9	7	0.16
5	0.41	4.59	0	1	5	5	0.08
8	1.80	6.20	0	2	17	8	0.22
2	0.31	1.69	0	1	2	2	0.15
4	0.71	3.29	0	1	5	4	0.18
3	0.75	2.25	0	1	3	3	0.25
4	0.71	3.29	0	1	5	4	0.18
8	2.73	5.27	0	3	8	8	0.34
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
2	0.34	1.66	0	1	3	2	0.17
8	3.38	4.62	0	4	20	8	0.42
8	3.53	4.47	0	4	20	8	0.44
7	2.24	4.76	0	3	31	7	0.32
6	0.73	5.27	0	1	8	6	0.12
6	2.57	3.43	0	3	13	6	0.43
8	2.64	5.36	0	3	10	8	0.33
3	0.43	2.57	0	1	3	3	0.14
4	0.73	3.27	0	1	4	4	0.18
7	1.56	5.44	0	2	10	7	0.22
16	7.71	8.29	2	8	20	16	0.48
10	4.69	5.31	0	5	20	10	0.47
1	0.30	0.70	0	1	1	1	0.30
5	0.98	4.02	0	1	6	5	0.20
1	0.09	0.91	0	1	1	1	0.09
3	0.94	2.06	0	1	4	3	0.31
1	0.17	0.83	0	1	1	1	0.17
3	0.23	2.77	0	1	3	3	0.08
4	0.21	3.79	0	1	5	4	0.05
7	0.37	6.63	0	1	8	7	0.05
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
12	10.67	1.33	7	11	14	19	0.89
3	0.52	2.48	0	1	3	3	0.17
11	5.73	5.27	3	6	13	14	0.52
1	0.08	0.92	0	1	1	1	0.08
5	0.24	4.76	0	1	5	5	0.05
7	0.40	6.60	0	1	10	7	0.06
5	0.80	4.21	0	1	8	5	0.16
6	0.67	5.33	0	1	8	6	0.11
19	7.41	11.59	3	8	54	19	0.39
8	4.44	3.56	1	5	8	8	0.56
1	0.26	0.74	0	1	1	1	0.26
37	24.23	11.77	12	25	105	40	0.65
12	5.23	6.77	0	6	72	12	0.44
10	5.57	4.43	2	6	14	12	0.56
26	17.60	6.40	9	18	44	35	0.68
8	1.52	6.48	0	2	34	8	0.19
10	3.97	6.03	0	4	13	10	0.40
4	0.93	3.07	0	1	4	4	0.23
7	4.83	2.17	0	5	8	7	0.69
3	1.33	1.67	0	2	3	3	0.44
11	4.44	6.56	0	5	13	11	0.40
2	0.51	1.49	0	1	2	2	0.26
515	189	320	44	226	1038	537	



Family III, Small Batch (<=8) 8 MC Experiment. The Manufacturing Period is 10-Shift.
The part scheduling rule is EDD. The numbers above the tool life utilization indicate the tool inventory level of that particular tool type.

The Hybrid Approach Experiment No. 9

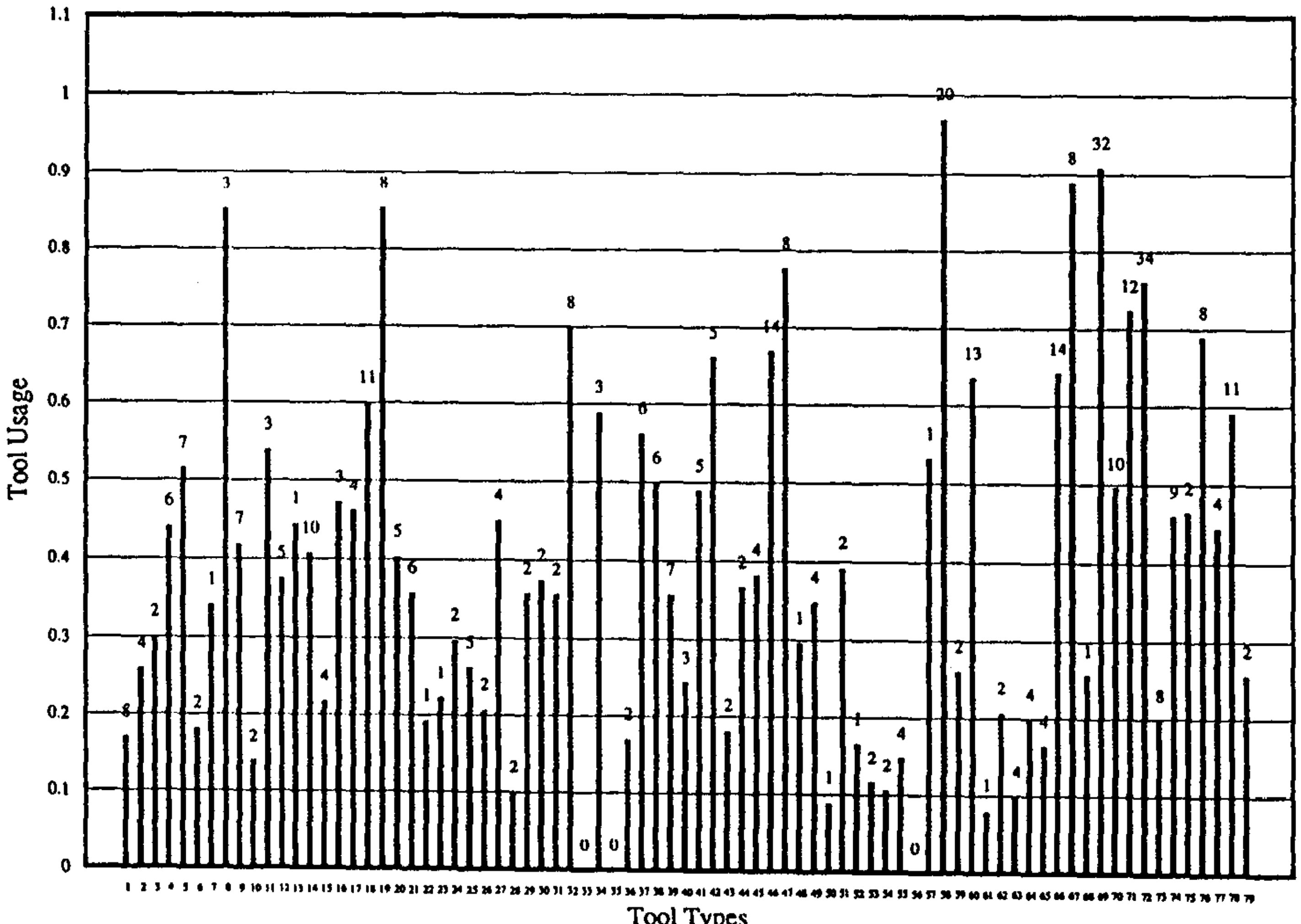
Makespan: 2465.7 Avr. Transport.Util.(%): 3.476

