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The Management Of Tool Flow

In Highly Automated

Batch Manufacturing Systems

Volume I

by

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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.

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ABSTRACT

An overall framework to provide a complete tool management solution to an existing or specified manufacturing system is constructed, and prototype software provided, for a hierarchy of levels of tool flow automation. The work is targeted at the design and operation of tooling systems for prismatic parts flexible machining systems ranging from stand alone unmanned machining stations to highly automated multi-machine multi-cell configurations.

The research work moves from identification and category definition of a tool flow network appropriate for the manufacturing requirements, through the careful selection and definition of operating rules and strategies to the evaluation of the options available for tool issue and assignment.

Two main computer aids (design facilities) to provide support in a systems thinking approach to tool flow management have been developed and tested with the aid of case studies. The essential role of these design facilities is the timely scheduling of tools to satisfy a short to medium term manufacturing task, and to examine the cost and number of captive tools under selected rules and strategies.

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VOLUME II : USER INTERFACE, CASE STUDIES, PUBLISHED PAPERS

GLOSSARY OF MAIN TERMS

ATS	Auxilliary Tool Store (tool store located at machine level and accessible by one or more machines).
Category A	A manual tooling system which only includes the primary tool stores (PTS).
Category B	A semi-automated tooling system which includes one or more auxilliary tool stores (ATS).
Category C	A semi- or fully-automated system which includes a secondary tool store (STS).
CTS	Central Tool Store (a tool store located at factory level and accessible to a cell secondary tool store).
Emulator	A term used to describe the suite of manufacturing systems software, developed in a parallel research programme, in the laboratory of the Department of Manufacturing Engineering, Loughborough University.
FTN	Functional Tool Number which identifies a tool type.
ITN	Individual Tool Number which identifies a unique tool.
LUT	Loughborough University of Technology
Machining List	A collection of ordered work lists for a particular machine.
Operation	A machining activity which selects and employs the same tool (ITN) continuously, in the spindle, until its return to the primary tool store.
PTS	Primary Tool Store (the machine integrated tool store).
STS	Secondary Tool Store (a tool store accessible by all machines in a cell configuration).
Tool	An entity which is considered to be assembled and preset.
Tool Flow	The controlled movement of tools around a flexible machining installation.
Tool List	A required tool sequence of tool types or functional tool numbers for a given machining list.

Tool Management	The total activity involved in the organisation, planning and timely scheduling of tools to satisfy a manufacturing task.
Tool-Oriented	The case where the high usage tools or tool sets are identified for the entire production mix and assigned to reside in particular tool stores, thus dictating the flow of work.
Work List	An ordered list of operations on a part, part set, or batch.
Workpiece-Oriented	The case where the flexible machining facility is supported with tools related to the actual orders, i.e. the manufacturing system is said to be demand-driven.

Chapter 1:
INTRODUCTION

A highly automated manufacturing system is a production system centred around the use of CNC machine tools which are linked together by automated equipment for the storage, transfer, and handling of both the workpieces and the tools. The whole system works under the control of a computerised system which assures the capability of dynamically changing the machining operations, according to the parts being manufactured and the flexible routing and automatic loading of the workpieces and tools. These highly automated manufacturing systems, and in particular the new multi-cell configurations, have been the subject of much study recently concerning the ability to respond to changes in production volume, machining method and production equipment, and at the same time achieve rationalisation of production control.

These highly automated manufacturing systems are very capital intensive and their introduction must still be carefully justified. Their design and operation has got the same range of problems as any conventional system but they are far more complicated. There is close interaction of the several areas and any decision making process must examine the whole system instead of the individual elements. The main subject of this thesis is the study of tool flow within a highly automated manufacturing system for the manufacture of prismatic components.

Economic and effective solutions to the tool flow requirements of highly automated flexible machining installations are becoming increasingly important. There is clear evidence of major hardware developments, by machine tool builders, towards increasingly sophisticated networks for the flow and the exchange of preset tools between a cell tool store and respective machine-based tool stores; and between a cell and a central tool store.

This level of complexity in tool handling requires a framework for the analysis, selection and evaluation of a suitable flow network and its transfer and control strategies. Analysis by modelling is the obvious route to approach this problem as experimentation with actual hardware is prohibitively expensive and alterations are difficult to implement. A computer aid to provide support in this systems thinking approach to tool management is thus necessary for fast, effective and economical network design, management and operation.

The work reported in this thesis focuses essentially on prismatic part manufacturing systems with parallels for other types of flexible machining systems. The work commences with an extensive literature survey of machining installations with advanced tool flow systems, some novel concepts and new developments in machining centre and turning centre technology, and supporting technologies. The integration of these elements and the design, operation, control and future trends for manufacturing systems are discussed in chapter three with a view to providing a setting for and clarifying the role of tool flow networks within each manufacturing concept said to evolve from the simplistic volume-variety relationship.

The categorisation of the tooling systems, in chapter five, provides a backcloth against which any defined tool flow network may be described. Pertinent issues in tool management are discussed in chapter four. These issues together with the classification permit structured representations of single and multicell tool management to be constructed in chapter six. These representations or activity flow networks are described in chapter seven using a concept of multi-subroutes. This forms the basis for the modelling representations in the computer aids described in chapters eight and eighteen.

Loading, scheduling and sequencing of parts through the manufacturing system in accordance with either a tool-oriented or a workpiece-oriented tool management strategy are described in chapter ten. The use of a second computer aid in computer assisted cluster analysis for quick determination of preferred tool cluster sets and for examining short range schedules of work for a tool-oriented tool management strategy is described in chapters eight to eleven. Strategies for higher level management of the tool flow are also presented in chapter ten. The selection, choice and effects of alternative operating strategies under a selected tool issue strategy, discussed in chapter eleven, and tool management strategy detailed in chapter ten are presented for each level of the tooling system hierarchy ranging from the cell down to the machine level are presented in chapters twelve through to fourteen.

The selection and evaluation of these strategies through modelling, discussed in chapter fifteen, will make possible a more substantial understanding of tool flow problems and economic solutions for flexible machining installations; and explore the relative merits of alternative designs and control strategies, algorithms for which are presented in chapters sixteen and seventeen, for flexible machining cells ranging from stand alone unmanned machining stations to highly automated multi-machine multi-cell configurations. These strategies are equally applicable to any batch manufacturing system, whether the enabling technology is high or low.

The process outlined above, moving from identification and categorisation of tool flow systems to the selection and evaluation of appropriate strategies is analogous to, though not primarily intended as, a design methodology. Much of the work, which has been strongly influenced by a club of collaborating companies and supported by the ACME section of the SERC, is based on case studies undertaken with the collaborators. Several supporting studies ranging from a single machine to a multi-machine cell have been undertaken and completed with the results being mainly documented in the appendices. Tentative and investigative links with other suites of software, particularly the LUT Emulator and the Process Planner of the Alvey Design to Product programme, have also been explored. The results of the research have produced a prototype tool management workstation available for industrial exploitation, see chaper eighteen.

The work reported in this thesis has been carried out in close collaboration with a number of parallel research programmes, in particular the project work on tool flow systems for cylindrical parts manufacturing systems and the implementation of tool flow within the LUT part flow Emulator, which are in themselves subjects of complementary theses. These have been described in the literature survey and cross referenced in the text.

Chapter 2:
LITERATURE SURVEY

2.1 Introduction

The scope of this literature survey is to give a background assessment of tool flow systems in flexible machining installations. The identification of the problems and the approaches adopted by other researchers in this area and the factors and influences on tool flow are covered.

These topics include the concepts of an FMS and the specifications, modelling, simulation, scheduling and assessment of flexible machining systems. The particular character of this field of research also necessitates a survey of current and anticipated tool flow systems and concepts for prismatic and cylindrical parts. A cross-section of currently operating flexible machining systems with particular emphasis on partial or fully automated tool flow networks are reviewed for systems ranging from stand-alone machines up to the cellular installations.

Research and investigations pertaining to live issues in FMS and tool flow in particular has been carried out internationally by prominent researchers in private institutes, universities and manufacturing plants. These findings are mainly reviewed in this literature survey.

2.2 Flexible Manufacturing Concepts

The concept of Flexible Manufacturing (65) has been rapidly developed and evolved from NC over the last 30 years. The developments in the electronic industry permitted solutions to be found to most of the old known problems, associated with all the types of manufacturing systems. The first radical development in flexible batch manufacturing was introduced by Williamson (323). The System 24 offered a challenge to conventional thinking in system configuration, machine tool design and in tool and workpiece flow. In the USA Cincinnatti's Variable Mission manufacturing system and Sundstrand's DNC system were claimed to be of comparable development (121). The several historical steps towards Flexible Manufacturing (FM) in the intervening years were : NC machines (automated process), NC machining centres (automated process and automated tool change), CNC (a control computer with a data bank which controls directly the NC - machine tool without using a tape), NC machining centres with automated workpiece change and measuring equipment, and the DNC support to small numbers of machines or the hierarchical DNC support to the multi-cell configurations (7). This range of hardware and the digital technology involved constitute the Flexible Automation found in current systems. The main inputs to the manufacturing system are technological, organisational, and quality control information, raw parts, tools and auxilliary devices such as fixtures, pallets, etc.; the main outputs are finished parts and information to the control system.

The concepts of FM focus on the flexible processing capability, and the combination of its constituent elements of work stations, material transport, tool transport and computer control so as to function as a true computer integrated system. There is not any rigorous definition of the concept of FMS (77). Any operable factory can be called a manufacturing system and flexible is a relative-adjective at best. The main difference between an FMS and all other types of manufacturing systems is the ability to integrate the management and control of the installation with the aid of a computer (137). Hannam (121) suggests that the FMS approach was developed in an attempt to realise the benefits of mass production (obtained through flow lines and transfer machines) in the batch production environment and describes the main engineering hardware elements which make up the visible elements of this concept.

The application of flexible automation is now a well established feature of batch manufacturing. Several definitions of the concept of an FMS have been offered, and there is extensive literature which describes the major applications in this area, some of which are reviewed here :

Marshall, P. (235) uses a manufacturing system approach in which the key word singled out is 'system'. This indicates the involvement of an organised, ordered and complete system. Almost equally important is the word 'manufacturing', suggesting the integration of all functions contributing to making products. 'Flexible' is the word with the widest significance. It seems that the most obvious interpretation of the word is in relation to the ability of the manufacturing system to be quickly and easily changed over to produce different components or products, and this indeed is a most important aspect. Billalis, N. (65) develops the concept of an FMS as consisting of a number of machine tools connected through a material handling system and all under computer control. The system can manufacture simultaneously several parts of different batches with small change-over requirements. Ranky, P. (269) defines an FMS as a system dealing with high level distributed data processing and automated material flow using computer controlled machines, assembly cells, industrial robots, inspection machines and so on, together with computer integrated materials handling and storage systems.

FMS can also be thought of as distributed management information system linking together intelligent subsystems and materials handling (268) . Bunce (72) provides the CAM-I definition which defines FMS as the integration of a series of interrelated activities and operations into processes of producing a product. Hartley, J. (124) broadens the concept of an FMS to encompasses not only machining processes but many other processes linked together to form a true FMS.

Within the framework of this thesis, an FMS is considered as a largely automated computer integrated machining installation with an integrated partial or fully automated tool handling system complementing a material handling system. While these machining installations have been defined and given a variety of names, all closely related to present technology - e.g. computerised manufacturing system (CMS), etc. The fundamental definition of an FMS, in the words of Buzacott and Shantikumar (75) is, "*a set of machines... linked by a material handling system and all under central computer control.*" This definition is broad and may encompass a variety of machine configurations in diverse applications.

Flexibility gives rise to many of the relative advantages of an FMS (41). Since machine tools are computer controlled, the system is flexible enough to produce a variety of parts by a simple change of software. A more up-to-date or complete review of the concepts of FMS is given by Frost and Sullivan in their report on Flexible Manufacturing Technology (181).

2.3 Specification, Design & Application of FMS

FMS is said to cover the middle area between the stand alone machining centres and flexible transfer lines. The transfer lines are used for mass production. They provide for high productivity catering for large batch sizes but are found lacking in flexibility of manufacturing a medium to large variety of workpieces. At one end of the spectrum, the stand-alone machining centres provide excellent flexibility with the ability to manufacture a wide variety of workpieces but with workpieces that may require many machining processes then productivity is low. They are therefore more suited to the low volume end of the spectrum of machining technologies. FMS can therefore be defined as a system which aims at combining both the features of flexibility and productivity. Flexibility and productivity should be seen as reciprocal features [277]. It is particularly difficult to combine the two in a FMS of batch production. The decision as to which should gain the most emphasis has come to depend more on business efficiency rather than machine efficiency [53].

Loose ranges of demand and variety for application areas of an FMS have been suggested by Kearney and Trecker [161], LeimKuhler [199], Hegland [135], Kusiak [194], Dupont-Gatelmand [104], Warnecke and Steinhilper [311], and Hutchinson and Holland [146] who also emphasise part size, workpiece accuracy and configuration, assembly and the product life cycle as factors. Variations of emphasis are also described by Minakata [243], and Primrose and Leonard [260,259] amongst others [42].

However, the prevailing notion of FM based on volume and variety alone is imprecise. The demands made by international competition and economic factors on manufacturing industry introduce additional factors. A manufacturing system has to demonstrate a high speed of response to the consumer, competitors and technological change [59]. High product quality and improved productivity, high capital equipment utilisation and reduced work-in-progress and lead times have also to be sustained.

A better selection procedure proposed by Gerwin and Leung [65] involves the consideration of the type of flexibility in the system. Flexibility, quality and lead times in the manufacture of a range of parts for which the system is intended, or to change, adapt and grow to accommodate the changing material influences on the system user are considered to be the most important criteria in the selection of an FMS. The categories of flexibility considered are:

- *Mix flexibility* : processing at any one time a mix of different parts which are loosely related to each other in some way, such as belonging to some part family;
- *Parts flexibility* : adding parts to or removing parts from the mix over time;
- *Routing flexibility* : dynamic assignment of parts to machines
- *Design change flexibility* : fast complementation of design changes for the manufacture of a particular part
- *Volume flexibility* : handling shifts in volume for a given part; or
- *Customary flexibility* : processing different mixes of parts on different FMS is in the same company.

The design process for an FMS starts with the compilation of the specifications for the system [144]. The main characteristics of the system in terms of output, capacity, desired utilisation, degree of automation, integration of the several elements such as materials handling system, tools handling system, workstation, control system; forementioned categories of flexibility required; requirements on quality, lead times, delivery, maintenance, cost and layout are the main quantities and qualities which must be specified. The compilation of these specifications is a very difficult task; their modification during the following phases of system development and assessment is possible but must be restricted to a certain level. Several design methodologies have been offered:

Barash, M.M. et al [54] report on the specification and design of FMS. The whole process is divided into five main steps. These are: Parts Selection - determination of the machining content of each part and of a typical batch size - determination of system functional elements, including all machine tool ones - composition of various system configurations, including various handling sub-systems - simulation of the operation of all variants to test their general performance - determination of the best system and justification of optimum operating rules for this system. The major units of this design programme are :

- *Unit machining operation* : This is an intersection of two sets. One set describes all the features to be machined. The second set contains processes with which such surfaces can be produced in general.
- *System functional elements* : Output of the machining operation is used to justify machine tool specifications such as sizes, number of controlled axes, etc. This information, combined with the desired production batch, gives the total number of machine tools in the system. The composition of the alternative system configurations is a manual operation carried out by the system designer.

Eversheim, W. [65] divides the specification and design of the FMS into 7 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 organisational control - justification of the economic operation of the organisational control - justification of the economic operation of the system.

The analysis of the machining requirements is based on a parts spectrum chosen as representative of the production of the company. Classification systems are very useful when analysing these parts. The choice of the structure of the system is based upon the machining requirements of the parts. Alternative structures are: Unmanned machining station (very high flexibility), flexible transfer line (low flexibility) and flexible manufacturing system (medium flexibility). The required machines should be specified according to type, size and number of machines. Their type and size depends directly upon the characteristics of the parts and the size and number of batches. The number of machine tools is specified from the produced quantity. Opitz, H. [65] gives a procedure to estimate the working space of machines. The choice of the transport system depends mainly upon the requirements of the modularity of the system and its possible expansibility. The necessary level of automation is obtained from the resulting setting-up and preparation times. Main areas which can be automated are the set-up of the parts and the tools and the integration of several operations into one machining station.

The planning of the necessary flexibility integrated in the system is also very important [103]. Several system configurations possess a different level of flexibility and they are suitable for different applications. The planning of the flexibility of the manufacturing system is also a stepwise process. Justification of the economic calculation of the system is assisted by simulation which can give accurate results about the performance.

Implementation of an FMS is also a stepwise function and can be done in three different ways. The first way is in a single operation, the second in machine tool oriented steps and the third one in functional steps. The implementation of the pilot plant in T.H. Stuttgart is described by G. Stute [295]. The optimal configuration of the system is based upon the use of decision tables [296]. Alternative solutions to each subsystem are ranked according to their suitability for the particular system and the decision tables are used to narrow down the number of alternative systems developed.

A more comprehensive methodology to develop alternative system configurations is described by P. Scharf [314]. An FMS is divided into machines and transport and storage for tools and parts. For each subsystem alternative designs are offered and a morphological analysis is used to obtain alternative system configurations. The basic criteria for selecting the best system between the alternatives are also described [61].

The transport system of FMS can be linear, loop, radial or network. A comparison of the suitability of each one can be made by the use of simulation. Vettin, G. [65] separates three types of system based upon the transport principle. The first type has a bidirectional movement of parts while the other two have unidirection. Their difference is that for the second one there is a separation between workpiece carriers and driving units. The suitability of each system to machine and part spectrum depends upon the number of machines, the available storage and the characteristics of the transport system. In order to evaluate all these factors and the several alternatives, simulation is the most suitable method.

Warnecke, H.J. [311] selects the workpiece spectrum in a two- stage data-reduction process. The parts have to be sorted into groups with the aid of a classification system and a parts list analysis. First step is the sorting rotational and non- rotational parts, and, within these main groups, into functional families. With the aid of the production-quantum-analysis one then orders the workpieces, according to quantity. A common form of the presentation of the production-quantum-analysis is the ABC-analysis. For the further planning steps the study of the A- and B- parts is usually sufficient, since the highest rationalisation effects can be obtained with these by proper investment measures.

2.4 Flexible Manufacturing with Automated Tool Management - An Overview

Within FMS, the management and control of tooling is one area in which very little effort has been expanded. A survey of tooling systems carried out by Hutchinson lamented this situation. " *Most FMS's have done a rather good job of supplying the machines with all of the production requirements except the tools*" [63]. There are however a few notable exceptions where, from the outset, the tool flow problem has been given the same degree of attention as the material flow, and where the design of the FMS has included the tool management system as a vital element of the overall concept. A cross section of the technical approaches adopted by machine tool manufacturers to increase the capacities of tool storage and supply locally and at a cellular level are reviewed together with flexible machining installations selected for their partial or fully automated tool flow systems. These systems are also represented schematically where possible using symbols, *figure 2.1* . A Classification of these systems is presented in chapter four. These systems are categorised into installations with:

a) manual tooling systems (machining centre technology), or
b) transferable disc or drum magazine systems, or
c) auxilliary tool store systems, or
d) secondary tool store systems
e) flexible transfer lines

However, the range of possibilities in this field is virtually infinite. Professor G. Stute [295] from Stuttgart University, Steinhilper and Hopp [65] suggest 16 variations on this theme where each variation is according to the number of tool transport units, the number of tool stores, whether the tool stores are fixed or movable and whether there is a tool store near the machine or not. Sultanov and Bruk [299] also present simple categories based on the volume / variety relationships.

2.4.1 Manual Tooling Systems

These systems usually only include the machine-integrated or primary tool stores (PTS). There are some exceptions where other novel concepts have developed to increase the number of tools available at the machine tool level.

These new developments are discussed here. A more detailed survey of these forms of tooling systems can be found in several studies including amongst others de Souza [97] and Shah [283]. The approaches adopted by machine tool manufacturers can be summarised into one of five categories :

a) A standard single integrated PTS,
b) A non-standard integrated PTS,
c) An interchangeable or transferable PTS,
d) Two or more integrated PTS's,
e) An integrated cassette system.

The standard single integrated primary tool store systems are readily described in manufacturers literature and not discussed in detail here. This form of PTS is the standard tool drum, chain, disc, etc., incorporated into the machine tool design.

The non-standard integrated PTS is a novel approach to increasing the number of tools held at the machine level in a confined space. Several designs have evolved and are discussed further in chapter four. One machine worthy of mention here is the Makino MC series of machining centres [222]. This machine has a drum type PTS with capacities for 30, 60, 99 or 120 tools. The tools are arranged in upto 4 concentric circles. Tools in any of the multi-circles can be readily accessed by the spindle via an integrated automatic tool changer or ATC. This machine has been integrated in many FMS installations in Japan and in Britain. Cummins Engines estimates that the tool drum of 60 tool capacity is sufficient for the range of components each machine handles as well as for sister tooling for the identified critical tools. Tool-changing is done manually and can be carried out while the machining is in progress. It is reckoned that no more than 20-30 tools would have to be changed every day.