Avr. MC Util.(%): 85.257

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Invent.	Tool Usage
8	1.36	6.64	0	2	20	8	0.17
4	1.04	2.96	0	2	5	4	0.26
2	0.60	1.40	0	1	2	2	0.30
6	2.64	3.36	0	3	13	6	0.44
6	3.10	2.90	1	4	8	7	0.52
2	0.36	1.64	0	1	3	2	0.18
1	0.34	0.66	0	1	1	1	0.34
3	2.55	0.45	0	3	5	3	0.85
7	2.93	4.07	0	3	17	7	0.42
2	0.28	1.72	0	1	2	2	0.14
3	1.62	1.38	0	2	5	3	0.54
5	1.87	3.13	0	2	6	5	0.37
1	0.44	0.56	0	1	1	1	0.44
10	4.07	5.93	0	5	11	10	0.41
4	0.87	3.13	0	1	6	4	0.22
3	1.41	1.59	0	2	4	3	0.47
4	1.85	2.15	0	2	8	4	0.46
9	5.40	3.60	2	6	11	11	0.60
5	4.27	0.73	3	5	5	8	0.85
5	2.01	2.99	0	3	7	5	0.40
6	2.14	3.86	0	3	8	6	0.36
1	0.19	0.81	0	1	1	1	0.19
1	0.22	0.78	0	1	1	1	0.22
2	0.59	1.41	0	1	2	2	0.30
5	1.31	3.69	0	2	5	5	0.26
2	0.41	1.59	0	1	2	2	0.21
4	1.80	2.20	0	2	9	4	0.45
2	0.20	1.80	0	1	2	2	0.10
2	0.71	1.29	0	1	2	2	0.36
2	0.75	1.25	0	1	2	2	0.37
2	0.71	1.29	0	1	3	2	0.36
6	4.20	1.80	2	5	6	8	0.70
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
2	0.34	1.66	0	1	2	2	0.17
6	3.38	2.62	0	4	9	6	0.56
5	2.50	2.50	1	3	6	6	0.50
7	2.49	4.51	0	3	15	7	0.36
3	0.73	2.27	0	1	4	3	0.24
5	2.45	2.55	0	3	6	5	0.49
4	2.64	1.36	1	3	4	5	0.66
2	0.36	1.64	0	1	2	2	0.18
2	0.73	1.27	0	1	2	2	0.37
4	1.53	2.47	0	2	5	4	0.38
11	7.36	3.64	3	8	12	14	0.67
6	4.66	1.34	2	5	7	8	0.78
1	0.30	0.70	0	1	1	1	0.30
4	1.39	2.61	0	2	4	4	0.35
1	0.09	0.91	0	1	1	1	0.09
2	0.78	1.22	0	1	4	2	0.39
1	0.17	0.83	0	1	1	1	0.17
2	0.23	1.77	0	1	2	2	0.12
2	0.21	1.79	0	1	3	2	0.11
4	0.59	3.41	0	1	4	4	0.15
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
11	10.67	0.33	9	11	11	20	0.97
2	0.52	1.48	0	1	2	2	0.26
9	5.73	3.27	4	6	10	13	0.64
1	0.08	0.92	0	1	1	1	0.08
2	0.41	1.59	0	1	2	2	0.21
4	0.39	3.61	0	1	4	4	0.10
4	0.80	3.21	0	1	4	4	0.20
4	0.66	3.34	0	1	5	4	0.17
12	7.71	4.29	2	8	24	14	0.64
5	4.44	0.56	3	5	5	8	0.89
1	0.26	0.74	0	1	1	1	0.26
25	22.72	2.28	7	23	47	32	0.91
10	4.96	5.04	0	5	26	10	0.50
8	5.79	2.21	4	6	10	12	0.72
23	17.51	5.49	11	18	29	34	0.76
8	1.58	6.42	0	2	18	8	0.20
8	3.68	4.32	1	4	8	9	0.46
2	0.93	1.07	0	1	2	2	0.46
7	4.83	2.17	1	5	7	8	0.69
3	1.33	1.67	1	2	3	4	0.44
9	5.33	3.67	2	6	9	11	0.59
2	0.51	1.49	0	1	2	2	0.26
362	188	174	61	227	510	423	

The Hybrid Approach Experiment No. 9 - Tool Usage



Family III, Large Batch (<=50) 8 MC Experiment. The Manufacturing period is 10-Shift.
The part scheduling rule is EDD. The numbers above the tool life utilization percentage indicate the tool inventory level of that particular tool type.