2.4.2 Transferable Primary Tool Store Systems

The main idea behind this concept is that the PTS on a machining centre can be completely exchanged with a fully set up replacement [38]. The Hulle Hille nb-h 70 machining centre [216] , *figure 2.2*, is equipped with two disc magazines, one on either side of its spindle. It's right hand disc has room for 24 standard tools, whereas the left hand disc is intended for special and duplicate tools and can be automatically exchanged with any of the three replacement discs. The four interchangeable discs, each has capacities of 23 tools, gives a total tool capacity of 116. The fact that this design has two working disc magazines means that, if necessary, whilst one disc is being used, manual tool changes can be made to the other. Manual tool changes can also be made to any of the three replacement discs.

The Yamazaki Machining System (YMS) installed at Minnokamo, Japan (44,124,11,233) is slightly different in concept to the Hulle Hille machine as it has only one 'working' disc magazine, which can be automatically exchanged with any one of four replacement discs. When the YMS wants to exchange one disc for another, the machining column moves along its X axis until its disc lines up with the required disc in the tooling corridor located behind the machine. It then automatically exchanges the two discs. Manual tool changes can be made at any of the three replacement discs. Each disc has a capacity of 30 tools giving a total disc capacity of 150 tools. The YMS, *figures 2.3*, ingeniously overcomes the problem of oversize tools by keeping them together with multi-spindle drill heads, in a special oversize tool rack separate from the discs.

The JOBS FMS concept (217) consists of 11 machining centres each served by a mobile tool cart carrying two discs, *figure 2.4* . Each disc has a capacity of either 18 or 24 tools, and is bi-directional. When a machining centre requires a new disc, or a pair of discs, to be exchanged with its existing pair, personnel in the tool room are informed in advance, by the control system and prepare a new tool cart. Once prepared the new tool cart is exchanged with the old one. By each machining centre a disc drive unit is set into the floor and when a tool cart moves over this, it drives the disc so the appropriate tool is presented to the tool change robot. A tool change robot is located on each machine and simply transfers tools from disc to spindle and vice versa.

Other machines in this category would include the Marwin Automax machines, *figure 2.5*, the Okuma machine design concept, *figure 2.6*, the White Consolidated (WCI) machining centre and the KTM FM200 (218). The WCI OM2A Omnimill (188) is equipped with a replaceable 30-tool drum as well as the standard 90-tool magazine. The Okuma machine design concept (224) is very similar to the WCI approach, although not yet evident in any current installation. The KTM FM200 (22) is a twin tool drum machine. The two tool drums, each with 60-tool capacity can be exchanged for new drums delivered by an AGV network (175). These machines are primarily 'system machines' which require a supporting automated or partly automated tool flow network similar to that described for the Yamazaki installation.

Each system shows a slightly different approach to the same problem, but in general the main advantage of the transferable PTS system is that a lot of tools can be changed in one action. This means that the machining centre can easily cope with substantially different components arriving one after another. This situation would occur most commonly in flexible machining cells (FMC) which is the type of system in which Huller Hille and Yamazaki machines are intended to operate. This is because an FMC is designed so that one or two multi-purpose machines can process a part family, each machine being able to carry out a number of different operations.

Disadvantages for the system occur when a component might require a few more tools than are present in the 'working' discs. To overcome this, either an exchange must be made with a replacement disc containing the extra tools and other necessary tools or a manual tool change must be carried out. It is better, of course, to ensure in the first place that the disc are sufficiently large to cope with all contingencies. In general a part family for an FMC or for an FMS will consist of geometrically similar components, but with specific minor differences in design. This means that if the components are designed with a view to minimizing the necessary tooling, then each component will require a high proportion or standard tooling for equivalent operations.

Hulle Hille [216] have obviously considered this factor because they have wisely included one fixed 'working' disc for standard tools whilst leaving the other interchangeable discs for any special tools that might be required by a particular component. This makes the Hulle Hille tooling system very efficient with regards to the number of tools in its discs. The Yamazaki machine on the other hand might well have to duplicate standard tooling from disc to disc in order to reduce the number of time consuming disc exchanges.

The JOBS FMS appears to have a very inefficient tool management system, as it is a relatively large FMS. Because of this, one would expect it to have maybe one or two multi-purpose machining centres to cope with any major design differences in it's part spectrum, and a greater proportion of specialized machining centres designed for particular operations. In this way process efficiency for the FMS can be improved. Specialized machining may need a large range of tooling but does not need to change all its tools in one action, as is implied by the JOBS FMS layout [217].

The transferable disc system is intended for situations where rapid changes of many tools are necessary. This situation occurs in a typical FMC where one or two machines need to be capable of carrying out different types of operations in order to process the part. However, a design such as the Hulle Hille nb- h 70 machining centre [216] which has one fixed disc for standard tools and four interchangeable discs for special tools is likely to be most efficient with regards to tool duplication.

Increasing the number of machine integrated magazines with ready access to the spindle via a tool changer was a solution favoured by many machine tool manufacturers. These machines were primarily intended as stand-alone machines or for incorporation into cells. Several approaches are evident, many being based on a tool-chain type of PTS. The KTM Fleximatic FM100 is an exception with two 60, 120, or 180 tools capacity drums and twin pallet shuttle [78]. The Okuma MC-508 horizontal machining centre [27] , primarily designed as an unmanned machining station is a 10-pallet buffer machine with two large tool chains containing a total of 152 tools. In fact, the system, which includes a loading arm running on a rail, can be extended to include four chains and a total of 300 tools. Mandelli's Regent series of machining centres [17] adopts a similar principle as the Okuma machining centre, with a double chain for a total of 120 tools.

Another approach to increasing the number of tools available is demonstrated by the Mori Seiki machining centre [27] . Above the normal 60-tool chain is a 40-tool chain for smaller tools such as drills. There is a small arm which hangs down from within the route of the small chain. It picks up the small tool and articulates outward before extending to the lower chain to install the tools into a holder. Only a few of these holders are placed in the lower chain, but nevertheless, it is claimed that many tools can be used. Ex-Cell-O [5] follows a different theme with four banks of 32-tool chain magazines that could be shuttled in and out as needed under computer control. These would be changed to hold different tools when not in use. The firms FlexCentre combines a second system which allows 16 multi-heads to be fed to the spindle by an overhead gantry arrangement. Littons [321] answer to the problem of tool replenishment is to integrate a pick-and-place robot with the machines 60-tool disc magazine. Feeding the robot is a slave drum.

Yasuda (125,279) has simply removed its 60-tool chains from the machine so that a number can be stored alongside the machine - five in the case of the 120N machine. A robot arm slides along above the chains, and removes the tools as necessary. A simple but inflexible system, in that the tools can be used at the one machine only. Therefore, the result as with all these types of systems is an unnecessarily large tool inventory, with a bad balance, and no incentive to rationalise tooling. These machines can be found in the Wartsila Vaasa factory in Finland (127,264,265).

OKK (125), has adopted a variety of systems to increase the number of tools available, but seems to have returned to the use of multiple chains. On the SMC400, there are three rectangular chains, each with 100 tools. Tsugami (97), has two horizontal chains of 120 tools above the body of the machine and the controller and a 20-pallet magazine.

Another novel method for increasing the tool availability is by employing cassettes of tools. OKK (125) has demonstrated a machine which has three stands to carry tool cassettes. The tool changer is mounted on slides on a column, so that it can move horizontally between the cassette and spindle, and vertically to access the required tool from the cassette. Each cassette is a vertical tool carrier of Z-section, so that it can hold two vertical rows of six tools. There are two cassettes on a twin table alongside the machine. The cassette can rotate on the stand to allow access for the second row of tools while the complete turntable rotates to allow access to the second cassette. In this way, each machine has immediate access to 24 tools.

Hitachi Seiki (127,130) has also tried many different approaches to integrating larger stores to machining centres. It has recently come up with a cassette system. The system is built around the HC400 horizontal machining centre with a PTS capacity of 30 tools. The sequence employed is that cassettes carrying four workpieces and upto three tools are loaded into the store and the tools and workpieces can then be transferred to the machine as required. Cassette systems are also employed by Hulle Hille in their nb-h 150, 210 and 260 machining centres (215) , in the Diedesheim Procass machining centre (206) and the Huron/Graffenstaden concept. This features the Huron CU101 horizontal twin pallet machining centre. At the rear of the Huron machine, a rail guided robotic tool changer carrying a cassette of eight tools, changes individual tools in the machine's tool magazines (265).

Werner and Kolb (116,232), also employ tool cassette transfer in their new Quick Tool Change (QTC) machining centre. The tool carriers used are low-cost comb cassettes, that can accommodate eight tools in a horizontal position. When tools are changed the cassette is fully engaged in the links of the lower horizontal chain strand. By either unlocking or locking the chain links in the 'transfer area' it is possible to remove or load not only individual tools but also four or eight tools simultaneously within a few seconds. Individual tools are loaded or removed in the 'basic position' of the comb cassette. In the first 'ejection position' it is possible to manually replace as many as four worn tools with sister tools, and in the completely ejected position as many as eight tools. An automated change of cassettes is possible with a manually controlled electric lift truck, or automatically with an unmanned transport system.

In the QTC system, the tools of up to five cassettes may be alternatively loaded or unloaded cassette by cassette within a few minutes. The chain magazine is divided up into a variably overlapping storage and changing area as well as fixed areas for standard tools and worn tools. This system shows a remarkable localised tool management system in that the tools are deposited in the respective areas after their use in the spindle. The provisioning of the respective area by movement of the magazine chain takes place parallel to machining time.

2.4.3 Auxilliary Tool Store Systems

With this type of system the auxilliary tool store (ATS) can range from just a simple rack as used in the Duplex system [117] to a fully enclosed automatic tool store which monitors tool life, tool off-sets and any other information relevant to the tool. An auxilliary tool store similiar to the latter has been proposed by Mandelli SpA for use in their Quasar system [25].

The Normalair-Garrett (NGL) FMC [26,102,173] at Crewkerne in Somerset consists of two KTM 560 machining centres, each equipped with drum magazines with capacity for 40 tools, *figures 2.7*. Both machining centres are served by a workpiece transfer mechanism and both drum magazines are supported by their own individual auxiliary tool magazines. The auxilliary stores are horizontally mounted chain type magazines with a capacity for 40 tools. There is no protection for the tools, which is a potentially serious drawback for an otherwise substantial initiative.

However as tool arrangement in the NGL ATS is presently sequential (i.e. each tool has its own fixed location and is arranged in order of use) no tool should remain in the system long enough to become seriously polluted. A sequentially arranged ATS is very simple to control but does mean that the sequence of tool use must be known before the start of an unmanned shift. Any changes made to the order of parts in the NGL system would require a complete re-sequencing of the tools in the ATS which would lead to a long machine down-time, NGL appreciate these problems and are currently evaluating a randomly arranged ATS [26] which will greatly improve the flexibility of this tool management system. The ATS's are automatically connected to the machine magazines (PTSs) by pick and place devices. Manual back up of the ATS is provided by the tool room. There is no automatic transfer of tools between the two ATS's which can possibly result in high duplication of tooling.

NGL could justify the use of such a system because they found that studies on a system without the ATS showed that the 50-tool magazines on the KTMs were simply not sufficient for the range of tooling required. For this two machine cell over 200 tools are required. JCB, Hitachi Seiki, Pegard, OKK, Mori Seiki and Yamazaki [139] have also developed this type of semi-manual systems. Very much in evidence for these ATS systems is the use of tool racks of large capacity supporting the machining centres.

Pegard [172,226] features Pegy the tool changing robot, which is floor mounted and mobile by means of a rail. Standing alongside the machine tool, it can remove a tool from the spindle and replace it with a fresh one from an adjacent tool magazine. Pegard has designed a rack-type tool store in which the tools are held horizontally. The cell Pegard has installed for Caterpillar incorporated the Pegy robot. The two Pegard Precivit 2MM machining centres in the cell are both partnered by a Pegy, putting 160 tools at the disposal of each machine. The Precivit machines are equipped with right angle heads so that they can machine all five faces of a component without relocation, important in Caterpillars case of heavy parts, such as frames and cases for earth moving equipment.

The Fritz Werner DFZ630 duplex cell [108,118,187] features an overhead gantry tool change robot transferring tools between the 40-tool magazines on two four-axis machining centres and a bed of movable storage racks behind the machines, *figures 2.8* . This concept was designed to be of use to any company in the business of small batch manufacture of prismatic components. The idea from the start was to provide a single off-the-shelf solution which would suit any customers' requirements. The only variations offered were in the number of machine tools, the size of the buffer store, and the size of the auxilliary tool racks. This philosophy has not changed much since 1983. However, one alteration in the design has been the incorporation of a portal robot for tool change. This is currently in use in the Mirlees Blackstone installation [184].

Mandelli has modified its Regent and Quasar range of machining centres by offering an auxilliary tool store system integrated with the machines. The design does not allow the operator access to the tools so the machines are supplied with automatic tool transportation. A robot transfers tools between the PTS and the static ATS. It is a circular machine to save space, and give the operator a good view [24].

The Scharmann Solon I employed at Howden Compressors [69] has two tool magazines, one with capacity for 40 tools, the other for 80, *figures 2.9* . The smaller magazine has to be loaded manually and not by robot. VEB Werkzeugmaschinenfabrik Aschersleben demonstrated a model of a prototype portal frame machining centre. A tool changing robot is mounted on a cross rail to transfer tools from a floor mounted pick and place device to the spindle. This device serves a 120-tool, rack-type store and a battery of cassettes [203]. Le Blond has demonstrated at the IMTS-84 exhibition a machining centre based cell with an automatic ATS holding 360 tools. A wire guided cart carries, reshuffles and replenishes tool cartridges from the ATS to the PTS [5]. Mazak also has a unique cell which consists of a machining centre with a rack type ATS called a 'Tool Hive' capable of storing upto 480 tools. Hitachi Seiki, Beaver and Mori Seiki [4] have also developed these type of semi-automated tooling systems.

These Auxilliary tooling systems have the advantage that they effectively expand the PTS, but unless there is automatic transfer of tools between the auxilliary stores then there is bound to be duplication of a good proportion of the standard tooling. Duplication has the following disadvantages:
a) Tools are expensive and if they are duplicated then there will be poor tool utilization which is wasteful.
b) Tool stores are very expensive. The more tools you need, the more expensive the tool store.
c) Tool search time is longer because more tools have to be searched through to find the required one. Tool search time can become critical if operation time is short.
d) If tool utilization is low then tools will be standing around for long periods of time and unless they are protected, they will become polluted.

Therefore, in order to reduce tool duplication, more flexible systems have been developed.

2.4.4 Secondary Tool Store Systems

This concept is similar to that of the Auxilliary Tool Store except any one ATS is not specifically intended for any specified machine.

The TOS Olomouc plant [305,306,329,330] developed by the VUOSO Research Institute of Machine Tools and Machining in Czechoslovakia uses an original and very versatile tool management system [331]. It's tool stores and tool handling units cannot easily be represented as a PTS, STS and ATS, as the tool arrangement is quite different to those in other systems, *figures 2.11 and 2.12* . The tool management system consists essentially of three components:
a) A tool handling unit and tool store for each machine. The tool handling unit can take tools from any of its neighbouring tool stores. Once it has found a tool it takes it to the tool changer which holds the tool until the machine requires it for machining. Once the machine is ready the tool

changer simply exchanges the new tool for the used tool and the tool handling unit places the used tool back in a tool store. Each tool store contains 144 tools.
b) One tool transport cart with capacity for 5 tools. This serves all eight tool stores and enables tools to be transferred from one tool store to another. The tool handling unit loads and unloads the tool transport cart when necessary.
c) A manual tool transport cart for each machine, with capacity for 6 tools.

There are 8 similar machining centres in the FMS each capable of 5 axis movement.

The TOS Celakovice plant [304] uses only two machining modules, but in this case the tool transport cart also serves the tool room which can make the system fully automatic, *figures 2.10*. The main criterion for a system as small as this is the highest productivity in the smallest space.

The Citroen Construction Mecaniques (CCM) [8,19,28] FMC at Meudon near Paris makes prototype parts for all companies in the Peugeot SA (PSA) Group, which manufacture Peugeot, Citroen and Talbot vehicles, *figure 2.13*. The FMS also processes parts for the group sponsored rally and Formula 1 cars. The FMC consists essentially of three Graffenstaden 5 axis machining centres. The tool management system consists of three components [31,261,262]:
a) An automatic Tool Room with capacity for 600 tools monitors tool-life and presets the tools. When tools are required from the automatic tool room by the machining centres, a pick and place device at the tool room loads the required tools into a tool rack with capacity for 20 tools.
b) Four tool racks: one for the tool room and one each for the machining centres; each with capacity for 20 tools. Once the tool rack at the tool room has been loaded, it is carried by an AGV to the rear of the machining centre which requires the tools. It exchanges the tool rack for one behind the machine, which contains worn, broken or tools the machine no longer required. A pick and place device is used to transfer tools between the tool rack and the machine's chain magazines.
c) Each of the Graffenstaden machines is equipped with two chain magazines, each with capacity for 50 tools. An ATC transfers tools between these and the spindle.

The Makino plant at Atsugi, Japan [10,23,220] has been constructed using the most up-to-date technology, *figure 2.14*. It is different from the conventional FMS in the way that dynamic scheduling and total tool management have been incorporated. The MAX FMS is highly flexible. It can manufacture on a one-off or batch production basis. It can produce many diverse types of parts and is capable of producing a single part from a multiple set-up fixture. MAX is capable of 550 different operations. It can produce 270 pieces in a 24 hour period, the average part machining time being 47 minutes. A highlight of the Atsugi factory is the Max tool management system which provides the ability to move tools from a tool warehouse to any of the 10 machining centres in the system. The tool warehouse stores up to 1008 tools which combined with the capacity of the machines yields an overall capacity of 1608 tools. An efficient tool transportation network links the tool warehouse and the individual machines. The tools can be randomly selected from the warehouse and transported by two tool carriers in 5 sets of 3 tools to the machines. This common base of technology has also been introduced in the UK [9].

The Cincinatti Milacron [6] installation at Vought Aerospace, *figure 2.15*, is another automated tool flow system similar to the CCM system installed at Meudon. It incorporates 4 Milacron T-30 90-tool capacity core machining centres served by three computer controlled carts for automatic tool supply. Spare tools are prepared in a 24-tool magazine at a tool setting area. An AGV will take the spare tool magazine to the machines needing the replacement tooling. Worn tools in the permanent magazine are replaced with the new tools from the mobile magazine by a transfer arm at the back of the machining centre. This tool changeover can be performed because the integrated magazine is split into two sections.

Hitachi Seiki, one of the larger Japanese machine tool manufacturers, has three flexible manufacturing cells (FMC's) installed in one shop. For large prismatic workpieces, there are four horizontal machining centres served by a rail guided trolley from a setting-up station on each side of the line. Tools are supplied on cubic pallets by the trolley to the sides of the machine. For the medium size prismatic workpieces there are two vertical and two horizontal machining centres served by another rail guided trolley. This FMC is comprehensive in that it includes a warehouse of 528 pallets accessed by a single stacker crane and a tool store. The tools are mounted in racks on a carousel in the store, and are accessed by a cartesian co-ordinate robot which loads them onto pallets which are transferred to the trolley to the machines. The trolley is also used for workpieces transfer. The third FMC is for turning. Tool changing is effected by a gantry mounted robot that draws Sandvik block tools from a magazine in the cell [20,129].

The Leyland Bus turnkey installation at Farrington, for the manufacture of city buses, bus bodies and coaches incorporates five identical Heller BEA2 machining centres laid out in a line and supplied with palletised parts by two AGV's. Each machine has a tool magazine with total space for 160 tools. The magazine is in two sections - a back two-tier section where each tier carries upto 60 tools, and a front section for upto 40 tools. Direct tool changing takes place between the front magazine and the spindle. The system operates a comprehensive tool management package which retains details of every tool item and assembly, along with its stock. Transfer into the tool magazine on the machine is done manually, but while machining is in progress. The operator manipulates the back section of the tool magazine until an empty pot is at the load/unload position and then inserts the tool into it. A photocell at the load point indicates to the system that the tool, associated with it's pocket number, has been inserted [176].

The OKK-FMS 'MCS 102' installation set up by Osaka Kiko [15] in Japan is a three machine FMC consisting of one vertical MCV-630 machining centre and two horizontal MCH-560 machining centres. Three STAC B120 tool stores of 116 tool capacity each are evident. These are linked by one railed vehicle. The STAC changes tools in the PTS magazine by commands given by the tool monitoring system which is also connected to each machine. This does not overlap with the PTS to spindle tool exchange.

JCB uses a Sandvik tooling system to support the machining centres. Each machining centre has an on-board tool management system. This system monitors and controls the movement of tools between the machine's 80-tool storage magazine and a dedicated 24-stations mobile carousel in which the tools are moved by an AGV between the machines and the tooling area when tool replenishment or refurbishment is necessary. The interchange of tools between the carousel and the magazine is carried out randomly [34,163].