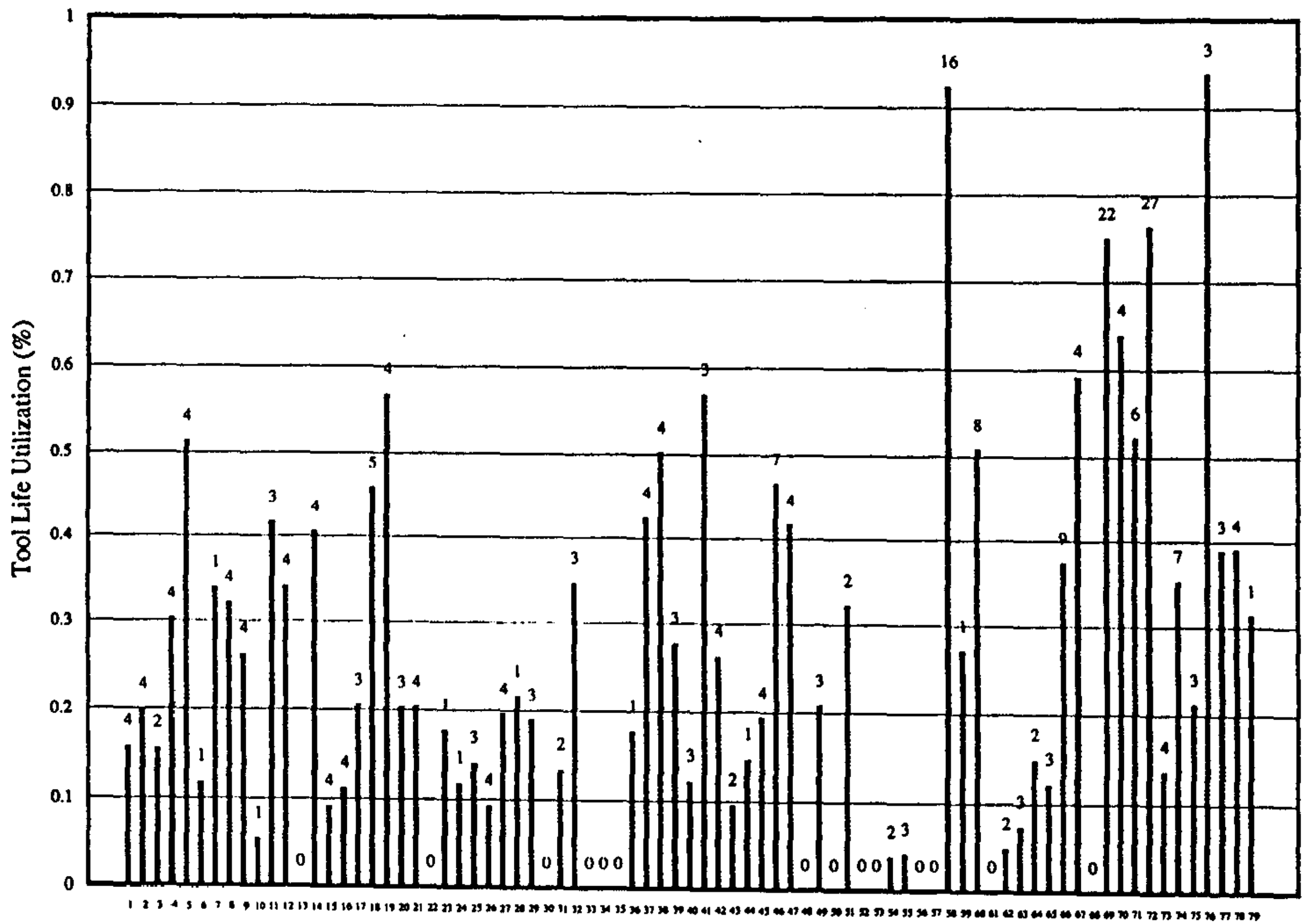
The Hybrid Approach Experiment No.22 (Cell No.1 - 4 + 4 MC)

Throughput Time :	2470.85	Avr. Transport Util.(%):	5.868
Avr. MC Util.(%):	90.802		

HYBRID SINGLE TOOLS STRATEGY(Cell #1)

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
4	0.63	3.37	0	1	21	4	0.16
4	0.80	3.20	0	1	6	4	0.20
2	0.31	1.69	0	1	2	2	0.16
4	1.22	2.78	0	2	14	4	0.30
4	2.06	1.94	0	3	14	4	0.51
1	0.12	0.88	0	1	1	1	0.12
1	0.34	0.66	0	1	1	1	0.34
4	1.29	2.71	0	2	11	4	0.32
4	1.06	2.94	0	2	14	4	0.26
1	0.06	0.94	0	1	1	1	0.06
3	1.26	1.74	0	2	8	3	0.42
4	1.37	2.63	0	2	8	4	0.34
0	0.00	0.00	0	0	0	0	0.00
4	1.63	2.37	0	2	12	4	0.41
4	0.37	3.63	0	1	5	4	0.09
4	0.45	3.55	0	1	4	4	0.11
3	0.62	2.38	0	1	5	3	0.21
5	2.30	2.70	0	3	8	5	0.46
4	2.28	1.72	0	3	4	4	0.57
3	0.61	2.39	0	1	8	3	0.20
4	0.82	3.18	0	1	6	4	0.20
0	0.00	0.00	0	0	0	0	0.00
1	0.18	0.82	0	1	1	1	0.18
1	0.12	0.88	0	1	1	1	0.12
3	0.42	2.58	0	1	4	3	0.14
4	0.37	3.63	0	1	4	4	0.09
4	0.79	3.21	0	1	7	4	0.20
1	0.22	0.78	0	1	1	1	0.22
3	0.57	2.43	0	1	4	3	0.19
0	0.00	0.00	0	0	0	0	0.00
2	0.27	1.73	0	1	2	2	0.13
3	1.04	1.96	0	2	3	3	0.35
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
1	0.18	0.82	0	1	2	1	0.18
4	1.70	2.30	0	2	10	4	0.43
4	2.01	1.99	0	3	10	4	0.50
3	0.84	2.16	0	1	11	3	0.28
3	0.37	2.63	0	1	4	3	0.12
3	1.71	1.29	0	2	8	3	0.57
4	1.06	2.94	0	2	4	4	0.26
2	0.19	1.81	0	1	2	2	0.10
1	0.15	0.85	0	1	1	1	0.15
4	0.78	3.22	0	1	5	4	0.19
7	3.26	3.74	0	4	8	7	0.47
4	1.67	2.33	0	2	7	4	0.42
0	0.00	0.00	0	0	0	0	0.00
3	0.63	2.37	0	1	4	3	0.21
0	0.00	0.00	0	0	0	0	0.00
2	0.65	1.35	0	1	2	2	0.32
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
2	0.08	1.92	0	1	2	2	0.04
3	0.13	2.87	0	1	3	3	0.04
0	0.00	0.00	0	0	0	0	0.00
0	0.00	0.00	0	0	0	0	0.00
10	9.24	0.76	6	10	12	16	0.92
1	0.27	0.73	0	1	1	1	0.27
6	3.06	2.94	2	4	6	8	0.51
0	0.00	0.00	0	0	0	0	0.00
2	0.10	1.90	0	1	2	2	0.05
3	0.23	2.77	0	1	5	3	0.08
2	0.30	1.70	0	1	3	2	0.15
3	0.37	2.63	0	1	4	3	0.12
9	3.38	5.62	0	4	21	9	0.38
4	2.37	1.63	0	3	4	4	0.59
0	0.00	0.00	0	0	0	0	0.00
19	14.26	4.74	3	15	52	22	0.75
4	2.56	1.44	0	3	35	4	0.64
5	2.61	2.39	1	3	7	6	0.52
18	13.75	4.25	9	14	26	27	0.76
4	0.55	3.45	0	1	12	4	0.14
7	2.48	4.52	0	3	8	7	0.35
3	0.64	2.36	0	1	3	3	0.21
3	2.82	0.18	0	3	3	3	0.94
3	1.17	1.83	0	2	3	3	0.39
4	1.57	2.43	0	2	5	4	0.39
1	0.32	0.68	0	1	1	1	0.32
250	101	149	21	141	476	271	