The Okuma Oguchi plant in Japan [123] consists of seven of the companies horizontal machining centres, four MC-5H models and three MC-6H models. Connected to the machining area is a tool control room with capacity of upto 500 tools. The tools are delivered to the magazine stations beside the 70-tool chains of the machines, for manual tool loading by Murata wire guided carts. The line produces 95 different workpieces in batch quantities of 10 to 20 , mostly lathe headstocks, machining centre spindle heads, grinder tailstocks and lathe saddles.

Murata, the manufacturer of textile machines, Warner Swasey machine tools and punch presses, has an installation of seven Yasuda and Okuma machining centres, *figure 2.16*. The tool store comprises of six carousels in which tools are carried on horizontal chains rotated by common drives. Each carousel holds 140 tools, so that a total of 840 tools can be carried. The AGVs are used to transfer tools held in discs to the machines. Each disc hold 15 tools. Special purpose loading arms rapidly exchange tools between the disc on the AGV and the PTS [128].

Scharmann's installation at Engel in Austria, used for the manufacture of plastics injection moulding machinery consists of three Ecocut 1 machining centres and one Dorries vertical turning centre. A pallet transfer mechanism is used for workpieces as well as for the tool drums. The pallets with tool drums are brought to the side of the machining centres where a special device then replaces the worn tools in the magazines with fresh ones from the drum so that tool exchange can take place without disrupting machining time. Scharmann has also installed two very similar systems at BMW at Munich. Both incorporate six Solon 2 machining centres supported by rail guided vehicles, and one also includes a fine boring machine. Another Scharmann system implemented at Caterpillars Lafayette plant in USA includes three Ecocut 1.3 horizontal machining centres with two Portec AGV's. Caterpillars Mossville plant also in the USA incorporates seven Solon 2 machines supported by rail guided vehicles. Both these plants also have the same tool flow system previously described [183]. The Brown Boveri installation at Baden in Switzerland for the manufacture of turbo chargers for diesel engines in the 600-25000hp range was supplied as a two-stage turnkey system by Scharmann. The Tufega 1 and Tufega 2 phases together incorporate four Ecocut 80-tool capacity machining centres. The tool flow system is based on the AGV moving tool drums between the machines and the tool room as in the previously described Scharmann installations [274].

The American Forth Worth division of General Dynamics, which manufactures the F16 fighter plane at a production rate of 150 per year, is a six machine cellular installation based around the SAJO machining centre, *figures 2.17*. Tool delivery to the machines is performed by an AGV network. A GMF cartesian robot MIA robot transfers tools between the pallet and the tool magazine on the machine tool. With a total of 684 tools available on the machines, capacity is available for sister tooling [182].

The GMF installation in Michigan incorporates a flexible machining cell designed to produce more than 60 parts mostly as one-offs. The FMC is set up, around a Makino MC1210 horizontal machining centre and a turning centre. Automatic tool replacement is carried out using a gantry robot. The turning centre is equipped with a 30 station tool magazine and an automatic tool change facility. Prepared tools are stored in the FMC in racks. The gantry robot servicing the tool area automatically selects the relevant tools from the racks and places them on a pallet which the AGV system then delivers to the machines. The gantry robot in the machining area picks up the tools one at a time and then loads them into the PTS [254].

The 'Small Parts' FMS installation at British Aerospace [46,166], Preston, is designed to produce small prismatic parts, *figure 2.18*. Upto fifteen different components are to be machined in batch sizes of five to ten. The FMS cell forms one of nine cells under factory level DNC control. The cell uses concepts first introduced in the revolutionary Mollins System 24 [323]. One of these features is the manufacture of families of nested components from a single block of material. The cell is designed to work in two levels. The machine tools are on the ground floor. Kits of tools and workpieces are assembled on pallets manually on the mezzanine level. Paternoster stores link the two levels. Tools are transferred to the machines where they are shuttled into the machine. A robot feeds two identical tools from the kit to the twin spindles of the Automax machining centre [175].

Toyoda Machine Works, IPA Stuttgart, IBM Italia, Toshiba and MBB have also automated the flow of tools. The IPA design is based on a proprietary AGV and robot. The Toyoda system in Japan is purpose built. The AGV carries a circular rack with a capacity of 14 tools. There are also some buffer stores with similar circular racks but with capacity for 20 tools, adjacent to the machines. The robot can load the tools at the central tool stores, transfer them to the buffer, and then transfer them when necessary to the PTS on the machines [124]. The IBM FMC at Vimercate, Italy, is based on the Mandelli Quasar machining centres and employs a tool store with a shuttle transferring tools to and from the Quasars [202]. Toshiba in Japan [128], and MBB in West Germany [320], both use an AGV transport network for the tool flow. MBB was one of the earliest systems to employ AGV's for this purpose [119,131].

The STS concept has a lot to recommend it, especially when the cell or FMS is large. This concept has also been applied at Butler Machine Tools in the UK, because it is envisaged that an 'unlimited amount of tool storage' will be required. A buffer store is close to each machine, and there is an overhead rail system to transfer tools between the stores, the buffers and the machines [177]. Yamazaki's 'green field' site at Worcester also employs a similar tool flow network, employing a 'tool highway' to transfer new or used tools individually between a tool store and the machines in several cells [37,179,189,190]. This Yamazaki 'Intelligent Mazatrol FMS', *figure 2.19*, as installed at Worcester is made available in configurations ranging from a single machine to a number of machines in a cell. The STS is a 'tool hive stocker' with a capacity for between 160 to 480 cutting tools [234]. A very fast tool robot of single tool capacity is able to load and transport tools from the tool hive into the primary tool store of any machine. The machines themselves have a PTS capacity from 30 to 120 cutting tools. A similar system also employing a tool 'highway' or overhead gantry is the two machine Cincinatti Milacron T10 cell which was on display at MACH '88 [207a]. The two T10 horizontal machining centres each had a capacity of 90 tools in two 45-tool chains, supported by an STS of four chains, each with 170-tool capacity. Although these overhead systems have the advantage that they do not take up floor space, they are less flexible than wire guided AGV's, and their design can be complex. In these cases, though the workpieces are large so it would not have been practical to use the same system to transport workpieces and tools.

The requirement for operating these overhead single tool transport systems is three-fold. Firstly, the transporter itself must be very fast and reliable. Secondly, the accessing time for tools from each of the stores must also be very rapid not only for search, load and deliver from the STS but also unload, replace and return from the PTS. To this purpose Cincinnatti claims an average of 6.5 r.p.m for each of its four STS modules. Finally, for the system to operate effectively, the PTS of each machine, particularly in the case of single tool carriers, should be partly loaded with required tools according to a capacity plan in order to overcome availability problems of the carrier, particularly in the case of cells. For all intensive purposes, the PTS capacities of such systems tend to be large, as is evident in the Cincinnatti and Yamazaki systems.

2.4.5 Flexible Transfer Line Technology

While almost unlimited flexibility has been reached with the aid of CNC machining centres, for small to medium scale production, relatively narrow limits of flexibility for tooling are set for current solutions of medium to large scale production, particularly in the automotive industry where there is a requirement for quick and automated conversion of production. CNC machining centres fail to achieve this objective because insufficient production capacity is provided by single spindle operation, low capacity spindle drives, and restrictions placed on the maximum size of multi-spindle head which can be carried, and indexing or positioning errors of the multi-head changeover unit. Two machine types have evolved to suit this flexible transfer line technology : the first is the special purpose CNC modular machine based on machining centre technology but with the capability for handling much larger workpieces and the second is the more common multi-tool head machines as manufactured by companies such as Cross (256).

Three notable design concepts have evolved to try and provide a solution to the problems outlined above. Hulle Hille have developed a flexible system, Orbiter, designed in the form of a basic modular unit. All the traditional machining processes from milling, drilling and to precision boring are featured. Various possibilities of expansion and nearly all conceivable multi-spindle head storage systems from one to, theoretically, an infinite number of storage locations ensure a comprehensive field of application from the individual machine to the flexible transfer line (214,256).

The Quattrex 500 Wanderer, offers similar technology to the Orbiter but is of a modular design. The Quattrex 500 production unit can be expanded in stages or altered in a variety of configurations to achieve completely different production facilities than those originally implemented. Several set-ups of production facilities using the Quattrex 500 have been demonstrated by the company (13,231).

Vigels Modulflex System is another variation on the theme of modular design, ideal for the machining of batches composed of different parts or families of workpieces. Modulflex, it is claimed, offers both the productivity of special purpose machines and the flexibility of machining centres (230).

2.5 Turning Centres

Automated tool changing was one of the first problems to be resolved in machining centre design, and has significantly expanded the role of the machining centre. Tool changing has also already been applied to NC punch presses and certain spark erosion machines. Automated Tool changing is one of the last areas to be tackled on the NC turning front. But with the NC lathe population now far outstripping all other NC machine tool types, more builders are turning their attention to the 'turning centre' concept (46).

It is desirable to draw a distinction between a CNC lathe i.e a 2D machine tool in its simplest form and a turning centre, which describes a substantially more automated machine tool. A turning centre will typically have automated workpiece handling facilities. Tool flow will be provided to give magazine support to tool turrets, contact probes will be included to monitor measurements on cutting tools and components and, in some areas, automatic chuck or chuck jaw changing is available. Each of these features is under the control of the NC part program.

In addition, four-axis twin-turret designs are widely used [237], the provision of a further axis i.e the C-axis for the positional control of the spindle is required when live tooling is employed. The increase in the use of turning systems with live tooling gives improved economic performance in many cases as secondary machine set-ups are made redundant. The task of providing the flow of cutting tools is made more complex as designers seek to provide increased power at the spindle.

A summary of the current state of the art in turning systems design is shown in *figures 2.20 and 2.21*. The provision of cutting tools is highlighted. A more detailed discussion can be found in research studies carried out by de Souza [97], Choi [84], and Zhang [333]. Classification and modelling of these systems is the subject of a complementary thesis, by Zhang Pan, at the department of Manufacturing Engineering at Loughborough University [332].

2.5.1 Stand Alone Turning Centres

Just as a machining centre can handle a range of metal-cutting operations at a single set-up, so can a turning centre. And there are now quite a few of these on the market, though few come equipped with automatic tool changers (ATC). It's still early days with ATC, particularly regarding UK applications and the activity tends to be directed towards conventional NC lathes.

Multi-function NC turning machines can perform a host of second operation work, in addition to conventional turning, at a single set-up. Tasks can include end, straddle, cam and slot milling, and cross and face drilling/tapping. And with the general trend toward smaller batch sizes, this approach can be most effective in terms of reduced work-in-progress and the cost of setting up and operating additional machine tools. Many of these new machines were on display at the MACH '88 exhibition at the NEC in Birmingham [192,257].

While actual designs vary - the attitude of the tooling turret/turrets and the use of radially arranged tool slides, for example - the machines do have some common features. These include a third axis of NC for the precise control of spindle rotation (for cross drilling and the like) and the means to power rotating tools. Some designs mix conventional and rotating tools on the same turret - others have separate turrets for each type - and some even offer an automatic tool change option for rotating tools.

Right angle attachments (for powered tools) are available on cross and in line turret configurations to suit most milling and drilling demands, And nearly all turning centres feature a separate drive system for the rotating tools, either individual motors or a shared system centred on the periphery of the turret.

Another model formed part of a two NC lathe FMS set-up to produce four shaft type parts. The turning centre featured three-axis contour milling and 12-station tool turret which could handle up to four drill/mill heads. A programmable bolt-on robot and a palletised-based materials handling system provide the link to the other machines.

This set-up also featured a new image sensing arrangement for automatic part recognition to enable random part manufacture without operator intervention. It also highlighted the growing importance of electronic gauging. This can be in-cycle or at an independent station to measure and classify workpieces transferred by robot from the second NC lathe. Both systems automatically correct tool offsets (to compensate for tool wear and thermal variations) by comparing a certain number of readings with basic component design tolerances held in the control's memory.

Tooling turrets feature prominently on most NC lathes, with turret capacities of 8, 10, 12, 14, 16 or more tool positions, 12 stations being most popular on drum types. But there are tooling systems, referred to as gang or free sets, which basically consist of a series of small toolholders mounted on a flat plate which fits directly on the machine's cross slide. Five holders is common and the cross slide movement is controlled by the NC system.

The main advantage claimed for this system, in addition to being fairly simple in design and therefore relatively cheap to buy, centres on indexing time and the ability to overlap adjacent tools for shorter machining cycles. The linear indexing motion of the slide is said to be much quicker than indexing a drum or disc type turret (even bi-directional units) and the use of grouped, cranked and straight tool holders enables turning operations to be 'doubled up' on certain jobs.

Such systems could also prove useful on relatively large batch work carried out at regular intervals. For in addition to saving tool indexing time, the tooling set-up for the job could be kept ready for use on its own mounting plate (which fits directly on the cross slide) in the stores.

There have been attempts to change cutting inserts automatically, but accuracy problems and tip shape restrictions are limiting the progress. And the sheer weight of changing complete tools - machining centre style - and the required size of the magazine have put many designers off this type of ATC.

However, there are companies that offer ATC as an option. HES is an example, with a version of its FLS 40 NC lathe. In this form, the machine has a six-station turret on the lower saddle and a milling/boring head on the upper saddle which is automatically served from an eight-station tool magazine. In a similar vein, the Sculfort CN25 NC lathe is supplied with an eight-station automatic tool changing system as an option to an 8- or 12-station turret.

A slightly different approach to ATC is offered by Les Innovations Mecaniques with its T9SCN slant bed NC lathe. This sytem is based on a 15-station chain type magazine and Multifix toolholders. The ATC pre-selects a toolholder while the previous tool is machining and 180 degree transfer takes place during a break in the cutting cycle. The toolholder blocks incorporate a coolant distribution system and a binary code to ensure correct tool selection. Along with options such as programmable tailstock, steady and bar feed, this lathe can now also be equipped with rotating tool heads for in-line milling and drilling operations.

The Citizen Cincom E-32 (97) has a rotary tool mechanism powered by a DC motor. Twelve positions are available on the turret. Clockwise and anticlockwise rotation allow for reduced tool change times and therefor reduced cycle times. The Cazeneuve HB-CND turning centre (97) has a 12-station turret. Conceived for using the maximum number of tools with the minumum intereference, it is coupled with a tool presetting system. A similar concept is used by the Takisawa TS-20 CNC lathe (97) which includes the exclusive Takisawa 'sleeve valve' allowing non-stop, random select and rapid indexing. The multi-station tool drum automatic machine on the Witzig and Frank Turmat, is built with 4, 6 or 8 stations with double indexing and therefore double the output (97). Quick reset and tool change times are possible. The Turmat allows machining on three sides of the component simultaneously. A system that allows tool change without the use of a toolchanger arm is the MCM.

Turrets can come in various shapes and sizes. Turrets provided by Siemens [97] cover many types, including ones of special design. Square, hexagonal, and rotary-plate turrets are available to match the particular job, number of tools and selectable positions. The Yamazaki Quickturn 20 [97] has an 8-position drum turret of octagonal shape which can be indexed and clamped in each tool position. The turret is bi-directional with no required tool holders.

The Nakamura-Tome CWE lathe TMC-2 drum type turret head provides for 12 tool stations [97]. This unique design optimises tooling combinations and minimises tool changeover time through the use of quick change tooling. Tools on the massive disc turret of the TMC-3 and TMC-4 lathes are in tool holders which are mounted on the turret by fastening of only one screw. This bidirectional indexing turret takes the shortest route to the next station. The quick change tooling minimises set-up time. Automatic tool change is available with Sandvik block tool units. Tool magazine stores 40, 60 or more production requirement. Tool change goes hand in hand with tool life, and a broken-tool monitoring system.

Other new designs incorporate twin spindle operation allowing two workpieces to be machined simultaneously. The LD 200-2-2 twin spindle CNC automatic is an example [100]. By incorporating the 'live tooling' power driven mechanisms to the turret, secondary operations, e.g. drilling, milling, tapping, etc., can be carried out in one set-up. This reduces the machine idle times and the set-up times. Other new technologies include automatic chuck jaw changing to accommodate a large range of component varieties [132,229], gauging systems for tools and workpieces and an in-process and post-process gauging system. Okuma has also developed a new gauging system which is claimed to improve both reliability and accuracy during sustained unattended operation. Overload and tool breakage detection have also become popular in new machine designs because they indicate when to change the tools.

2.5.2 Modular Tooling Systems

A lot of the recent ATC activity has come from the tooling side of the business, where the use of a split type of tooling system, with lightweight and interchangeable tool heads and a toolholder which remains in the turret at all times, is attracting attention. In addition to offering automatic toolchange, by robot arm devices and tool storage magazines,this concept can also simplify and speed manual tool change because the actual tool changeover is quick and the tool holder datum remains constant. The use of these modular tooling systems has also increased the tool storage capacity and the availability of tools at the machine level. They also enhance the standardisation of tooling system design. These systems, now very much in evidence, have brought versatility and ease of setting to the stand-alone CNC lathes [165].

Several systems which come into this category [333] are : Karl Hertel's Flexible Tooling System, Krupp Widia's Widax Multiflex Tool System, Kennametal's KV Tooling System, and Sandvik's Block Tooling System. The Hertel and Sandvik tooling systems have the unique features of being compatible with tool changing features on machining centres as well as on the turning centres. Evidence of this can be found in the JCB Transmissions plant at Wrexham [34].

2.5.3 Lathes with Primary Tool Stores

Although the ATC is now standard for machining centres, the turret is still considered the standard tool holding device for lathes, because it has been more cost effective than tool magazines (PTS). However, the PTS concept is recognised as indispensable for the development of sustained unattended operation of CNC lathes. As previously discussed, another trend in turning centres is towards multiple machining models. The strong demand for integrating these secondary processes with the primary turning processes, has given rise to this type of machine and it is now becoming increasingly popular (225). The PTS on these lathes serves to increase the local tool storage capacity as tool life for turning tools is quite short (15 minutes in some cases) and a large number of tools is required for operation to be conducted for more than a couple of shifts without operator attendance. The use of the PTS can be summarised in the following three points :

a) spare tool selection : when a tool wears out, it is replaced with a spare from the magazine thus allowing the machining cycle to continue.
b) set-up change : After the set-up has been changed, the cutting tool for the next set-up is selected from the magazine so that the machining is continued on the next workpiece as quickly as possible.
c) multi-function or second-op. : Workpieces which require secondary machining processes can be handled on a single machine. Evidence of systems with an integrated PTS (333) include : Warner & Swasey WSC-8E7, the Index GSC-65, Slant Turn 40-N ATC Mill Centre, EMAG MSC 22, the Heinamann Flexible Compact System with upto 120-tool capacity and the Heid FMS 530 which features tool pallets and a gantry type tool changer.

2.5.4 Cellular Turning Systems

In highly automated batch manufacturing systems the primary tool magazine is supplied with tools automatically to facilitate a longer period of unmanned operation. This tooling system configuration can accommodate a wide spectrum of component varieties. The forementioned categories of tooling systems may be integrated through a tool transfer network to form a multi-machine flexible machining cell (188). Evidence of this level of tool flow automation can be found in very few installations. Two examples are provided by Hitachi Seiki and EMAG. The Hitachi Seiki installation with three CNC lathes and a horizontal machining centre has been designed for machining batches of 460 different gears. A gantry has been equipped over the three lathes for the tool changer to move along. It transfers tools between tool turrets and the tool magazine. The EMAG FMC transfers tools in pallets by a rail guided vehicle from the central store to a specified machine. Other examples of this level of automation are evident at Yamazaki's Worcester plant (190) and the Pratt and Whitney plant in Georgia (178).

2.6 Scheduling

One of the most important operational problems in Flexible Manufacturing Systems is the Scheduling problem (292). Some attempts have been made to model and study the problem (194). Many solutions are provided by various researchers, most of them representing an "n" job, "m" machine, job shop scheduling method extended for FMS. Most of these solutions provide approximations and cannot consider real-time changes in the FMS at the required speed, and the new schedule generated for the entire FMS system, frequently, cannot be executed by the FMS control system, the tool management system and the material handling system. Ranky (270) identifies processing time of scheduling or rescheduling as the biggest drawback. Based on the published literature, the FMS scheduling problem is not easier to solve than the scheduling problem in the classical manufacturing systems. It is even more complex due to new variables related to the specific resources, for example, automated materials handling systems, automated tool handling systems and fixtures. The approaches to the scheduling problem offered can be classified into heuristic, optimal control, mathematical, multi-objective, dynamic and artificial intelligence techniques. As mentioned earlier, the scheduling of an FMS is similar to that of scheduling a job shop, since the processing of various items on a common set of machines requires effective methods to reduce problems associated with competition for resources. Early systems for scheduling job shops typically tested very simple heuristics in a simulation environment [(244)] and were not close to optimal. Conway et al [(87)], Jones [(155)], Coffman [(86)] and Baker [(50)] provide good examples of simple job shop despatching rules and the general scheduling problem. Further enhancements to heuristic scheduling were made by Iwata et al [(153)] with the consideration of manufacturing systems incorporating automated tooling systems, and Sriskandarajah et al [(291)]. Hirtz [(138)] also discusses the flow shop approach to scheduling of FMS's. Other Heuristic algorithms are discussed in Lin and Lu [(201)], Iwata et al [(150,151,152)], Lagewey [(198)] and Nakamura et al [(99,246)].