The Hybrid Approach Experiment No.22 (Cell No.1 - 4 + 4 MC) - Tool Life Utilization



Family III, Small Batch (<=8) 4 + 4 MC Multi Cell (Cell #1) Experiment. The manufacturing period is 10-shift. The tool life utilization is 90%.

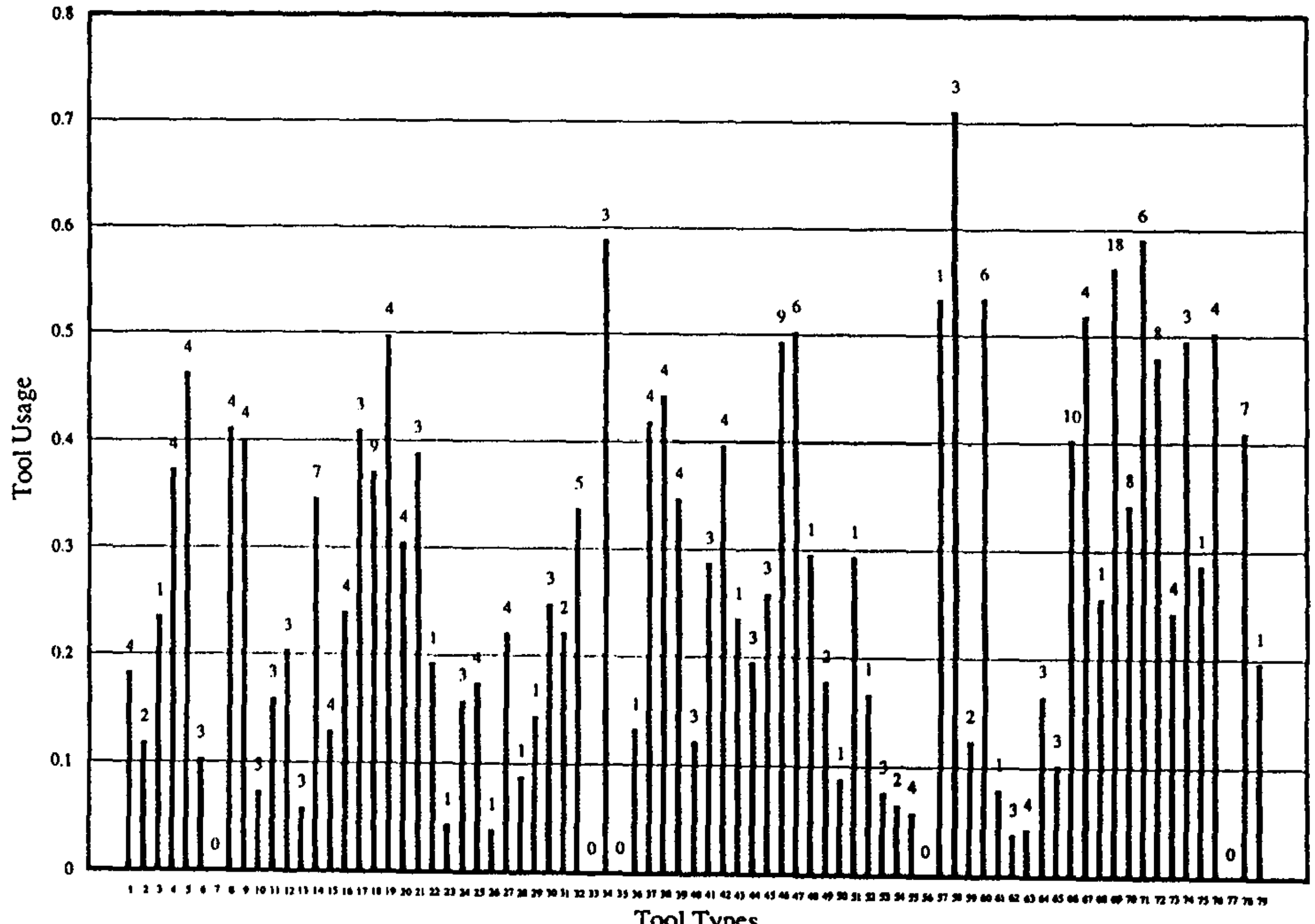
The Hybrid Approach Experiment No.22 (Cell No.2 - 4 + 4 MC)

Throughput Time : 2365.1 Avr. Transport.Util.(%): 7.196

Avr. MC Util.(%): 96.385

HYBRID SINGLE TOOLS STRATEGY(Cell #2)

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Inv.	Tool Usage
4	0.73	3.27	0	1	27	4	0.18
2	0.24	1.76	0	1	2	2	0.12
1	0.24	0.76	0	1	1	1	0.24
4	1.49	2.51	0	2	17	4	0.37
4	1.85	2.15	0	2	15	4	0.46
3	0.31	2.69	0	1	3	3	0.10
0	0.00	0.00	0	0	0	0	0.00
4	1.65	2.35	0	2	13	4	0.41
4	1.61	2.39	0	2	22	4	0.40
3	0.22	2.78	0	1	3	3	0.07
3	0.48	2.52	0	1	4	3	0.16
3	0.61	2.39	0	1	5	3	0.20
3	0.18	2.82	0	1	3	3	0.06
7	2.42	4.58	0	3	14	7	0.35
4	0.52	3.48	0	1	7	4	0.13
4	0.97	3.03	0	1	8	4	0.24
3	1.23	1.77	0	2	9	3	0.41
9	3.33	5.67	0	4	12	9	0.37
4	1.99	2.01	0	2	4	4	0.50
4	1.22	2.78	0	2	16	4	0.31
3	1.17	1.83	0	2	9	3	0.39
1	0.19	0.81	0	1	1	1	0.19
1	0.04	0.96	0	1	1	1	0.04
3	0.47	2.53	0	1	3	3	0.16
4	0.70	3.30	0	1	5	4	0.17
1	0.04	0.96	0	1	1	1	0.04
4	0.89	3.11	0	1	9	4	0.22
1	0.09	0.91	0	1	1	1	0.09
1	0.14	0.86	0	1	1	1	0.14
3	0.75	2.25	0	1	3	3	0.25
2	0.44	1.56	0	1	3	2	0.22
5	1.69	3.31	0	2	5	5	0.34
0	0.00	0.00	0	0	0	0	0.00
2	1.18	0.82	1	2	2	3	0.59
0	0.00	0.00	0	0	0	0	0.00
1	0.13	0.87	0	1	1	1	0.13
4	1.67	2.33	0	2	10	4	0.42
4	1.77	2.23	0	2	11	4	0.44
4	1.39	2.61	0	2	20	4	0.35
3	0.37	2.63	0	1	4	3	0.12
3	0.86	2.14	0	1	5	3	0.29
4	1.59	2.41	0	2	6	4	0.40
1	0.24	0.76	0	1	1	1	0.24
3	0.59	2.41	0	1	3	3	0.20
3	0.78	2.22	0	1	5	3	0.26
9	4.44	4.56	1	5	12	10	0.49
6	3.02	2.98	0	4	13	6	0.50
1	0.30	0.70	0	1	1	1	0.30
2	0.36	1.64	0	1	2	2	0.18
1	0.09	0.91	0	1	1	1	0.09
1	0.29	0.71	0	1	2	1	0.29
1	0.17	0.83	0	1	1	1	0.17
3	0.23	2.77	0	1	3	3	0.08
2	0.13	1.87	0	1	3	2	0.07
4	0.24	3.76	0	1	5	4	0.06
0	0.00	0.00	0	0	0	0	0.00
1	0.53	0.47	0	1	1	1	0.53
2	1.42	0.58	1	2	2	3	0.71
2	0.25	1.75	0	1	2	2	0.12
5	2.67	2.33	1	3	7	6	0.53
1	0.08	0.92	0	1	1	1	0.08
3	0.12	2.88	0	1	3	3	0.04
4	0.18	3.82	0	1	5	4	0.04
3	0.50	2.50	0	1	5	3	0.17
3	0.31	2.69	0	1	4	3	0.10
10	4.03	5.97	0	5	33	10	0.40
4	2.07	1.93	0	3	4	4	0.52
1	0.26	0.74	0	1	1	1	0.26
18	10.14	7.86	5	11	53	23	0.56
8	2.74	5.26	0	3	38	8	0.34
5	2.96	2.04	1	3	7	6	0.59
8	3.84	4.16	0	4	18	8	0.48
4	0.97	3.03	0	1	22	4	0.24
3	1.49	1.51	0	2	5	3	0.50
1	0.29	0.71	0	1	1	1	0.29
4	2.01	1.99	0	3	5	4	0.50
0	0.00	0.00	0	0	0	0	0.00
7	2.87	4.13	0	3	8	7	0.41
1	0.20	0.80	0	1	1	1	0.20
262	88	174	10	131	564	272	



Family III, Small Batch (<=8) 4 + 4 MC Multi Cell (Cell #2) Experiment. The manufacturing period is 10-shift. The tool life utilization is 90%. The scheduling rule is EDD. The numbers above the tool life utilization figure indicate the tool inventory level of that particular tool type.