The scheduling of FMS's also lend themselves to mathematical techniques, typically integer programming methods. From scheduling theory, it is known that the problem is NP complete and can be approached by handling a two stage procedure viz station loading and operation scheduling [(195)]. Stecke [(293)] has identified several objectives which could be used to formulate the loading problem (e.g. balance the assigned machine processing times to fill the tool magazines as densely as possible). The constraints in such a problem would include tool capacity and assignment of the required number of operations and tools to at least one machine. Stecke has formulated the loading problem as a non linear 0-1 mixed integer program model. She applies linearization procedures in this problem to facilitate solution. Kusiak [(196)] has proposed simple integer program models based on practical assumptions. Though the models are static, Kusiak points out that they can be applied to dynamic situations as well.

Several researchers have tried to solve the scheduling problem where there are multiple objectives by goal programming. Locket and Muhleman [(193)] handle the problem by achieving a balance between a smooth work load and maintaining production with due date. Kim [(193)] discusses the problem with the objective to compromise the conflicting objectives from different functions of an organisation and deals with the dynamic features of critical resources or bottlenecks in a company. O'Grady and Menon [(240,249)] present a planning framework which enables the selection and scheduling of a subset of prospective orders which constitutes the best compromise solution in relation to a set of conflicting performance goals. The modelling approach includes concepts drawn from 0-1 programming, boolean relationships and the weighted attainment form of goal programming. Tool magazine capacity is considered as the limiting factor in the system and influences the selection of sub sets of the product range.

Most of the scheduling, or sequencing models so far discussed are unfortunately deterministic and static. In reality, manufacturing systems are stochastic and dynamic. FMS is a dynamic system and not stochastic at least less stochastic than other manufacturing systems. Stecke [(293)] and Browne et al [(70)] have indicated the inadequacy of classical off-line scheduling methods and have stressed the need for a real-time on-line scheduling policy which can take care of the dynamics of Flexible Manufacturing Systems. Such a system is operative at the Makino Milling

Machine Company in Japan. The S-POS system evaluates the current status of the available resources and calculates the priority of every job in the system before allocating production resources [219].

Recent approaches in tackling the scheduling problem have been made using expert systems which provide a suitable framework to develop such a real-time on-line scheduling system. The techniques of artificial intelligence and expert systems, in particular, end themselves as a suitable candidate to make the real-time scheduling problem more tractable. In the context of the scheduling problem, an ideal expert system would adaptively governs the overall behaviour of the system. To do this the scheduling problem would repeatedly interpret the current situation predict the future, diagnose anticipated problems, formulate a remedial plan and monitor its execution to ensure success [133]. The concepts of expert systems as applied to solve some of the problems in scheduling a FMS are discussed by Subramanyam et al [298]. Recent developments of artificial intelligence techniques and the application of these techniques using LISP are addressed by Shaw et al [284].

2.7 Scheduling Under Tool Availabilty Constraints

An FMS can only achieve high machine utilisation if its production schedule part mix is in balance with the capacities and the tooling of the system. This issue is dealt with at the strategic planning level of the three-tier FMS decision making hierarchy proposed by Suri and Whitney [300]. A lot of recent research activity, using mathematical modelling techniques, has been directed at the third or real-time level, incorporating other details such as tooling constraints.

O'Grady and Menon [251] have set up a modelling framework for determining a master schedule of orders for processing by an FMS. This framework uses a goal programming approach with binary variables, boolean expressions and a weighted attainment function. They supplemented this work with specific supplementary elements for a complete model of FMS [258]. This encompassed hierarchic formulations of tooling and multiple process routes, compact representation of duplicate tooling at the machines, compact representation of parts with similar tooling and formulation of weighted preferences for multiple objectives. The model is structured using standard mathematical programming software. Much emphasis has been put on compromise solutions rather than pursuit of global optimality. The model is complex with considerable computational considerations. Sarin and Chen [278] address the problem of determining the routing of parts and the allocation of tools to the machines so as to minimise the total machining cost of the operations. This machining cost is assumed to depend upon the tool-machine combination. The model considers tool life, tool slot capacity, and congestion. The model is unique among other mathematical models, but just as complex, because of the consideration given to the limited availability of the machines and the cutting tools, by adding a constraint in the model formulation that states that the processing times of the parts assigned to a tool cannot exceed its tool life. Stecke [293] uses a 0-1 linear mixed integer program to balance the assigned machine processing times and to minimise workpiece movements. The model emphasises the problem of possible tool slot savings. However the finite lives of the tools are not considered. The proposed solution procedure requires the tedious step of linearising non-linear terms. A branch and bound solution for this problem which avoids the linearisation step and solve the model directly was later developed by Berrada and Stecke [62]. Rajagopalan [266] also attempts to use the Stecke model to obtain better production schedules without an iterative process. A revised formulation of the variable is presented. A mixed integer linear programming model is used and two types of heuristic solution procedures are also presented.

Kusiak [197] formulated a 0-1 mixed integer linear program for the machine loading problem. The strength of the proposed loading model is in it's linear structure and some practical constraints like tool life and tool slot limits. However, the model suffers from the following limitations :

a) the operations of a batch are assumed to be uniform and continuously divisible,

b) a new tool is assigned each time a batch is assigned to a machine even though that tool has already been loaded on that machine, thereby resulting in more tools being assigned to a machine then required,

c) every operation of a batch is assumed to have identical processing times,

d) tool lives are assumed to be the same irrespective of the batches and the machines to which they are assigned.

Chakravarty and Shtub [81] formulate a tool allocation and workpiece assignment problem as 0-1 mixed integer linear model. The decision variables correspond to the allocation of tools to the machines. The objective is to minimize total processing time. In this model parts are assigned to only one of the machines, assuming that the machine can handle all the operations of that part. Consequently, part routing does not exist. The model does not consider tool life and primary tool capacity limitations.

Carrie and Perrera [78,79,80] developed a linear program model, which has not been evaluated. The model selects from a list of orders to be processed, a subset of orders to be launched to comply with tool and machine capacity. It seeks to minimise an attainment function, defined as the summation of the products of deviation from the desired level and a weighting factor for each parameter. The parameters which are included are :

a) the machine hours available,

b) the capacity of each machine's tool magazine,

c) the number of standard tools at each machine,

d) the number of non-standard tools required by each part at each machine,

e) the due date of each order, and

f) the number of each type of tool available.

The Carrie and Perrera model needs further assessment and no optimal formula has been proposed, rather it has been shown that the problem is one with many parameters.

Several other heuristic scheduling models have also been developed to avoid the complex computations in the mathematical approach. Chakravarty and Shtub [82] have further developed a heuristic model based on their previous non-linear integer model. The model seeks to select a set of parts from a master list of parts, needing processing, in an efficient way so as not to violate the machine magazine capacity and to minimise the number of tool set-ups required. The model uses tool and pallet grouping procedures to achieve this objective. The model also has the capability to suggest capacity expansions in the number of machines, number of pallets or the number of tool holding slots in the tool magazines.

El-Gomayel and Nader [108] also use tool grouping procedures to minimise machine set-ups and tooling. They employ group technology principles to determine the part groups and hence the tool sets needed. Parts can then be allocated in any sequence to each tool set. Cluster Analysis techniques [91] is another solution procedure used effectively to reduce cost and greatly simplify tool management. Cluster tooling analyses the operations on each machine in a group, to find tool families which can be machined one after another using the same tooling with the same set-up. This approach was discussed earlier with regard to the Makino installation.

2.8 Models of FMS

The problems posed in the design and control of FMS are similar to those posed by any conventional manufacturing system but far more difficult. Therefore algorithms must be developed which will assist the computer to handle every possible contingency [286]. The computer is actually responsible for taking every decision and human intervention should be kept to a minimum.

There are many different kinds of decisions to be made. Hence, there are many different ways to model the same system, depending upon emphasis given to different aspects. Perhaps the most obvious technique for evaluating design alternatives is computer simulation. A number of high level simulation languages have been developed in recent years to ease the task of developing simulation models. There are, however, some inherent disadvantages to simulation, such as difficulties in interpreting the statistical output, knowing when equilibrium has been reached and the like. The principal shortcoming of simulation insofar as system designers are concerned is the need to specify everything in detail before any information is returned. What is needed are simple mathematical models which clarify the intricate relationships among the design parameters and performance measures. The task of developing such models both requires and provides a deeper understanding of the structure and behaviour of the real systems.

Given the multitude of models which could be generated for various problems associated with FMS, it is useful to develop some terminology to categorise them. With respect to the form taken, there are three broad classes of models: physical, simulation and analytical.

Physical models, also called emulators, make use of hardware devices which are sufficiently similar in their characteristics to those of the real system to draw inferences about how the real system would behave. Simulation models take the data used by the real system and, through step-by-step duplication of the changes that data would undergo as the real system operated, transform it into output measures. Although it conceptionally amounts to little more than a straightforward "book keeping" procedure, implementation on a computer permits rapid processing of vast quantities of data. Analytical models present quantities and relationships as mathematical variables and expressions, which are then manipulated (mathematically) to yield the desired information. The use of a computer may or may not be required to "solve" the mathematical problem.

A model may be either descriptive or normative. A descriptive model merely attempts to capture the essential aspects of a system in order to provide information about the system or its performance as it is understood to operate. Input parameters, control rules, operating policies and the like are either built into the structure of the model or are taken as given. No attempt is made within the model to determine what anything should be. A normative model, in contrast, leaves certain variables of the system description unspecified initially and employs some specific algorithm to determine what they should be. System objectives must be made explicit and incorporated into the model.

In this survey of some models available, three categories are considered. These are the closed queueing network mathematical models, discrete simulations and specific simulators for looking at problem sections of the overall system [273].

2.8.1 Simulation Models

The most appropriate method to study FMS is the use of digital simulation techniques. Specific simulation languages or high level languages e.g. Pascal are used to model particular system and examine the influence of the several parameters. The basis of the normal type of simulation is to refer to a step-by- step calculation of how a proposed system will perform. Because every event is considered in as much detail as is required or as the model will allow, it is possible to build into a model all the decision-making logic that the final system will use. This enables much more realistic predictions to be made about a system's performance. The first simulation package of a library of subroutines was the General Simulation Package (G.S.P.) developed by Tocher [302] and there has been considerable development since then. A brief history of the development of these packages and a discussion of the different types of simulation is given by Mills [90] and Kay [158]. These packages now form the basis of most simulation work. Some of the simulators developed by researchers in the field of FMS incorprating some level of tool flow are reviewed. A more complete survey of generalised models has been undertaken by Shires,N [285] and Newman [248].

Meyer, R.J. and Talvage, J.J. [237] have simulated the operation of the Caterpillar FMS and Stecke, K.E. and Solberg, J.J. have tested, by the use of this model, several loading and control strategies for the system, and they have compared them with the one applied already for this FMS. Rajagopalan,S. [266] attempts to combine a few of the five production planning problems identified by Stecke so as to obtain better results without an iterative process.

Chan, W.W. and Rathmill, K. [63] have simulated the operation of the FMS proposed by the ASP committee and the results were that without any breakdowns included in the model and not so much abstraction of the system as far as tools flow is concerned, than an average actual utilisation of 80% of the machine tools is not an unrealistic assumption to be made.

Iwata, K. et al [153] examine tooling within FMS from the view of production scheduling and have developed a programme to simulate this. The model allows the determination of schedules of machining and transporting parts, and of transporting cutting tools simultaneously so as to minimise the makespan of production.

Cook, N.H. [68] provides a computer methodology to evaluate FMS feasibility relative to a given part mix, using both technological and cost information. A heuristic procedure selects a near optimal configuration of machine tools from a large set of possible systems, automatically assigning tools and routing parts. Performance is verified by simulation and finally, costs are allocated.

Hutchinson, G.K. [147] has simulated the system existing at Allis-Chalmer. This system was entirely designed with the aid of computer simulation. At an early stage of the design process, the decision was made by Kearney and Trecker to develop a simulation model of the FMS which could be used as an experimental laboratory to test ideas and trade-offs about the design of the system and its controls.

Crookall, J.R. and Jamil, A.T.M. [92,93,94] provide a performance comparison between random and optimal sequencing of numerically controlled operations involving combined positioning and tool changing by computer simulation. The "job line" concept is developed, which for a component is the characteristic curve of optimal sequencing on a range of possible machines. This leads to the identification of "job families" based upon performance matching jobs to machines, representing an optimal programming strategy for this kind of numerically controlled operation, thus maximising its utilisation and increasing the economic batch range. Better utilisation in mismatched circumstances, e.g. slow tool changing or positioning systems, may be obtained by the machining of components in multiple set-ups and hence optimising the sequence for the group rather than the individual parts: this possibility is examined. Optimum arrangement of tools and the use of duplication of tools to preserve sequential selection, are factors which are also examined.

Carrie, A.S. [79] presents a report on the use of simulation in a company in Scotland who have just commissioned an FMS for the manufacture of large complex castings. Some detailed results are presented using the MAST package. Kusiak, A. [196] surveys simulation approaches which have been applied to FMS to solve a large number of problems that the FMS concept can generate.

Billalis et al [206] and Doulgeri et al [101] have also included some measure of tool flow within their simulators. Generally, virtually none of the simulators pay detailed attention to tool flow because of the huge overhead incurred in data requirements, processing and capacities. Tool flow is thus included mainly for completeness. There are also very few cases where the dual flows are competitive and it is found that it is more usual to examine the flows in isolation.

Shires, N. and Roberts, E.A. have developed a fast system emulator using pascal and incorporating some parallel processing at Loughborough University of Technology [60a]. This work is also the subject of a complementary thesis [285]. The Manufacturing System Emulator provides a detailed modelling and determination of dynamic values of system parameters. The work includes an evaluation phase, carried out using an Evaluator. This work is also the subject of a complementary thesis [248]. The Emulator and Evaluator, their enhancements and their links with the tool flow models are discussed in some detail in chapter three.

Various other research groups from, Texas A and M, Toronto, Stuttgart, Draper Labs, Harvard and MIT have investigated operational problems of FMS. Buzacott and Yao [74,328] review models which were developed to study FMS. Chrystall, C. and Kaye, M [85], Grant, H. [112], Warnecke, H. et al [312] review more recent contemporary simulators such as 'MUSIK', 'SCHED-SIM', 'MAST', 'MICROSAINT', 'MODELMASTER', 'SIMFACTORY', 'WITNESS', 'XCELL' and 'GRAFSIM' [18] amongst others.

2.8.2 Mathematical Models

These are the simplest models based in the computer analysis of Networks of Queues (CAN-Q). These models work with little data input and can be used only in the early stages of system design.

The CAN-Q developed by Solberg, J.J. [288] has been tested by Rajagopal, K. and Rathmill, K. [271], and they concluded that it is very limited in its ability to mirror detailed aspects of a production system and have pointed out six fundamental limitations of it's application.

The Solberg model [287] represents as a closed network of workstations and queues. From a technical standpoint, the model is a special case of a category of queueing networks known as closed Jackson Networks [154]. The theory is established to supply the solution to the set of equations which determines the equilibrium probability distribution for all possible stages of the system. From this, one can in principle determine virtually any kind of steady-state performance measure one would want to consider.

A generalised modelling system has been developed at Cranfield [272]. This is based on the Solberg model and is a micro-computer based design tool developed to provide a first approximation of the behaviour of an FMS. The model requires only basic information describing system hardware within an FMS, can be provided quickly and cheaply and numerous design alternatives considered.

Kay, J.M. and Walmsley, A.J. [157] consider that the tooling problem may be reduced by imposing restraints on the parts' designers and thereby reducing the number of tools required, but in some cases this may be of limited value and it may be necessary to ensure that the tooling system is designed to maximise the efficiency of the system. As an aid to the designer, two computer models have been developed which allow ideas and the effects of the various system parameters to be tested. The first model allows a system comprising of one machine, one primary store and one secondary store. The second model allows a system of several machines and their associated primary stores linked to a single common secondary store.

Suardo, G.M.S. [297] analyses workload (and tool) distribution effects on the performance of an FMS by modelling as a closed network of queues. The workload optimisation is stated as a well-behaved non-linear optimisation problem.

Buzacott, J.A. and Shantikumar, J.G. [75] provide models showing the desirability of a balanced workload, the benefits of diversity in job routing and the superiority of a common storage for the system over local storage at machines. The models are also extended to allow for material handling delays between machines and for unreliable machines.

Sarin and Wilhelm [156,322] review mathematical models which address planning and operational problems.

2.8.3 Specific Tool Flow Models

In a manufacturing system there are several areas where specific modelling may be required. Where such an area may be considered in total or partial isolation, the modelling may be performed separately. The categories above looked at the total system, but it is possible to obtain results for a particular problem area, in this case tool flow, and use them as inputs to the main simulators. A brief review of such models is given here.

To aid the design of a tooling system, two simulation programs have been written at Cranfield viz. ToolSim1 and ToolSim2. The ToolSim1 model is a single machine model whilst ToolSim2 is an extension to the former allowing a multimachine model to be developed. The models assume a dedicated transport system for each link between stores and are discussed by Kay and Walmsley and by Rathmill et al [157,158,159,160]. Further extensions are made to model by Hong, L.K. [143] and Papagiorcopulo [252].

Hankins, S.L. [120] has developed a simulation program to gauge the interference of the machine tool magazine with the spindle utilisation. This has been implemented at Cincinatti Milacron [63].

Crite et al [90] have developed a detailed simulation called PathSim using SLAM to analyse the performance of an automatic tool handling system. Unlike the Cranfield work where a dedicated transport system for each link in the movement of tools is assumed, PathSim allows the use of "addressable" type material handling devices for both the tool and part movement subsystems. PathSim concentrates on the study of the operating parameters particularly the use of different tool cart control algorithms.

ElMaraghy [107] has developed a general purpose simulator called FMS-SIM as well as an all encompassing simulation package called TOLSIM for designing and evaluating automated tooling systems. The package is written in FORTRAN IV and produces statistical reports on utilisations, average size of queues and parts processed.

Renault Automation have developed the SAME/FMS simulator [36], designed to model automated or manual machine shops. The simulator considers tools in 'tool batches' only. Lucertini and Nicolo [205] also consider the movement of tool sets in their quadratic assignment workstation setup model.

Other simpler models concerned with a particular feature of an automated tooling system, for example, the toolroom have also been developed by Brohan [67,68,69], Polstore [43], and Systam [149]. Kellock [164] reviews five similar models : TOMAS from Sandvik Coromant caters for all aspects of tool stock control in the tool stores and at the machine magazine through an item level control feature. Toolware from ISIS Informatics allows users to check a central database for tool availability, tooling costs, calibration and standards for tooling as well as handling tool issue and return. THe Microbore TMS from Gildemeister-DeVlieg is mainly a data handling system which focuses on tool preparation and presetting. The CTMS system from David Maxwell Consultants covers such activities as single tool issue and return, assembly and kit specifications for automatic building and breakdown of tool assemblies, presetting of kits to specified dimensions, control of gauge calibration and automatic tool purchase. The Zoller Super-Brain TMS from Hahn and Kolb GB provides geometric, technical and graphical recording of all tools, fixtures and measuring instruments. These models are thus primarily concerned with the organisation of the toolroom and the kitting-out of tool sets for despatch to the FMS.

Hannam [122a] describes a software package called CADETS (Computer Aided Design Encompassing Tool Selection) aimed at providing the designer with an interactive means of creating features which are related through the software to the tooling available to machine them. This computer assisted control of tooling thus tackles two aspects: control of tooling specified at the production planning stage and the control of tooling effectively specified by designers when they create part geometry.

Seliger et al [281] have built upon their experience of the generalised simulator 'MOSYS' to develop a parameterised simulation system 'TOSYS' to model a FMS with an integrated tool handling system. The model is structured using a block orientation language and offers a limited exploration of tool management operating strategies. A complementary model to that described in this thesis but for highly automated turning systems has been developed by Zhang, P. [332,333]. This work is also the subject of a complementary thesis.

Two other parallel research programmes also consider tool flow at a lower level than that described in this thesis. A knowledge based model has been developed to consider both part and tool flow integration [316]. This model considers tool flow at two levels. At the first level an infinite PTS capacity is assumed and no secondary tool store is present and hence no tool transfer or tool sharing is considered. The output from this level is primarily a maximum tool requirement. At the second level the user is presented with an option either to manually input the tools into the PTS or to generate and assign kits from an STS. The output from this level is a tooling schedule. The implementation of tool flow in the Emulator for parts is at a relatively early stage [239] but is as for the knowledge based model. The incorporation of tool flow principles generated within this thesis will be implemented in the dynamic environment of the Emulator.

Little attention either practical or theoretical has been paid to the crucial areas of levels of performance improvement, control complexities or to the factors controlling the efficiency of automated tool flow systems.

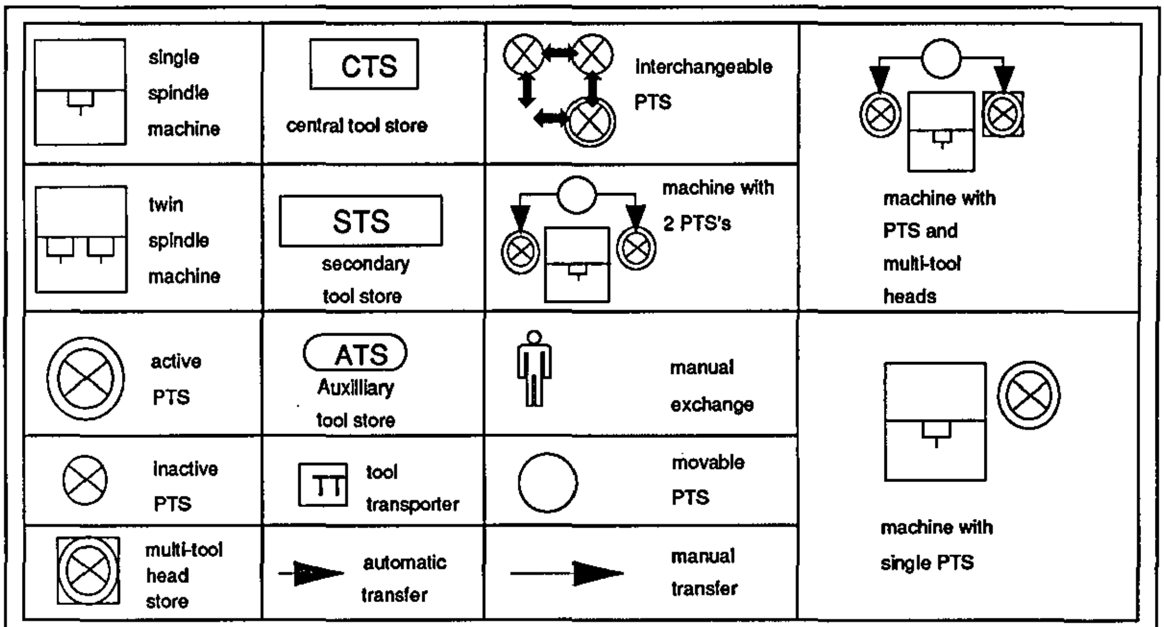


Figure 2.1 | TOOL FLOW SYSTEMS - SCHEMATIC REPRESENTATIONS | LUT - FMS Research Group

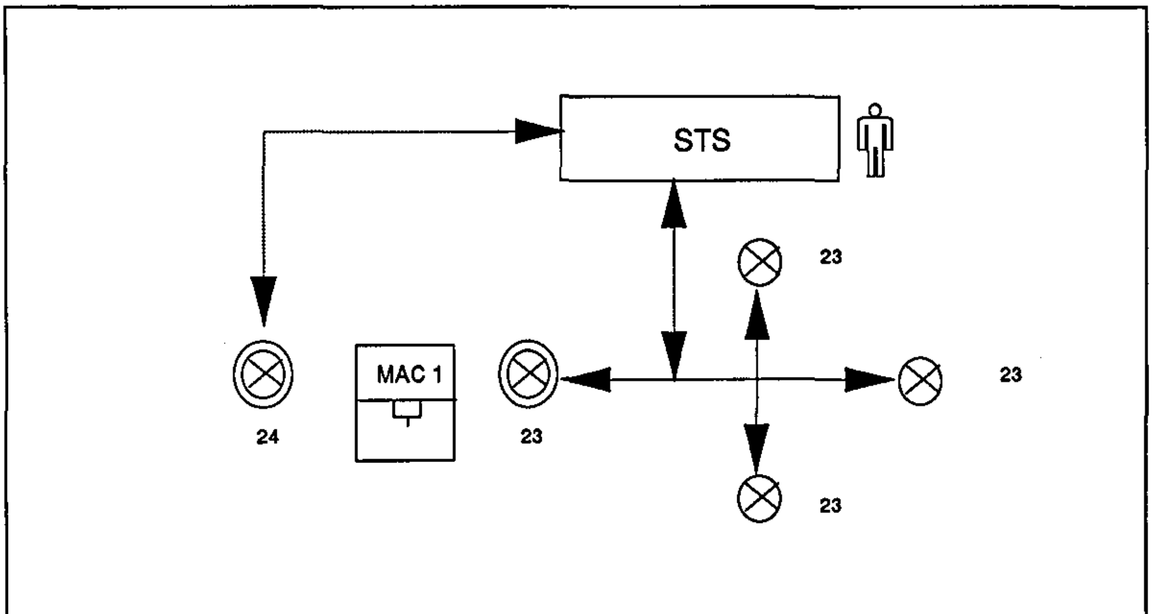


Figure 2.2 | HULLE HILLE nb-h 70 [ref. 216] | LUT - FMS Research Group

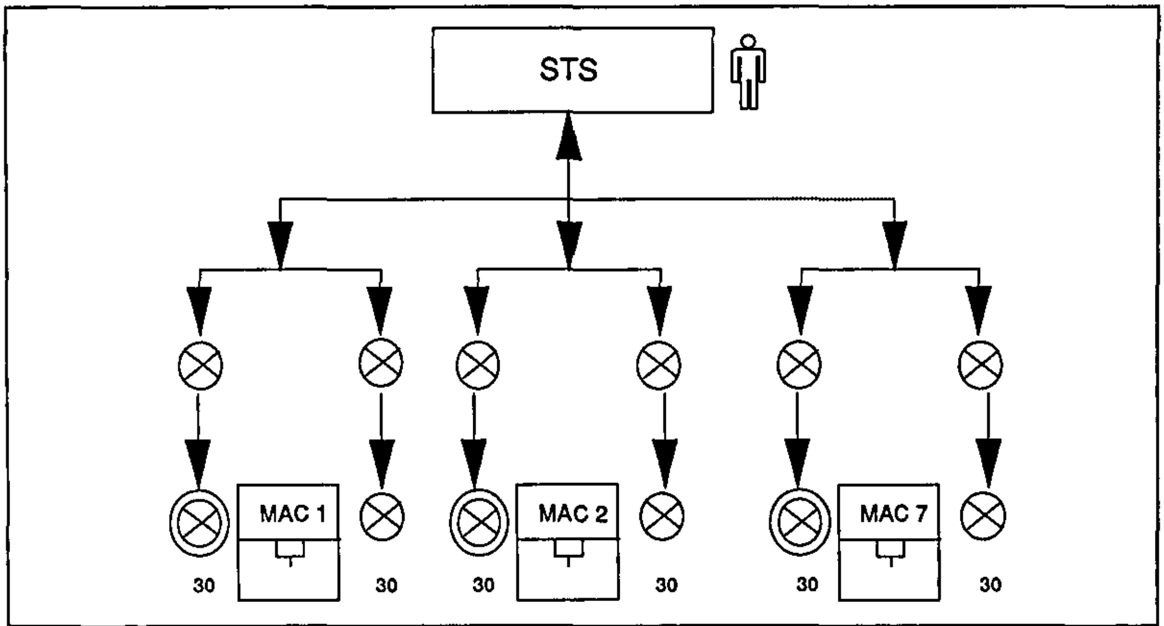


Figure 2.3	YAMAZAKI LINE A [ref. 233]	LUT - FMS Research Group

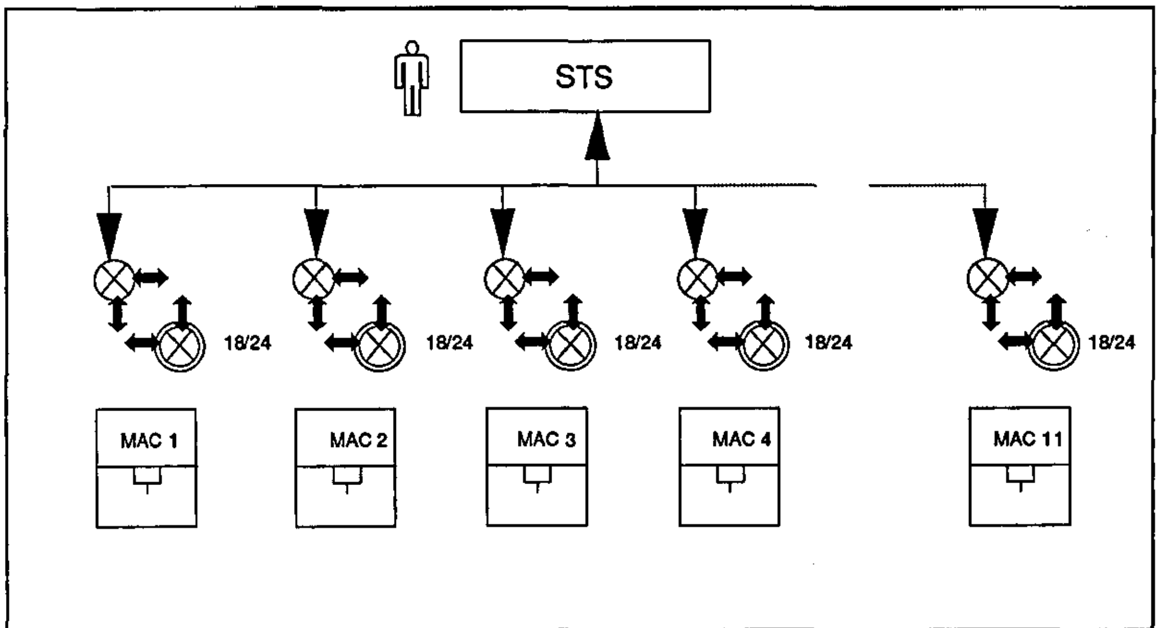


Figure 2.4	JOBS FMS CONCEPT [ref. 217]	LUT - FMS Research Group

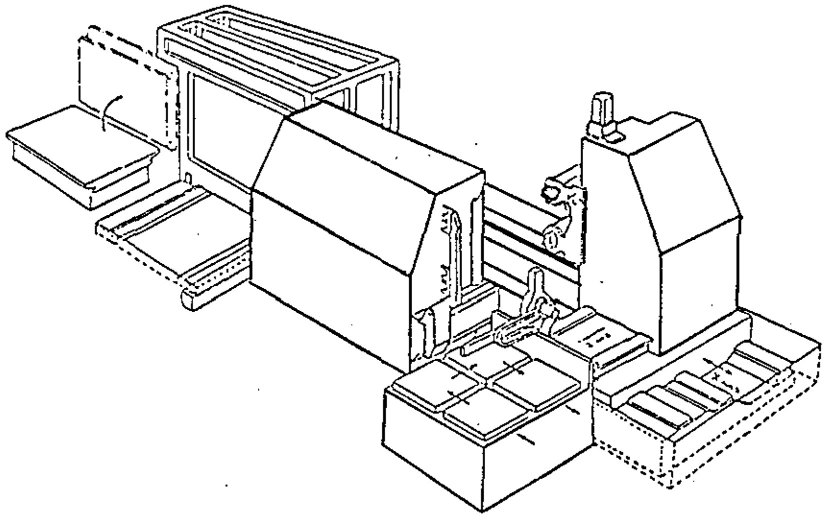


Figure 2.5	AUTOMAX MACHINING CENTRE [ref. 48]	LUT - FMS Research Group

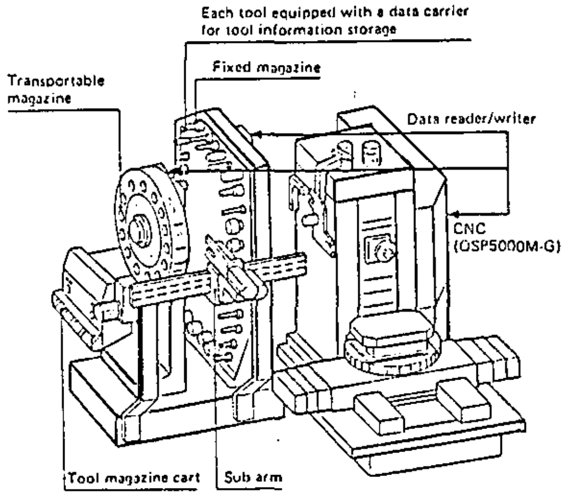


Figure 2.6	OKUMA MACHINE DESIGN CONCEPT [ref. 225]	LUT - FMS Research Group

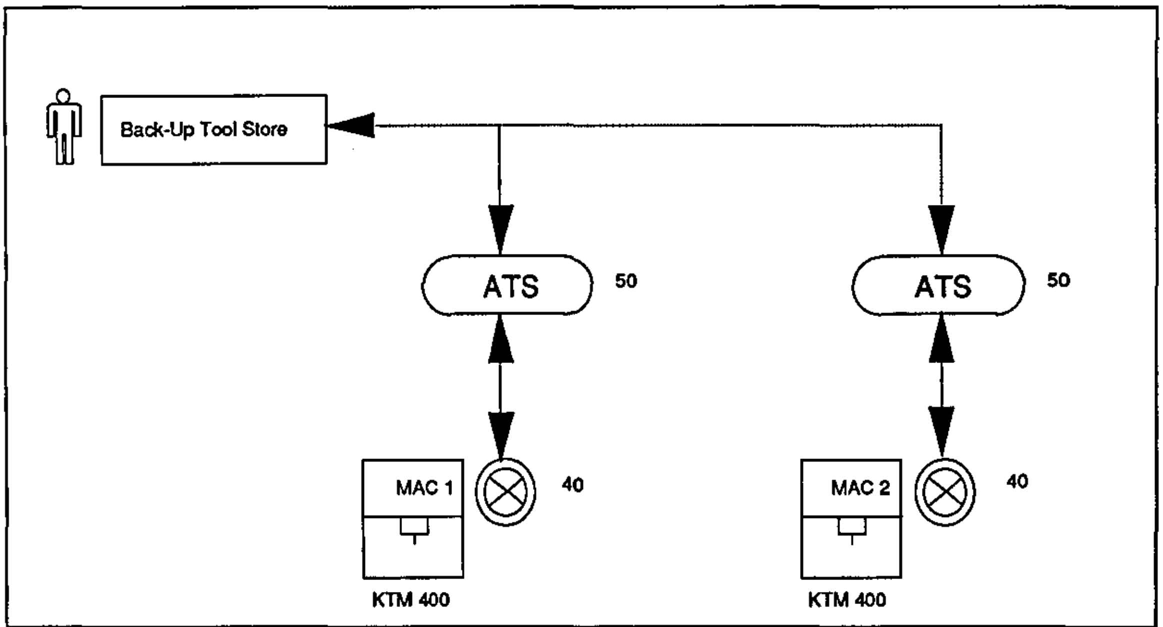


Figure 2.7 | NGL FMS CREWKERNE [ref. 26] | LUT - FMS Research Group

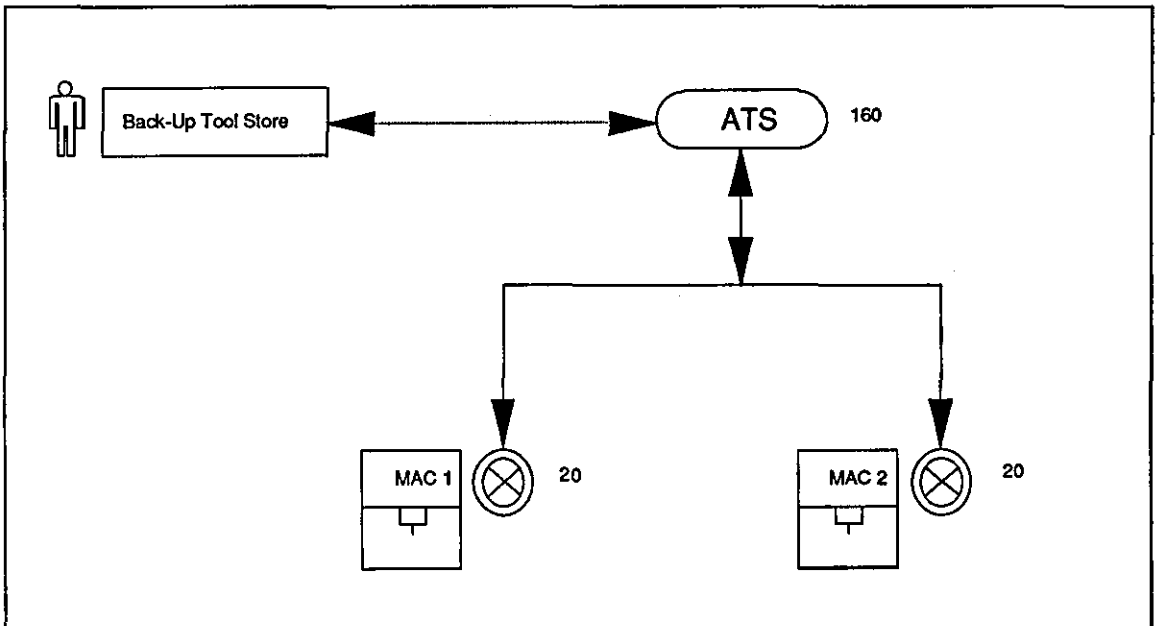


Figure 2.8 | WERNER DUPLEX CELL [ref. 108] | LUT - FMS Research Group

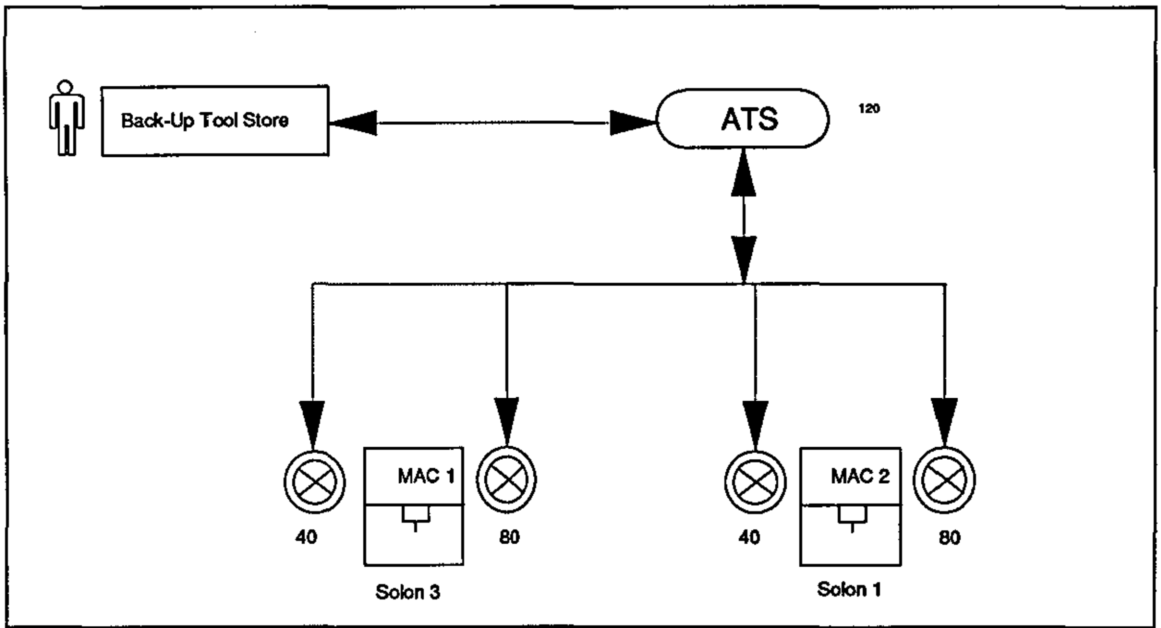


Figure 2.9

EXTENDED SCHARMANN CELL AT HOWDEN COMPRESSORS [ref. 89]