The Hybrid Approach Experiment No.20-1

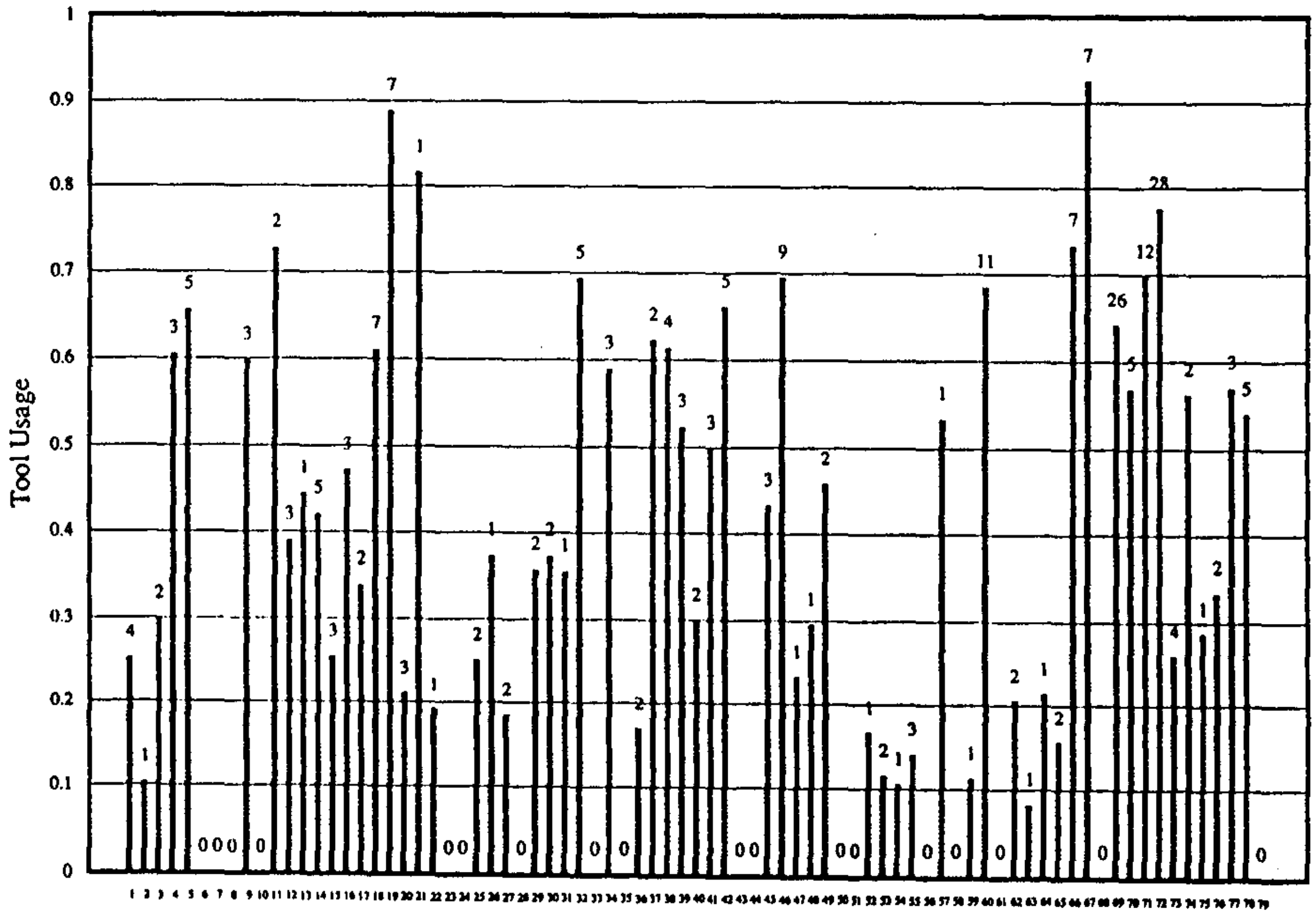
Throughput Time : 2465.7 Avr. Transport.Util.(%): 2.985

Avr. MC Util.(%): 87.040

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Usage	Tool Invent.
4	1.01	2.99	0	2	12	0.25	4
1	0.10	0.90	0	1	1	0.10	1
2	0.60	1.40	0	1	2	0.30	2
3	1.81	1.19	0	2	6	0.60	3
4	2.62	1.38	1	3	6	0.66	5
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
3	1.79	1.21	0	2	9	0.60	3
0	0.00	0.00	0	0	0	0.00	0
2	1.46	0.54	0	2	4	0.73	2
3	1.17	1.83	0	2	3	0.39	3
1	0.44	0.56	0	1	1	0.44	1
5	2.10	2.90	0	3	5	0.42	5
3	0.77	2.23	0	1	5	0.26	3
3	1.41	1.59	0	2	4	0.47	3
2	0.68	1.32	0	1	2	0.34	2
5	3.05	1.95	2	4	5	0.61	7
4	3.56	0.44	3	4	4	0.89	7
3	0.64	2.36	0	1	4	0.21	3
1	0.82	0.18	0	1	2	0.82	1
1	0.19	0.81	0	1	1	0.19	1
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
2	0.50	1.50	0	1	2	0.25	2
1	0.37	0.63	0	1	1	0.37	1
2	0.37	1.63	0	1	2	0.19	2
0	0.00	0.00	0	0	0	0.00	0
2	0.71	1.29	0	1	2	0.36	2
2	0.75	1.25	0	1	2	0.37	2
1	0.36	0.64	0	1	1	0.36	1
4	2.78	1.22	1	3	4	0.69	5
0	0.00	0.00	0	0	0	0.00	0
2	1.18	0.82	1	2	2	0.59	3
0	0.00	0.00	0	0	0	0.00	0
2	0.34	1.66	0	1	2	0.17	2
2	1.24	0.76	0	2	3	0.62	2
3	1.84	1.16	1	2	4	0.61	4
3	1.57	1.43	0	2	8	0.52	3
2	0.60	1.40	0	1	3	0.30	2
3	1.50	1.50	0	2	3	0.50	3
4	2.64	1.36	1	3	4	0.66	5
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
3	1.30	1.70	0	2	4	0.43	3
6	4.18	1.82	3	5	6	0.70	9
1	0.23	0.77	0	1	1	0.23	1
1	0.30	0.70	0	1	1	0.30	1
2	0.92	1.08	0	1	2	0.46	2
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
1	0.17	0.83	0	1	1	0.17	1
2	0.23	1.77	0	1	2	0.12	2
1	0.11	0.89	0	1	1	0.11	1
3	0.42	2.58	0	1	3	0.14	3
0	0.00	0.00	0	0	0	0.00	0
1	0.53	0.47	0	1	1	0.53	1
0	0.00	0.00	0	0	0	0.00	0
1	0.11	0.89	0	1	1	0.11	1
7	4.80	2.20	4	5	7	0.69	11
0	0.00	0.00	0	0	0	0.00	0
2	0.41	1.59	0	1	2	0.21	2
1	0.08	0.92	0	1	1	0.08	1
1	0.22	0.79	0	1	1	0.22	1
2	0.31	1.69	0	1	2	0.16	2
5	3.67	1.33	2	4	10	0.73	7
4	3.70	0.30	3	4	4	0.93	7
0	0.00	0.00	0	0	0	0.00	0
21	13.47	7.53	5	14	25	0.64	26
5	2.84	2.16	0	3	14	0.57	5
8	5.59	2.41	4	6	9	0.70	12
18	13.98	4.02	10	14	20	0.78	28
4	1.04	2.96	0	2	10	0.26	4
2	1.12	0.88	0	2	2	0.56	2
1	0.29	0.71	0	1	1	0.29	1
2	0.67	1.33	0	1	2	0.33	2
2	1.14	0.86	1	2	2	0.57	3
4	2.16	1.84	1	3	4	0.54	5
0	0.00	0.00	0	0	0	0.00	0
196	105	91	43	139	258		239