LUT - FMS Research Group

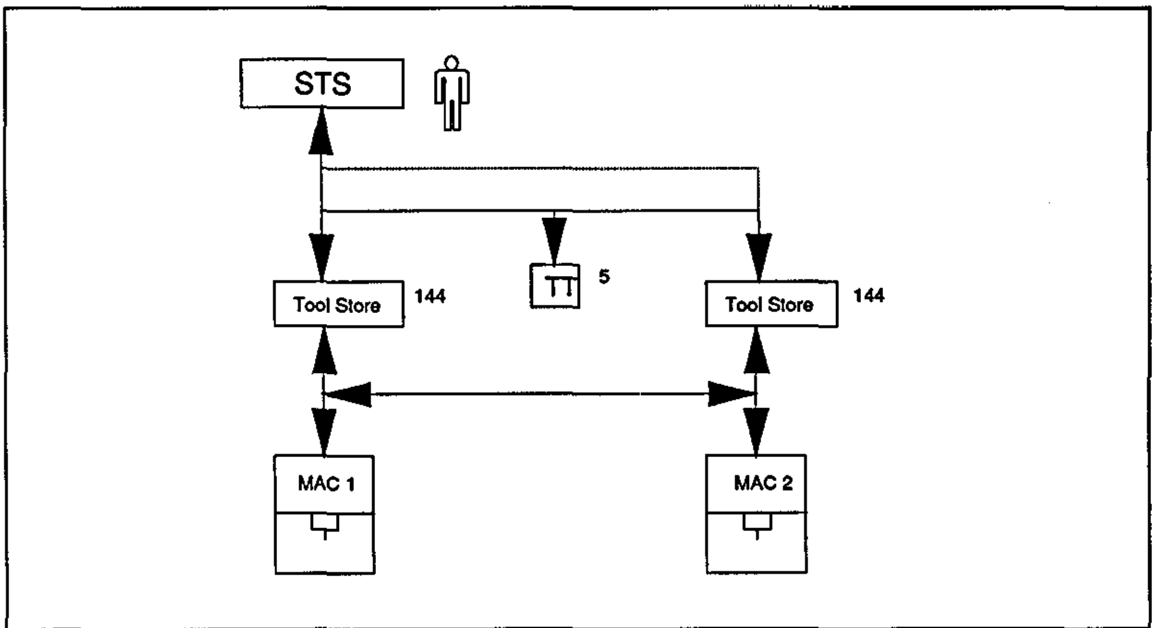


Figure 2.10

TOS CELAKOVICE FMS [ref. 304]

LUT - FMS Research Group

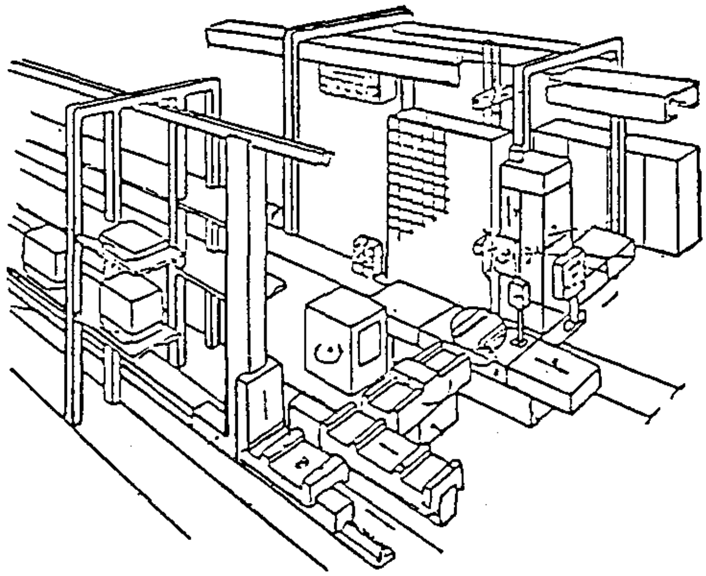


Figure 2.11 | TOS OLOMOUC FMS [ref. 305] | LUT - FMS Research Group

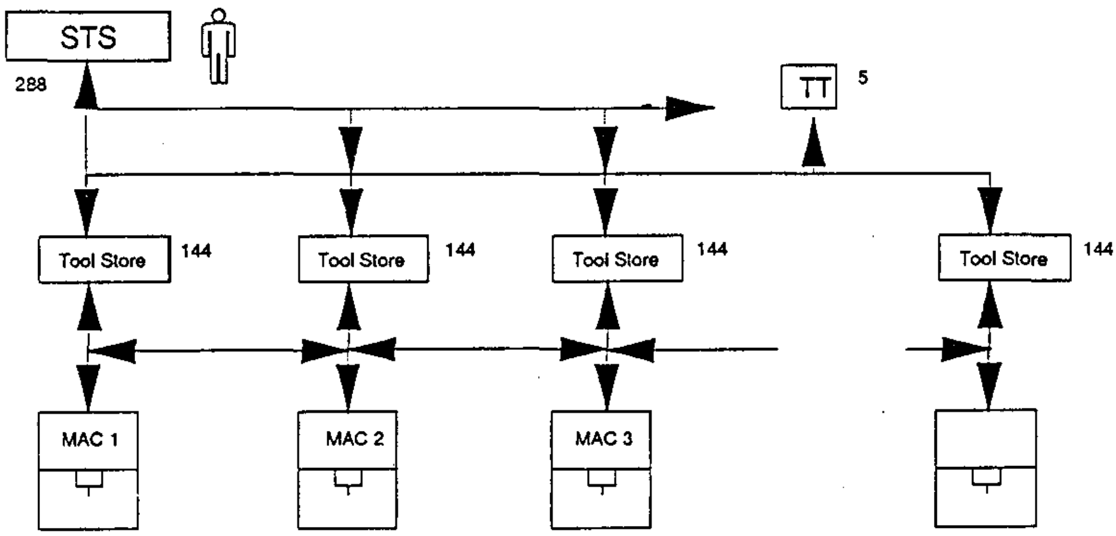


Figure 2.12 | TOS OLOMOUC FMS [ref. 305] | LUT - FMS Research Group

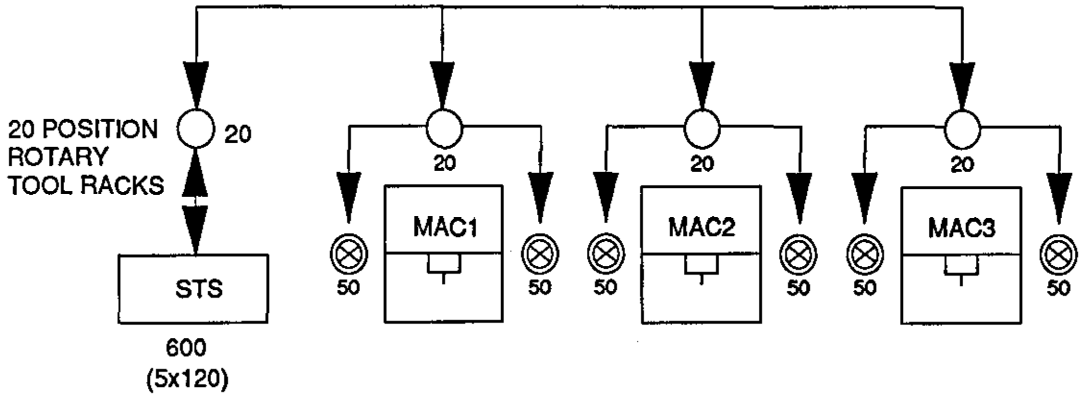


Figure 2.13	CITROEN INSTALLATION AT MEUDON [ref. 8]	LUT - FMS Research Group

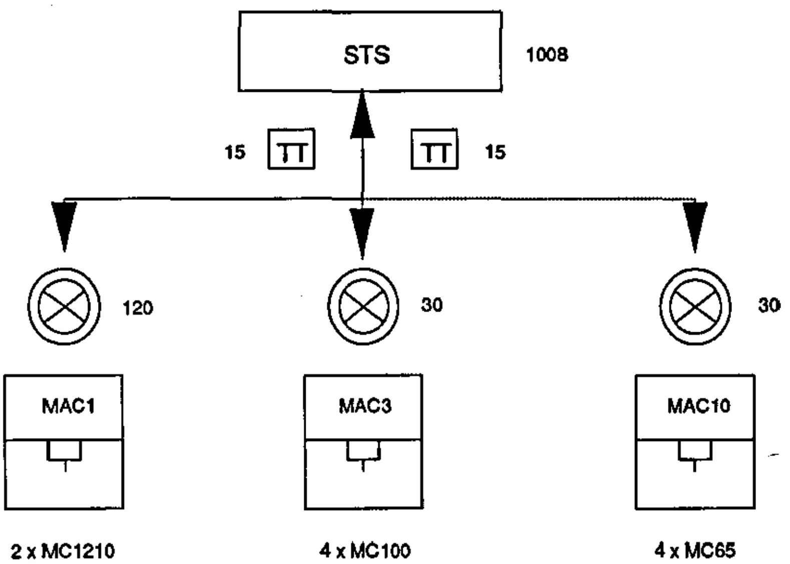


Figure 2.14	MAKINO 'MAX' FMS AT ATSUGI [ref. 23]	LUT - FMS Research Group

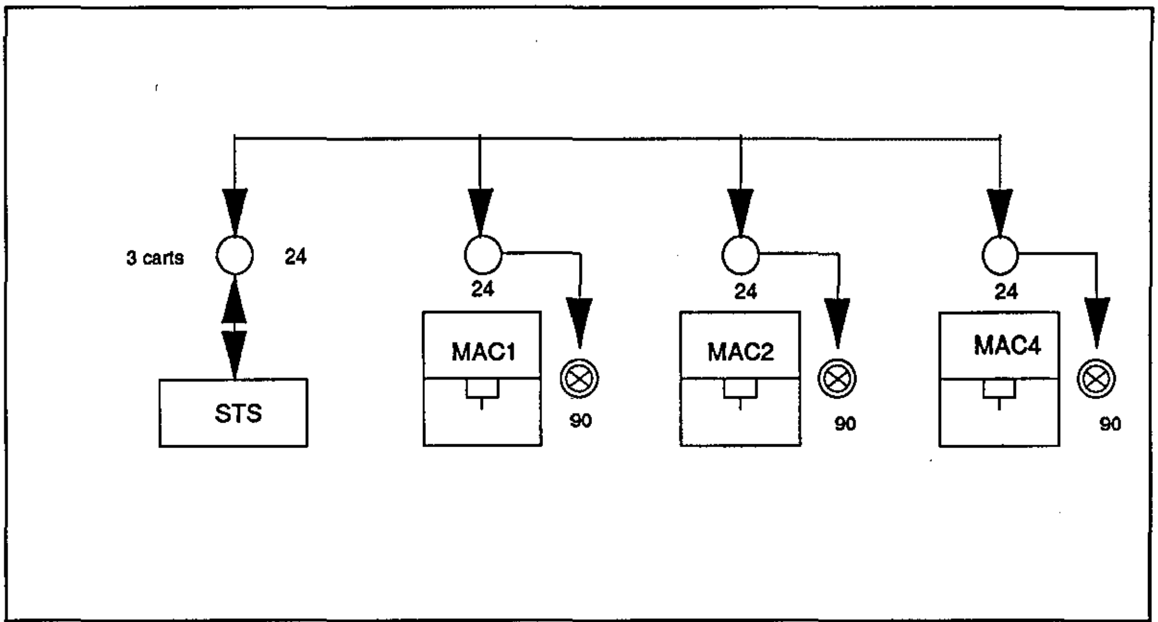


Figure 2.15	CINCINNATTI FMS AT VOUGHT AEROSPACE [ref. 6]	LUT - FMS Research Group

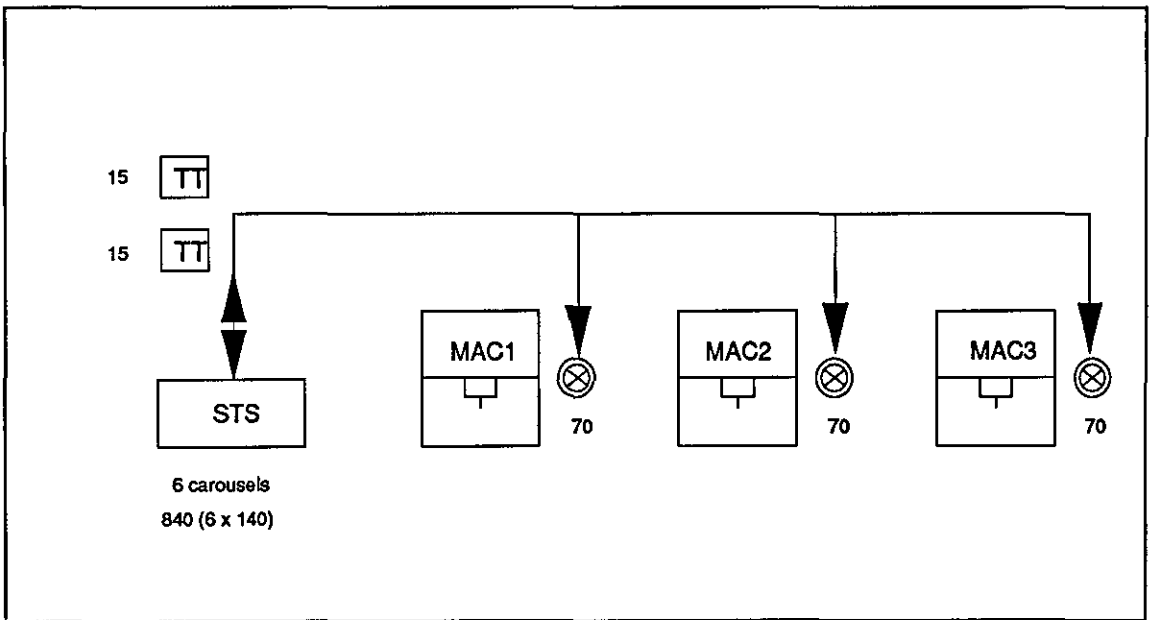


Figure 2.16	MURATA FMS [ref. 128]	LUT - FMS Research Group

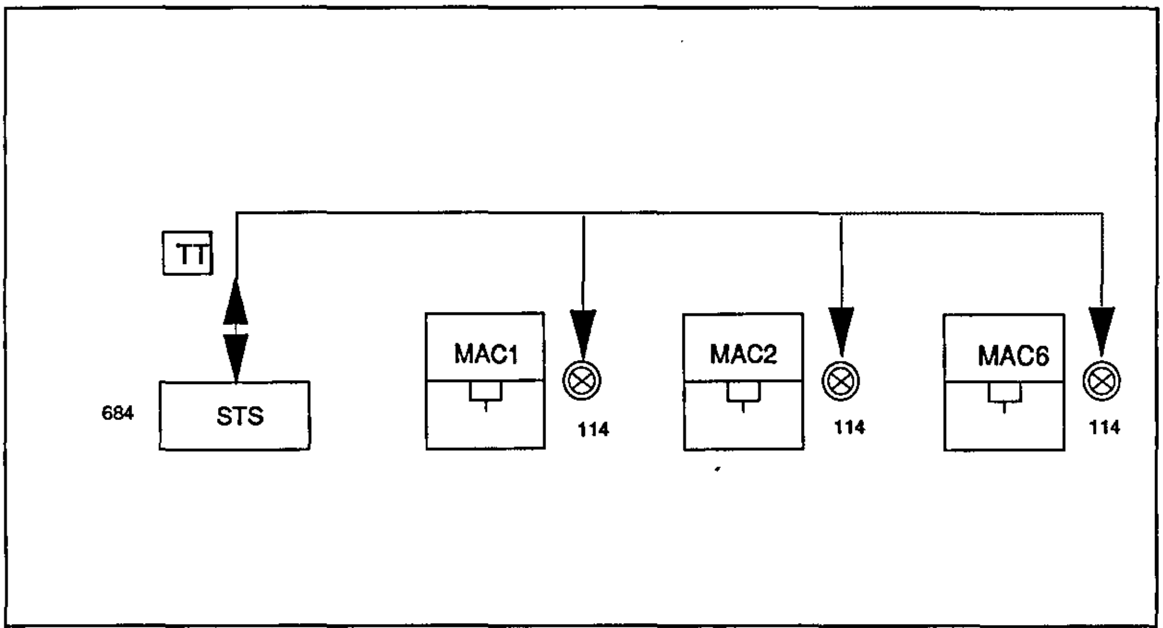


Figure 2.17 | GENERAL DYNAMICS FMS AT FORTH WORTH [ref. 182] | LUT - FMS Research Group

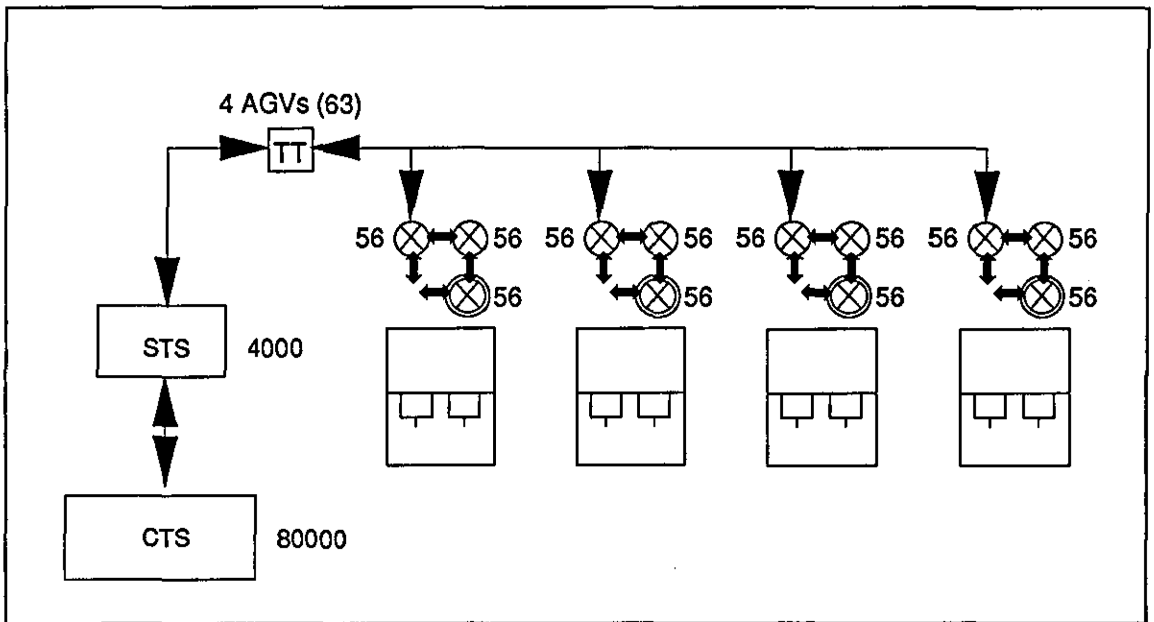


Figure 2.18 | BAe SMALL PARTS FMS AT PRESTON [ref. 48] | LUT - FMS Research Group

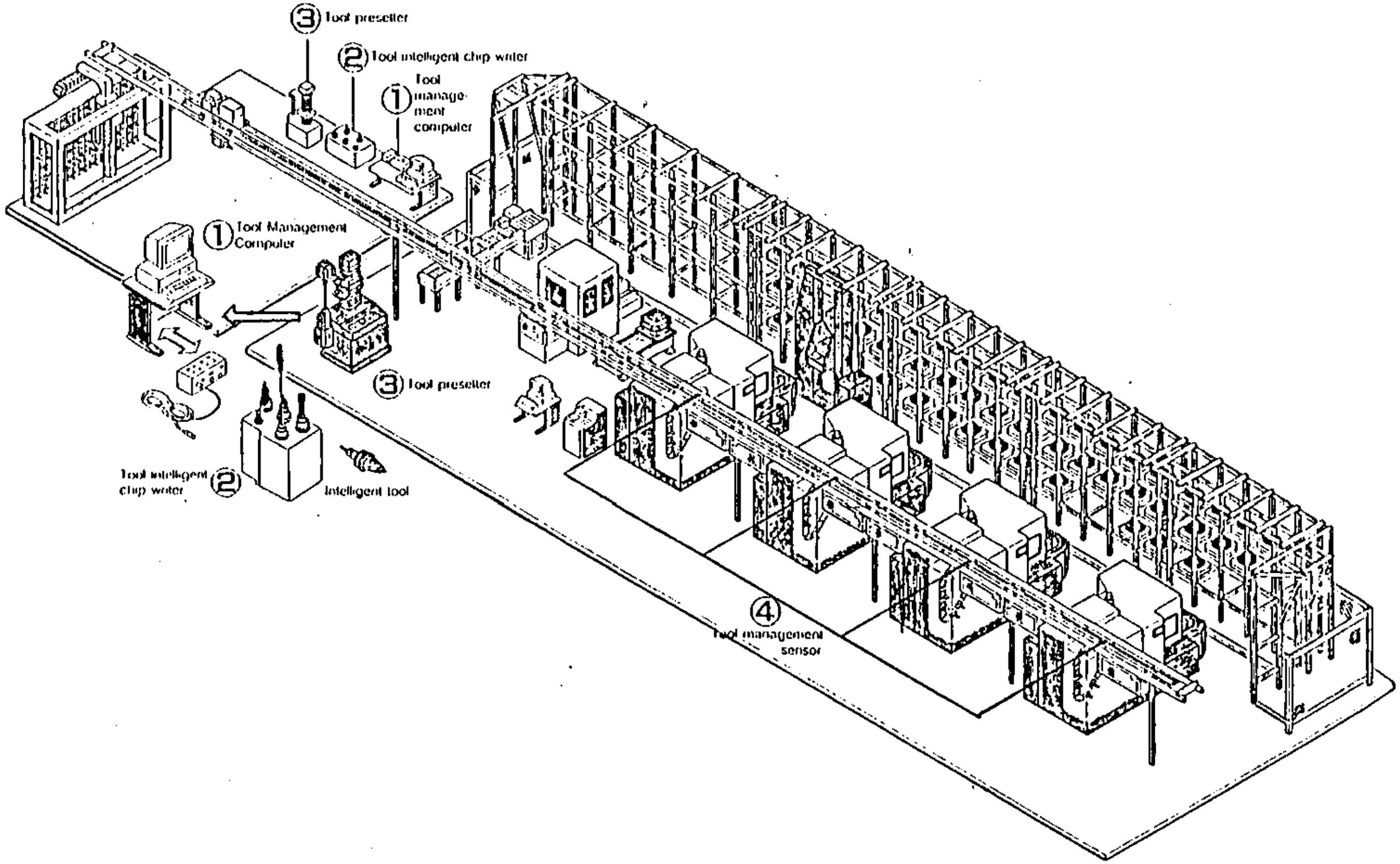


Figure 2.19	YAMAZAKI INTELLIGENT MAZATROL FMS [ref. 233]	LUT-FMS RESEARCH GROUP

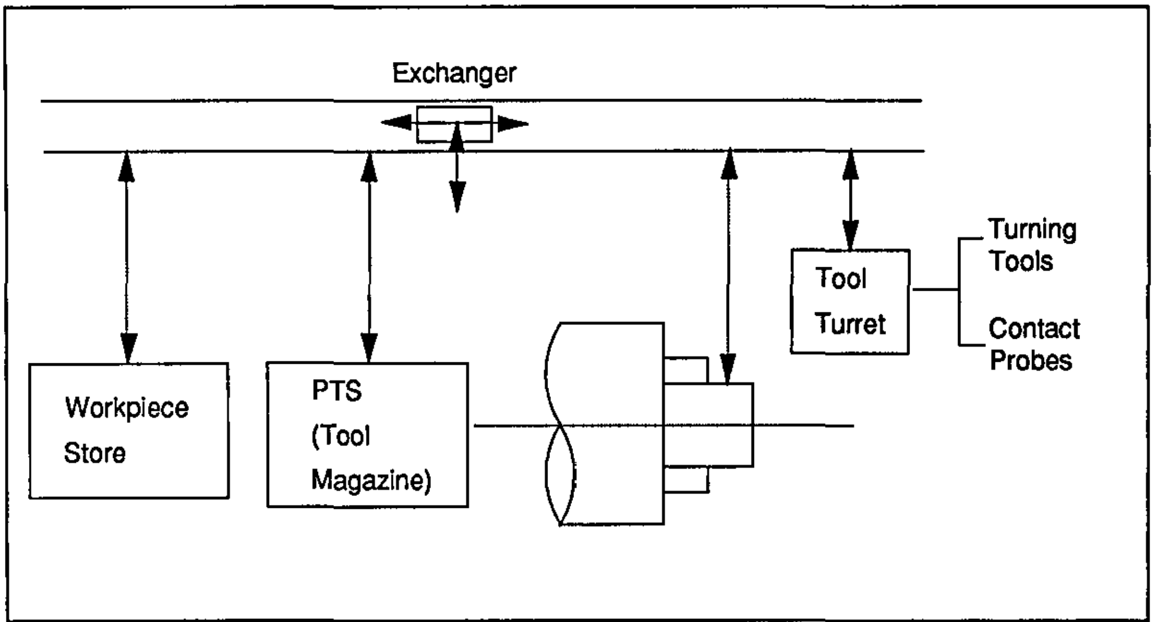


Figure 2.20	TURNING CENTRE - BASIC FEATURES [ref. 333]	LUT - FMS Research Group

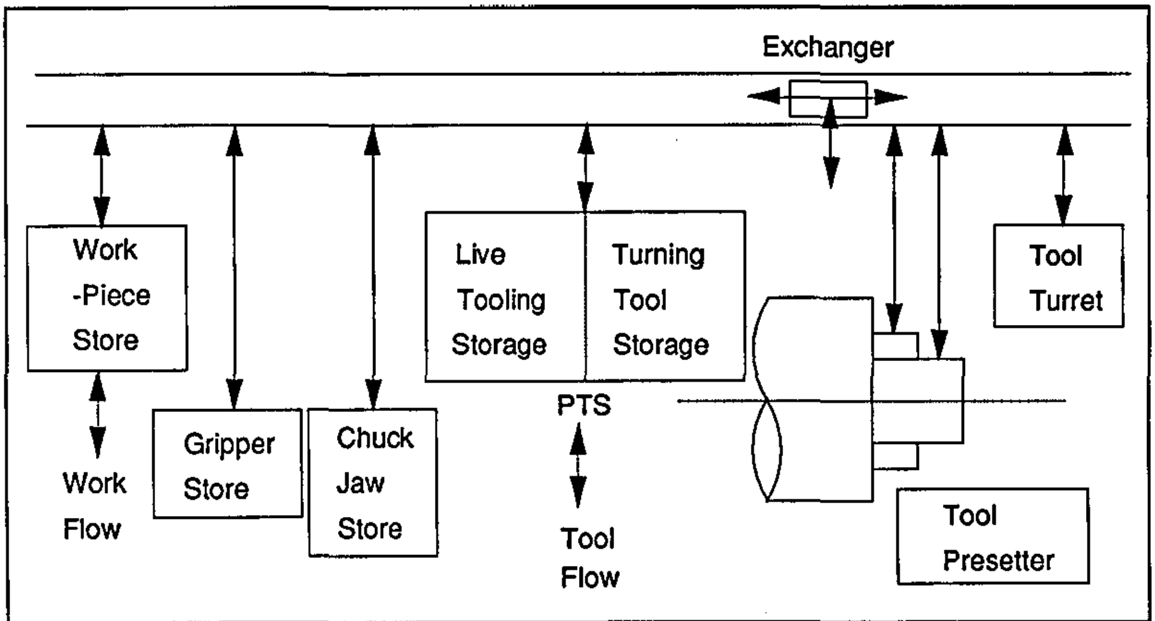


Figure 2.21	TURNING CENTRE - ADVANCED FEATURES [ref. 332]	LUT - FMS Research Group

Chapter 3 :
MANUFACTURING SYSTEMS

3.1 Introduction

The purpose of this chapter is to introduce the reader to the spectrum of possibilities, incorporating flexibility, for batch manufacturing. Four manufacturing system configurations, that vary from a single highly automated machine tool to a completely new factory or 'green field' site, and their uses are described. The trends in flexible manufacturing, the design considerations and a design aid are also discussed. The emphasis in this chapter is on material handling systems, and the design and operation of a manufacturing system. Tooling system design and operation for this hierarchy of manufacturing systems is discussed in subsequent chapters.

3.2 Flexible Configurations

The classification of a particular manufacturing system usually results from the extent of its production flexibility, its mode of operation as well as the properties of its machine tools, materials handling system, tool handling system, storage areas for in-process inventory and computer control. The classification also has to involve the variety of components to be manufactured, batch size, batch frequency, minumum throughput times for critical orders and the level of investment. The interpretation of component variety is also a significant factor. Based on this interplay between volume, variety and manufacturing system factors, *figure 3.1*, four distinct configurations are possible, *figure 3.2* . These are:

(a) Flexible Manufacturing Module (FMM)

(b) Flexible Machining Cell (FMC)

(c) Flexible Manufacturing System (FMS)

(d) Flexible Transfer Line (FTL)

3.2.1 The Flexible Manufacturing Module (FMM)

The basic composition of the FMM consists of a stand-alone machine tool such as the machining centre, a transport function with a robot or pallet changer and machine monitoring system for unmanned operation. The FMM is capable of operating for long periods of time with minimal attention because of the multi-pallet design usually found in such systems [115,145]. Manually loading and unloading of both workpiece and tool magazines typically leads to the two shifts unmanned, one shift supervised, pattern of operation. The FMM requires a suitable quantity of tooling (e.g. for tool breakages), multi-part program storage, and conditional programming capability in order to run unmanned. The FMM is designed to produce a fairly large variety of manufactured parts but in fairly low volumes. The FMM's random processing capability parallels the efficiences of FMS. The FMM is usually the building block for the following three configurations as it is easily integrated into systems, because they have many of the extended features required for an FMS module, including multiple pallet storage and buffering capabilities enabling the FMS to operate unattended for long time periods.

3.2.2 The Flexible Machining Cell (FMC)

The FMC is the simplest, most flexible and operationally distinct machine group within the manufacturing systems environment. The FMC is viewed as being most effective when applied to the production of many different workpieces, each being produced at a low production rate. The distinguishing characteristics of the FMC are the automated flow of raw material to the cell from an input buffer, total machining of the workpiece across the machines within the cell and transportation of the finished workpiece to an output buffer for eventual removal to its next destination. The FMC is thus made up of a number of FMM's and is in itself a higher level building block for an FMS as it contains all the components of an FMS.

The FMC is more readily accepted by industry at this time because of its relatively low cost and simplicity in contrast to the higher cost and more complex nature of an FMS. In more highly developed examples of FMS installations, the distinction between an FMC and a FMS label is often a matter of argument, as there is no firm dividing line between the two levels of automation. The cell at best is considered as an activity specific system and is generally limited in its constituent elements whereas a turn-key FMS is at least partly designed to suit the particular application and does not have the same size limitations.

3.2.3 The Flexible Manufacturing System (FMS)

In an FMS, palletised workpieces of different types are randomly and simultaneously transported between and processed at various machine tools, cells, and other workstations, according to individual processing and production requirements, under automatic computer control. The FMS can be considered as a multi-cellular system or as a disordered system of machine tools in a process-independent layout. It is the part types that are to be processed by an FMS which defines the constituent machine groups (cells) or machine tools. The FMS requires automated or semi-automated transport of workpieces and tools between buffers and machines and the loading and unloading of these elements. It possesses advanced auxilliary functions for machining operation, monitoring function, and requires NC data control, scheduling and production control. The limits on the flexibility of the system are usually tool quantities and supply mechanisms, material handling techniques, the types and numbers of pallets and variable routing and organisation control i.e the real time control capability.

3.2.4 The Flexible Transfer Line (FTL)

The flexible transfer line is designed to produce a high volume of manufactured parts at the lowest cost, and is usually dedicated to producing a particular manufactured part or a closely related part family for a substantial period of time relative to the production time of a single part. Hence, the variety of parts produced is low and the quantities high. Because of the very short cycle times normally associated with these systems, unlike the FMS, the FTL may not be based on a CNC machine configuration as it would be uneconomical to have a machining centre at each stage on the line. Different approaches are evident but the nature of the benefits are the same. The costs involved in changing from one part to another is usually high and only justifiable because of the large volume to be produced (259,260). Typical relationships between costs and process flexibility are shown in *figure 3.3* . Cross (207b), a producer of FTL's, has developed the cell manufacturing concept to include transfer lines. These cellular transfer lines are able to manufacture a wide variety of parts of closely knitted family types. This concept, which can be implemented in phases, evolved from the customer requirement not to have dedicated transfer lines. Thus, the random FMS concept is employed in its least flexible form. This permits the integration of many different controller systems. For this strategy to be sucessful, the FTL producer has to get into the investment 'bed' with the user right at the start. The incorporation of head-changers within FTL's has largely eliminated the need to overproduce, then change over to new part production. It is estimated that a single head changing machine is equivalent to three single spindle machines.

3.3 The Trends in Flexible Manufacturing

Considerable changes in user attitudes have been engendered by technological and economic driving forces at the present time in industry. The initial investment in the early eighties were centred on the monolithic turn-key FMS installation. Currently the previously described FMC is set in the context of the effort to introduce some degree of CIM (Computer Integrated Manufacturing) integration, *figure 3.4*.

The initial challenge in flexible machining was seen to be the design and installation of large complex multi-disciplinary FMS (39,104,160). Little emphasis was given to the links back into what is now seen as the CIM structure. The situation is now very different and reflects the recognition in many countries in Europe (2,12,14,25,40,55,141,290,313), USA (71,56) and Japan (255) and by many companies that a full-scale FMS, with all its consequences for the integration into the management of manufacturing makes very heavy demands on the management and engineering skills of the user company. This relative inexperience frequently shows in areas such as maintenance and tool management. Technological changes, particularly in hierarchical DNC/CNC distributed control systems have exerted a strong influence on the economics and specification of manufacturing systems (59). The contrast is to be seen by comparing *figures 3.5 and 3.6*. It is now much more difficult today to convince financial and technical people that an all-embracing system under the control of an host computer is something which they can handle, absorb and support. This is largely due to long start up periods, long project lives and delayed returns associated with this manufacturing technology, but other contributing factors are inadequate tools of financial analysis, a gap in management communications and risk aversion and the fear of failure for those involved in the project (95).

A much higher degree of confidence is generated if one can offer a solution which achieves the production requirements through some degree of synchronisation of machining carried out in a single or a number of co-ordinated machining cells (144). Furthermore, changes in financial evaluation procedures, setting up of strategic technology teams, initiation of major education and training programmes, incorporation of long term strategies into short term performance measures, estabilishing specific technology inputs to the manufacturing strategy and restructuring the organisation will also bolster confidence (247). This challenge of transformation is evident in some of the larger organisations which have adopted this cellular manufacturing systems technology, and re-inforced the CIM structure and its interfaces, *figure 3.4*.

With this new technology the conventional primary FMS objectives of keeping work-in-progress to a minumum, reducing lead times, reducing support labour, and facilitating the introduction of new products at two to three times the existing rate on half the current design and development lead times can be achieved and at the same time all the components needed for assembly are available as required and those involved in the project are satisfied.

This type of multi-machine multi-cell structure, where each cell is relatively simple, and which is now seen to emerge in a number of cases is shown in *figure 3.6* . There is, of course, an alternative i.e. a flowline approach, *figure 3.7*, such as adopted by Holset, *figures 3.8*, [185]. This serial approach to multi-cell design almost mimics a flexible transfer line. The 'Advanced Integrated Manufacturing System' (AIMS) at Rolls Royce in Derby, is further evidence of this approach. The four million pound investment is considered a benchmark for companies with high added value in small batches or as one-offs [47]. Yet another typical multi-cell configuration with a high degree of synchronisation of each cells output into an assembly area is displayed at the Yamazaki installation at Worcester, *figure 3.9*, [189]. This approach to parallel multicell design is sometimes referred to as a star configuration. The cells are generally configured from standard hardware and software, and are generally limited in the number of machines that can be included and the number of interfaces that can be accepted. Simulation studies carried out at Cincinnatti Milacron have shown that four-machine cells are generally considered to be the most appropriate size. If correctly supervised, it is estimated that such a cell could replace upto thirty conventional machines. Control and integration of auxilliary functions are also of prime importance, as in some cases, such cells could not only revolutionise a factory but replace it. Several configurations have been suggested by Kusiak [194], but generally two or more cells can be strung together under a host computer. This is the route to large scale automation now being followed by some companies [166] . The position these multi-cell systems occupy in relation to the traditional FMS can be shown in the volume vs. variety graph in *figure 3.10*.

Recent advances in turning centre technology and the incorporation of live or driven tooling has largely eliminated the need for hybrid cells i.e. cells with machining centres as well as turning centres. Where it is necessary to have turning and prismatic operations, turning centres with tool magazines are becoming the norm. There is little doubt that these developments will be further refined towards one-hit machining or the single-machine cell.

Evidence of the CIM *bottom-up* approach is apparent in recent literature [207] and in current installations such as SAGEM and Huron/Graffenstaden in France [172], Mori Seiki [123] and Hitachi Seiki [16] in Japan, and Victor [56], British Aerospace [16,111], Cross International [134,162], and Holset [315,185] as well as very recently Cummins [32] in the UK.

The installation at British aerospace provides a typical example of the multi-cellular *star* configuration trend in flexible manufacturing. The system was introduced in three stages. Stage 1, consisted of two twin-spindles and stores. Stage 2, added four more machine tools and stage 3, added a co-ordinate measuring machine (CMM). Work flow and tool flow are highly automated in this installation. The tool flow automation is of particular interest as it introduces the concept of a central tool stores (CTS). This CTS is shared by a number of cells and the flow to and from the cells STS is highly automated. The AIMS facility at Rolls Royce [32,33,73] also falls under the category of a CTS system as the CTS supplies a number of the cells, although the tool flow network itself is not automated. The phased development of flexible machining is now a normal feature of factory enhancement as it allows the user to increase his investment as his experience grows.

It is generally accepted that such a phased approach is now essential not ony to manage cash flows effectively but also that experience has shown that it can sometimes take upto two years for fixtures and part programs to be designed and developed, not considering training requirements. Thus, not to leave such a massive investment idle, machine tool manufacturers themselves suggest that the customer let the system grow with his experience.

Specific problems are posed in the automotive industry such as over capacity, the need to interest the customer, and the considerable time lag between having component designs which can form the basis of manufacturing equipment purchase and having those designs completely frozen. These have made it necessary, in part, to employ flexible machining cells which provide all the flexibility of a transfer line, but offer other positive features which improve on the transfer line, such as the ability to incorporate design changes upto, and in some cases even after the beginning of production. These new flexible cells or transfer lines have to provide the same cycle time throughput as the older transfer lines [162].

3.4 The Design Considerations

There are many important concepts which relate to the designing of a manufacturing system, *figures 3.11 and 3.12,* [248]. The central task is to identify the manufacturing requirement and then seek the specific solution. These encompass part volume and variety, productivity versus flexibility, manufacturing modes and numerous workpiece attributes. There are several important design considerations [52,161]. These are:

(a) *Adaptability to change*: There is a basic requirement for building productive flexibility into a manufacturing system. This is particularly important in situations where there is likely to be drastic variations in the product mix. The manufacturing system should be able to produce a mix of component types simultaneously and at varying production rates whilst maintaining a continuous flow and without the continual requirement for resetting of the machines. This allows a minimisation of in-process inventory and increased machine utilisation which is one of the major economic forces observed to be driving the rapid implementation of these highly automated manufacturing systems.

(b) *Equipment dependability*: Equipment dependability is one of the key factors in system design. The materials handling system must be of a rugged design to withstand the long periods of operation necessary in the use of such expensive systems. Machining centres must be designed to withstand the rigours of continuous machining cycles. Generally, the modules in the system must have a higher dependability than that required for stand-alone equipment if the manufacturing system is to meet its objectives.

(c) *Dedicated or random manufacturing system*: A dedicated system machines a fixed set of part types with well defined manufacturing requirements over a known time horizon. The 'random' manufacturing system on the other hand machines a greater variety of parts in random sequence. One of the most noticeable changes in recent times has been the shift from dedicated systems to random systems, which can process a larger family of parts having a wider range of characteristics.

(d) *The importance of modular machine tool selection*: It is very important to select the machine modules to meet the workpiece needs although the modules themselves in terms of basic design and concept may be standard. This modularity has the advantage of reducing risk to the user because of the previously tested designs with respect to both hardware and software. These modules can use modular workpiece, tool transport and handling equipment, and standard computer and control systems. These modules can then be readily configured into systems whose features are optimised to the short and long term needs of the user. In addition, it makes the systems easily reconfigurable as future plans change. This modular approach also provides the added advantage of allowing the user the freedom to move towards phased implementation of an advanced manufacturing system, starting from modules and gradually progressing towards full integration by the incorporation of additional modules, as appropriate. Thus the system as a whole may be unique but the elements in the system are not necessarily unique.

(e) *Stand-alone versus system*: This is basically dependent upon part volume and part variety. The stand-alone concept is used to produce high-variety, low-volume workpieces. The major advantage of this concept is its high degree of flexibility. Engineering changes are easily incorporated and tooling changeover periods between batch production runs are minimal. The system concept is designed to produce mid-volume, mid-variety workpieces. The stand-alone concept is inferior to the system concept in that it lacks management control, has inherent inefficiences and is characterised by the ever present re-tooling and set-up requirements.

(f) *Material handling forms*: There is no single method of material transportation for all manufacturing systems. The choice of handling system is dependent collectively upon the component characteristics such as size and weight, the production rate and number of machining stations present in the system, and the flexibility of routing.

(g) *Matching the machine tool to the manufacturing task*: The balance between machine tool capability and workpiece requirements is imperative as is whether the machine tool is to be implemented within a cell configuration or operated as a stand-alone machine. Batch quantity, lead times, process times, cycle times, multiple or single set-ups and required throughput dictate the quantities for each process or machine type required. Equipment improperly designed for its processing requirements will lose accuracy, alignment, produce inferior parts, and will necessitate earlier equipment replacement. However, when the balance is maintained, tool life, cutting efficiency and machine utilisation are maximised.

(h) *Integrating specialised processing capability*: The requirements for specialised machines must be carefully assessed. Two factors which most often necessitate this capability are narrow tolerances and a high rate of production. The design of early FMS installations, for example, was impeded by the absence of ready made solutions for supporting machinery. Washing stations, CMM's and deburring machines which could be integrated into these installations posed particular problems. The granite bed technology used for the CMM seemed ill suited for incorporation into an FMS, as the vendors of such equipment understandably did not have a deep knowledge of the system into which the equipment was to be installed. Therefore, the onus to some extent was on the turn-key supplier to make sure that the interfaces to the vendors equipment was fully understood. In the longer term it is possible that communications standards like MAP, or even simpler networking capabilities such as ethernet, will help simplify the interfacing problem [142,263].