The Hybrid Approach Experiment No.20-1 - Tool Usage



Part Type = 70, # MC = 4 + 4, Batch Size <= 50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90 %.
Part Scheduling Rule = EDD, The numbers above the tool life utilization figures indicate the tool inventory level of that particular tool type.

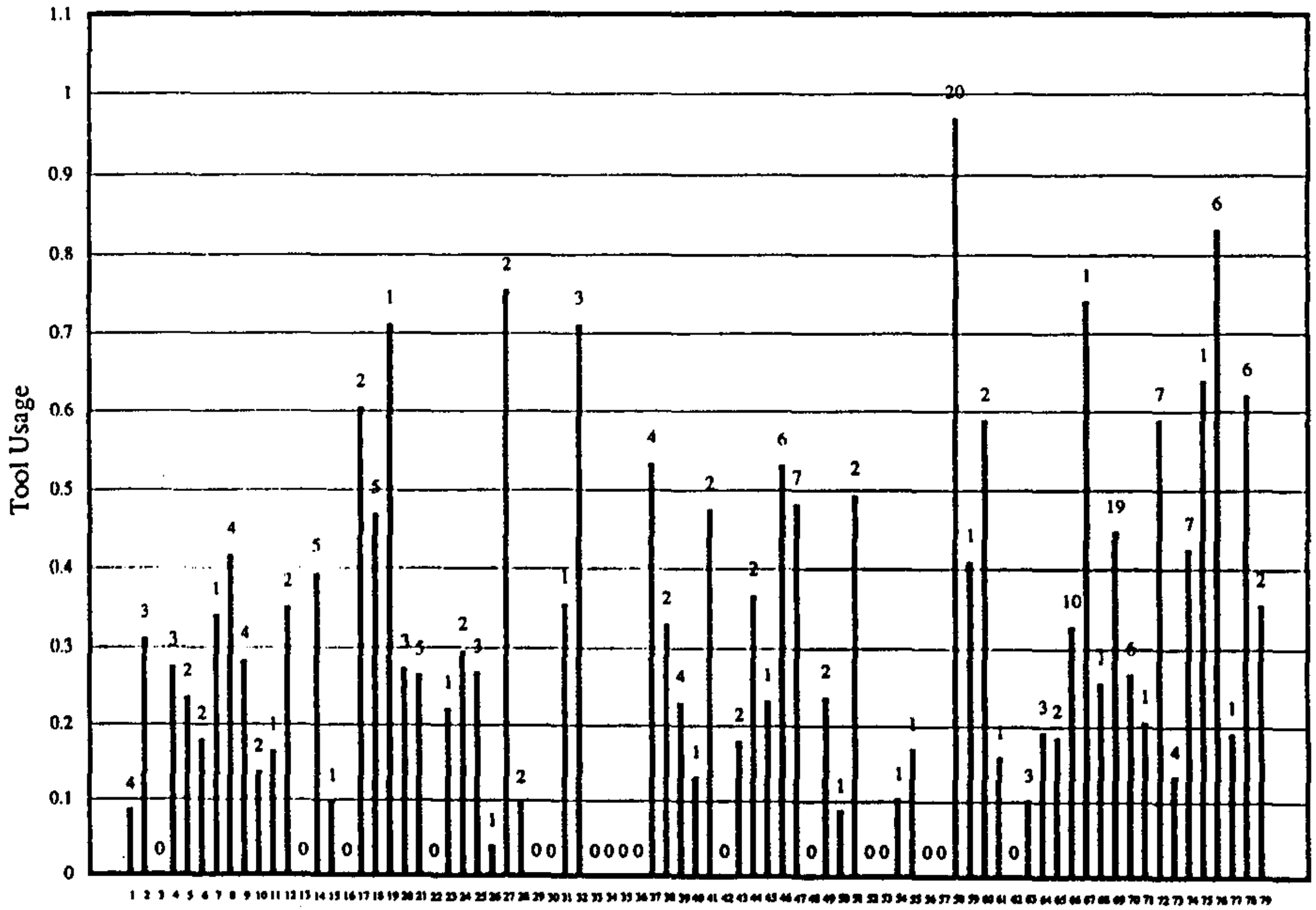
The Hybrid Approach Experiment No.20-2

Throughput Time :	2225.05	Avr. Transport.Util.(%):	3.353
Avr. MC Util.(%):	92.499		

HYBRID SINGLE TOOLS STRATEGY

Requested Tool Size	Actual Use	Residual Tool Life	No of SpentTools	Min.Tool Requirement	Max.Tool Requirement	Tool Usage	Tool Invent.
4	0.35	3.65	0	1	8	0.09	4
3	0.93	2.07	0	1	4	0.31	3
0	0.00	0.00	0	0	0	0.00	0
3	0.83	2.17	0	1	7	0.28	3
2	0.47	1.53	0	1	2	0.24	2
2	0.36	1.64	0	1	3	0.18	2
1	0.34	0.66	0	1	1	0.34	1
4	1.67	2.33	0	2	4	0.42	4
4	1.14	2.86	0	2	8	0.28	4
2	0.28	1.72	0	1	2	0.14	2
1	0.17	0.83	0	1	1	0.17	1
2	0.70	1.30	0	1	3	0.35	2
0	0.00	0.00	0	0	0	0.00	0
5	1.97	3.03	0	2	6	0.39	5
1	0.10	0.90	0	1	1	0.10	1
0	0.00	0.00	0	0	0	0.00	0
2	1.21	0.79	0	2	7	0.61	2
5	2.35	2.65	0	3	6	0.47	5
1	0.71	0.29	0	1	1	0.71	1
3	0.82	2.18	0	1	2	0.27	3
5	1.33	3.67	0	2	6	0.27	5
0	0.00	0.00	0	0	0	0.00	0
1	0.22	0.78	0	1	1	0.22	1
2	0.59	1.41	0	1	2	0.30	2
3	0.81	2.19	0	1	3	0.27	3
1	0.04	0.96	0	1	1	0.04	1
2	1.51	0.49	0	2	8	0.75	2
2	0.20	1.80	0	1	2	0.10	2
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
1	0.36	0.64	0	1	2	0.36	1
2	1.42	0.58	1	2	2	0.71	3
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
4	2.13	1.87	0	3	6	0.53	4
2	0.66	1.34	0	1	2	0.33	2
4	0.92	3.08	0	1	7	0.23	4
1	0.13	0.87	0	1	1	0.13	1
2	0.95	1.05	0	1	3	0.48	2
0	0.00	0.00	0	0	0	0.00	0
2	0.36	1.64	0	1	2	0.18	2
2	0.73	1.27	0	1	2	0.37	2
1	0.23	0.77	0	1	1	0.23	1
6	3.19	2.81	0	4	6	0.53	6
6	2.90	3.10	1	3	4	0.48	7
0	0.00	0.00	0	0	0	0.00	0
2	0.48	1.52	0	1	2	0.24	2
1	0.09	0.91	0	1	1	0.09	1
2	0.99	1.01	0	1	5	0.49	2
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
1	0.11	0.89	0	1	2	0.11	1
1	0.17	0.83	0	1	1	0.17	1
0	0.00	0.00	0	0	0	0.00	0
0	0.00	0.00	0	0	0	0.00	0
11	10.67	0.33	9	11	11	0.97	20
1	0.41	0.59	0	1	1	0.41	1
2	1.18	0.82	0	2	4	0.59	2
1	0.16	0.84	0	1	2	0.16	1
0	0.00	0.00	0	0	0	0.00	0
3	0.31	2.69	0	1	3	0.10	3
3	0.58	2.42	0	1	3	0.19	3
2	0.38	1.63	0	1	4	0.19	2
10	3.28	6.72	0	4	14	0.33	10
1	0.74	0.26	0	1	1	0.74	1
1	0.26	0.74	0	1	1	0.26	1
18	8.06	9.94	1	9	21	0.45	19
6	1.61	4.39	0	2	11	0.27	6
1	0.21	0.79	0	1	1	0.21	1
6	3.54	2.46	1	4	9	0.59	7
4	0.54	3.46	0	1	8	0.14	4
6	2.55	3.45	1	3	6	0.43	7
1	0.64	0.36	0	1	1	0.64	1
5	4.16	0.84	1	5	5	0.83	6
1	0.19	0.81	0	1	1	0.19	1
5	3.11	1.89	1	4	5	0.62	6
2	0.71	1.29	0	1	3	0.36	2
191	78	113	16	113	253		207

The Hybrid Approach Experiment No.20-2 - Tool Usage



Part Type = 70, # MC = 4 + 4, (CELL #2) Batch Size <= 50, Manufacturing Period = 10-Shift, Permissible Tool Life = 90 %.
Part Scheduling Rule = EDD, The numbers above the tool life utilization figures indicate the tool inventory level of that particular tool type.

REFERENCES OF THE APPENDICES

1. Clancey, W. J.,
"Viewing knowledge bases as qualitative models", IEEE, Expert, No.2, 1989, pp. 9-23.

2. Cullen, J. and Bryman, A.
"The knowledge acqusition bottleneck : Time for reassessment ?", Expert Systems, Vol.5, No.3, pp.216-225.

3. De Souza, R.B.R.
"The management of tool flow in highly automated manufacturing systems", Phd Thesis, LUT, 1988

4. De Souza, R.B.R. and Bell, R.
"A tool cluster-based strategy for the management of cutting tools in flexible manufacturing system", Journal of Operation Management, Vol.10, No.1, pp. 73-91,1991

5. Doukidis, G. I. and Whitley, E.A.
"Developing expert systems", Cratwell-Bratt, 1988.

6. Dubas, M.
"Expert systems in industrial practise : Advantages and drawbacks", Expert Systems, August 1990, Vol.7, No.3, pp.150-156

7. Feigenbaum, E.
"Handbook of AI", Stanford University, 1982.

8. Luger, G.F., and Stubblefield W.A.
"AI Design of expert systems", Benjamin/Cummings Publication Company, California, 1989.

9. KES Manual, Template Software, Virginia, 1990.

10. Kinoglu, F. et al.
"Expert systems model for the Design of the process", Smart Manufacturing with Artifical Intelligence, 1987

11. Kumara, S. et al.
"An introduction to Artifical Inteligence", Industrial Engineering, December 1986, pp. 9-20

12. Ranjit, R.
"A premier on Taguchi method", Van Nostrand Reinhold, New York, 1990

13. Shaw, M.J.P. and Whinston, A.B.
"Applications of Artifical Intelligence to planning and scheduling in flexible manufacturing", Flexible Manufacturing Systems : A Review of Modelling Approaches for Design, Justification and Operation", Flexible ManufacturingSystems : Methods and Studies, Edited by Kusiak A., Elsevier Science Publishers B.V. (North Holland), 1986, pp. 223-242

14. Siegel, P.,
"Expert systems - A non-programmer's guide to development and applications", Tab Books, 1986.

15. Waterman, D.A.
"A guide to expert systems", Addison-Wesley Publishing Company, 1985.