(i) *Supervisory control*: The use of hierarchical control in multi-cell manufacturing systems using a range of possible cell structures from manned machining stations to highly automated configurations has to be thought out very carefully and matched to the manufacturing task.

(j) *Small parts design considerations*: The three variables of size, weight and cycle time will affect the selection of the system elements especially the material handling system in terms of speed and frequency of events.

(k) *Multiple parts loading*: Some systems will allow for multiple parts loading on pallets. When multiple part loading is possible, it allows the pallet cycle time to be longer than the part cycle time, thus significantly reducing the material handling events in the system. Although this allows maximum efficiency of parts loaders/unloaders; the inherent danger is accessibility to the various surfaces of the workpieces due to their adjacent physical relationships.

(l) *Choice of tool and pallet management systems*: The installed machine capacity must relate to the work volume and mix, and as every part loaded on to each machine also *binds* a specific tool kit, pallet and fixture there is a requirement for pre-planning and down-loading of these elements to the right tool store and work load-pallet areas. The provision and selection of these secondary subsystems will affect overall performance. The compromise which must be sought is between machine utilisation and pallet inventory; machine utilisation and tool inventory; and batch variety, sequencing, and changeover, versus machine, pallet and tooling availability. The temptation is to over provide tooling and pallets to lift any constraint from this aspect, but this will only lead to the inefficient use of the total resources, which is what the concept of FMS aims to avoid. The need for modelling and simulation is clear in this respect.

3.5 The Operational Considerations

Major operational considerations necessary for a typical FMS include the following:

(a) *Workpiece and fixture control*: The control system needs to keep track of the location of all workpieces and fixtures, both in the FMS and in queues available to the FMS.

(b) *Part routing control*: The efficient and automated production planning and control system is necessary to enable the system to switch from one part mix to another; not necessarily of the same part types. This requires automatic operation assignment procedures and automatic pallet distribution calculation capability.

(c) *Material transport system control*: The current location of all transport devices and their status needs to be monitored. This can be achieved by the use of stored control algorithms for the loading, unloading and transporting of workpieces.

(d) *Work flow and machine allocation control*: The control system needs to be able to select an appropriate part mix and part quantity. Each part may be machined individually and not necessarily in batches. In this case the number of part types that can be machined simultaneously without using batches needs to be determined.

(e) *Work station control*: The instructions necessary for carrying out the required process on a given workpiece on a given workstation needs to be managed by the control system. Provisions may be necessary for operator intervention and the restraining of process cycles at the work station.

(f) *Operation control*: The ability to interchange the ordering of several operations for each part type may be necessary. There is usually some required partial sequential structure for a particular part type. However, for some operations, their respective ordering is arbitrary. In this case the control system must be able to reroute these operations in real time to machines which are idle. This decision will depend upon the current system state.

(g) *Dynamic routing control*: The ability to handle breakdowns, and to continue producing the given set of part types must be inherent in the control system. This ability will exist if either the part type can be processed via several routes or each operation can be performed on more than one machine.

(h) *Part program control*: Where NC machines are present in the FMS, the various part programs must be able to be transmitted to the machines as required. The use of hierarchical DNC/CNC control systems are now very much in evidence [47,175]. Provisions must be made for editing of these programs.

(i) *Tool control, tool life control and diagnostics*: The control system should have the ability to replace worn-out or broken cutting tools, change tools in a tool magazine to produce a different subset of the given part types, to record the tools required and amount of life that is used up for each processing operation, to record tools present at each workstation and the tool life status of each tool; to update the historical life experience for each tool type and to schedule tool assignments or kits to the workstations at the appropriate time. The control system should also include such features as on-line diagnostics, combined with feedback control of machining and of the location of workpiece surfaces, surface quality, in-process inspection and control. While some of this capability is already in existence and being applied, much of it is still being actively researched and developed [58].

(j) *Other operational considerations*: Several other features need to be considered. These are provision of management types of performance reports, visual display of key status items, production planning and two way communication with the system manager.

3.6 The Multi-Phase Development of Manufacturing Systems

Either of three alternative approaches may be adopted in the introduction and implementation of automated manufacturing systems. The first approach is a total system implementation using a turn-key system purchased from a turn-key supplier, the second is a phased introduction or *top-down* approach to design of manufacturing systems, and the third is the multi-cellular or CIM *bottom-up* approach. The latter approach has been previously discussed with regard to trends in manufacturing system design; and attention will be focussed in this section on the two former approaches. Both approaches experience basic stages of development but differ in their suitability to the manufacturing concern wishing to implement the manufacturing system. The total system implementation is more suitable to the user with experience in the handling of large projects.

Very few companies are equipped with the necessary skills to manage a turn-key system and thus most opt for a phased-in installation. This phased-in approach becomes necessary once it is recognised that the FMS is just one element in the overall organisation and that deficiencies in areas outside the FMS may well limit its performance. The multi phase development of an FMS provides the opportunity for a manufacturing organisation to grow into new technology and new manufacturing methods. The advantages, although subtle, provide important benefits as the total system becomes an operating facility, but caution is advocated as such a neat solution to manufacturing system design might not offer all that is required of a manufacturing system.

The *step by step* or *modular building block* concept was pioneered by KTM, amonst others [161,253,258]. Six stages have been identified for each FMS module selected. These are as follows : planning, engineering activity, manufacture and assembly, shipment, installation and implementation. Many examples of KTM systems employing this design concept are evident.

Planning is the first step in the system definition. During this period, the proper concepts are selected and developed to a proposed level of definition. This includes the specification of the machine modules, the selection of the material handling module and specification of a floor plan, the siting of the FMS and the specification of the tools, fixtures and process sequence.

The *engineering activity* that follows specifically defines all module designs and functional relationships. Simulation is used at this stage to simulate the materials handling and tool handling activities. The requirements and specification of control software are identified and system software is written. Tooling and fixture lists are generated and NC software produced.

Manufacture and assembly involves material procurement, machining, unit assembly and machine erection. Lead times are established for fixture build up, contractor activity, delivery, manufacture, assembly and tool delivery, and proved out of manufacturing and assembly methods takes place. *Shipment* involves testing the equipment at the suppliers site and shipment to the users site.

Installation shifts activity to the user site. Modules are once more tested as units to assure performance to specifications established during the engineering stage. The materials handling module is integrated with the machines and the system software is proved out.

Implementation is the final stage which integrates all the modules. Final testing is performed to establish system productivity, accuracy and managerial performance to levels initially established in the planning stage. Production may begin at this final stage. If the phased-in approach has been adopted and planned productivity achieved as the machine modules were implemented, incremental needs may be defined using the same basic stages outlined. This means that a company can begin with the lowest possible investment and that the technology can be absorbed and optimised before moving on to the next stage. This can be particularly important in small companies with limited resources. There are now many companies who have attained very significant benefits at this first level of sophistication.

A deviant system concept which combines this *top-down* approach, of planning for the final system but implementing the modules in phases, has been adopted by Giddings and Lewis in the USA.

3.7 The LUT FMS Design Aid

A coherent suite of data-driven software for manufacturing system design and assessment and mounted on a dedicated workstation has been developed at Loughborough. Two major phases are recognised, *figure 3.13* . Firstly, an evaluation phase provides rapid appraisal of system performance using average measures based on queueing theory. Secondly, an emulation phase generates detailed dynamic statistics. A scaled layout is input and material flow paths defined. Specific demand patterns are emulated using animation, under system constraints and with defined operating rules. The emulation modules are processed in parallel. This design aid is the subject of a parallel research programme and a forthcoming complementary thesis [265]. In collaborative interaction with this research project three networks have been defined for modelling of part and tool flow :

(a) *Mutually Exclusive* flow networks: A system with this flow network has two separate networks for parts and tools transportation,

(b) *Single Function* network: The parts and the tools are moved on the same network at the same time, and on the same transporter. This network and the *mutually exclusive* flow network can be handled in the tool flow modelling algorithms presented in chapters sixteen and seventeen.

(c) *Shared Flow* network: The parts and tools share the same network and the same transporters but they cannot be transported together. This network cannot be easily modelled with the algorithms due to part flow constraints.

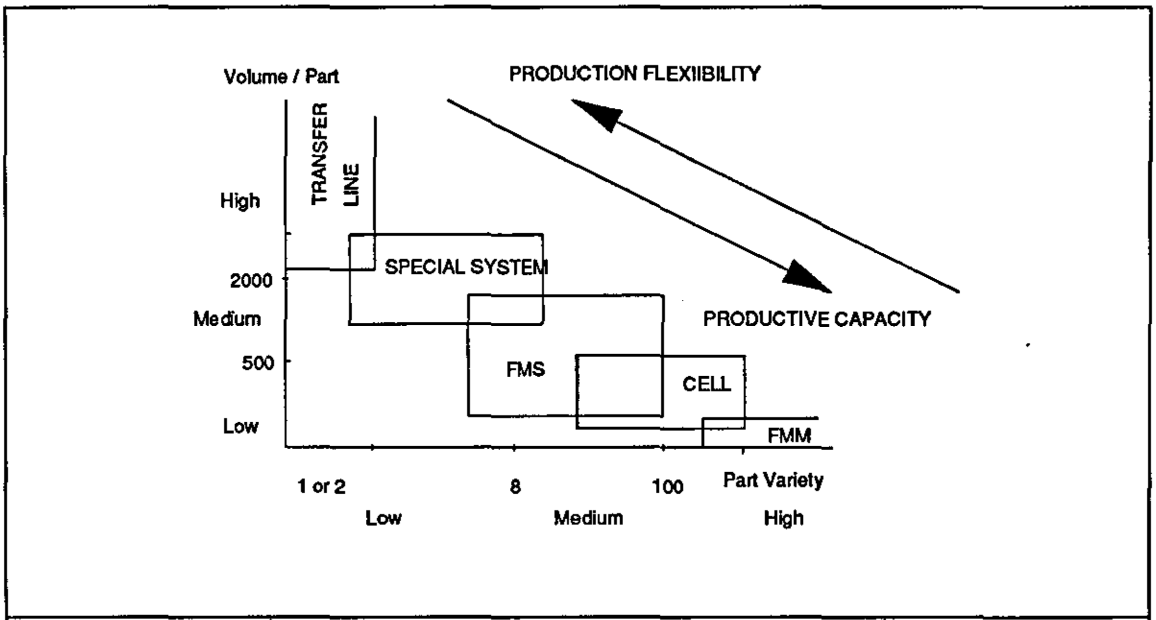


Figure 3.1

MANUFACTURING CONCEPTS
- PRODUCTIVITY vs FLEXIBILITY [ref. 161]

LUT - FMS
Research Group

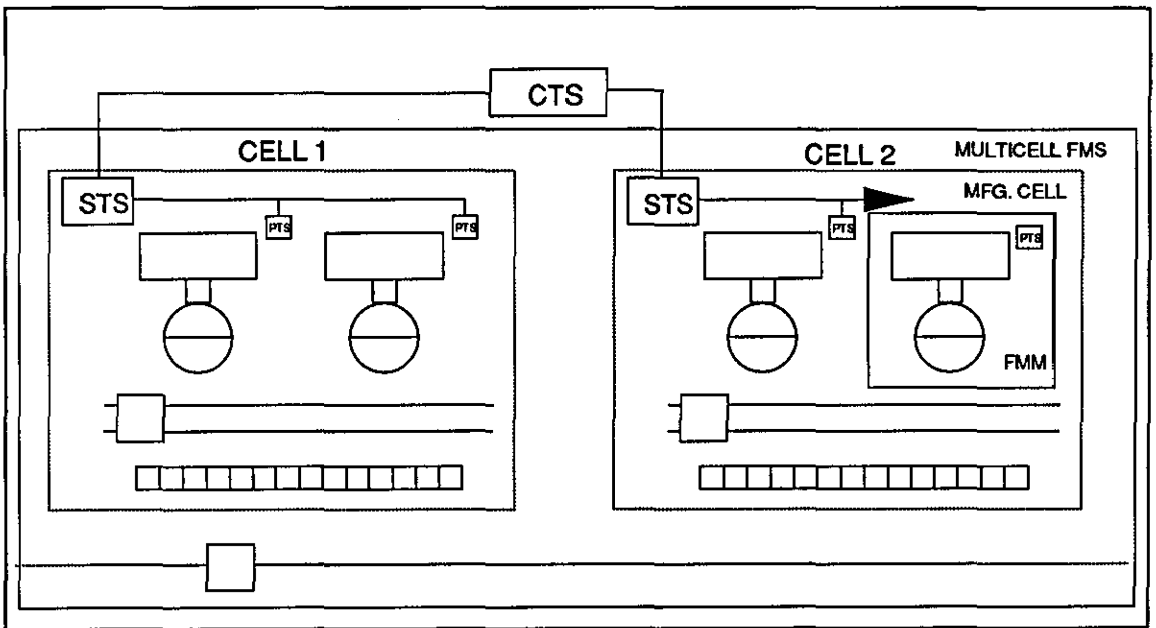
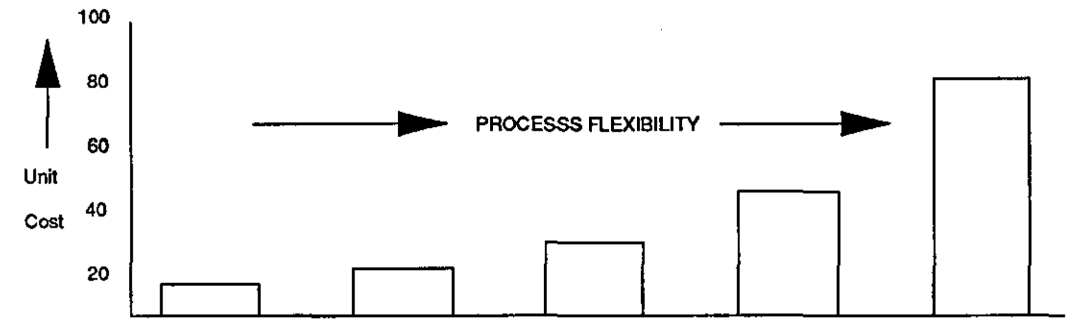


Figure 3.2

MANUFACTURING SYSTEMS
- CONFIGURATIONS

LUT - FMS
Research Group



Type	Transfer Lines	Flex. Trans. Line	Free Flow F.S	FMC Based System	FMS
Process	Seq. Processing of large batches	Seq. Processing of medium batches	Seq. Processing of small Batches	Random Processing of small batches	Random Processing of random batches
Flexibility	Total Dedication	Semi Dedication	Temp. Dedication	Random Proc.	Totally random
Part Variety	Large Part Variety	Increased Part Variety	Med./High Part Variety	Med./High Part Variety	High Part Variety

Figure 3.3

COST / PROCESS FLEXIBILITY RELATIONSHIP

[ref. 207b]

LUT - FMS
Research Group

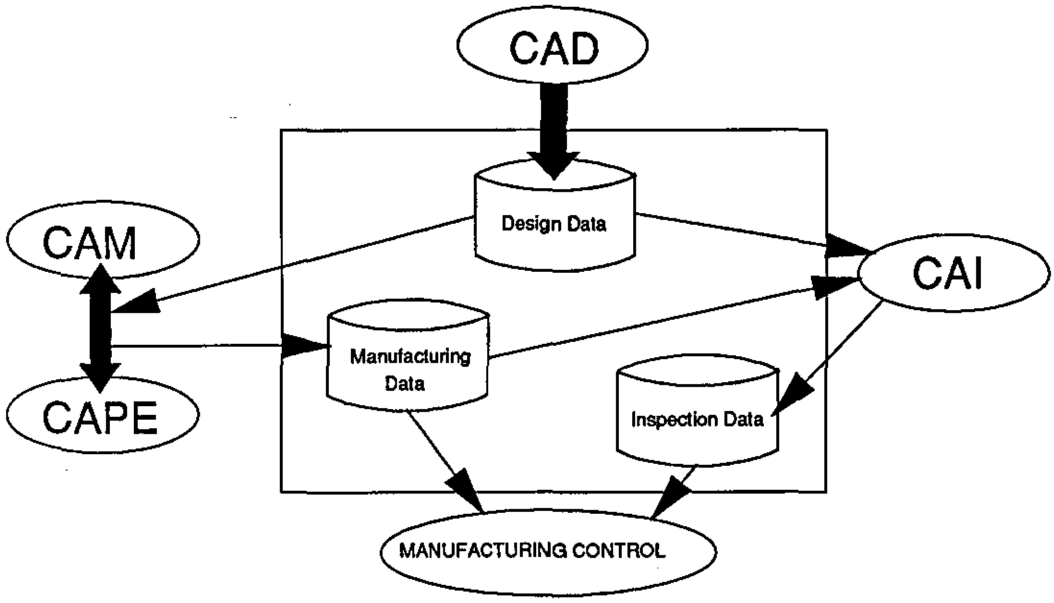


Figure 3.4

A COMPANY VIEW OF
COMPUTER INTEGRATED MANUFACTURING
[ref. 111]

LUT - FMS
Research Group

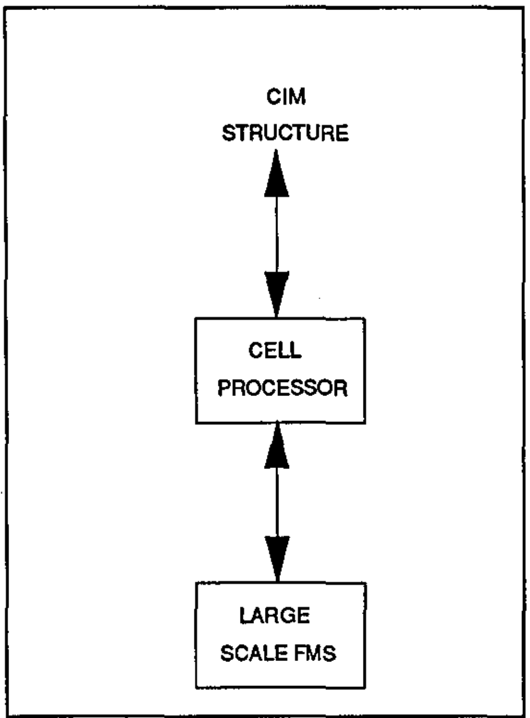


Figure 3.5 | SINGLE-CELL FMS | LUT-FMS RESEARCH GROUP

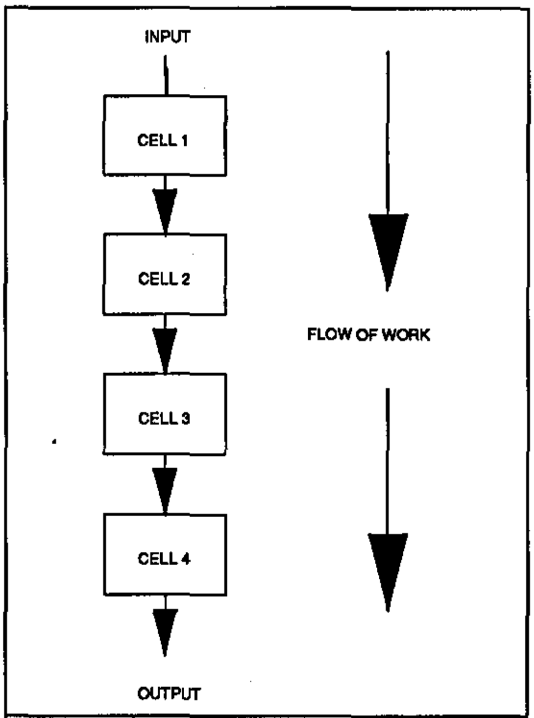


Figure 3.7 | 'FLOWLINE' MULTI-CELL | LUT-FMS RESEARCH GROUP

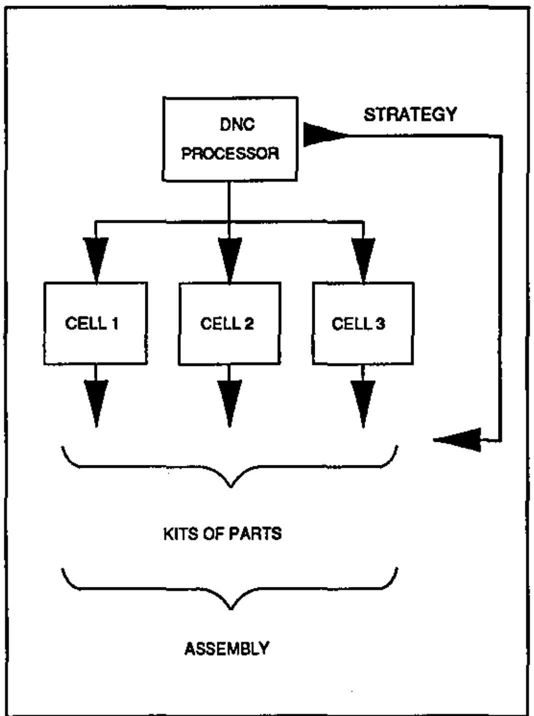


Figure 3.6 | PARALLEL MULTI-CELL | LUT-FMS RESEARCH GROUP

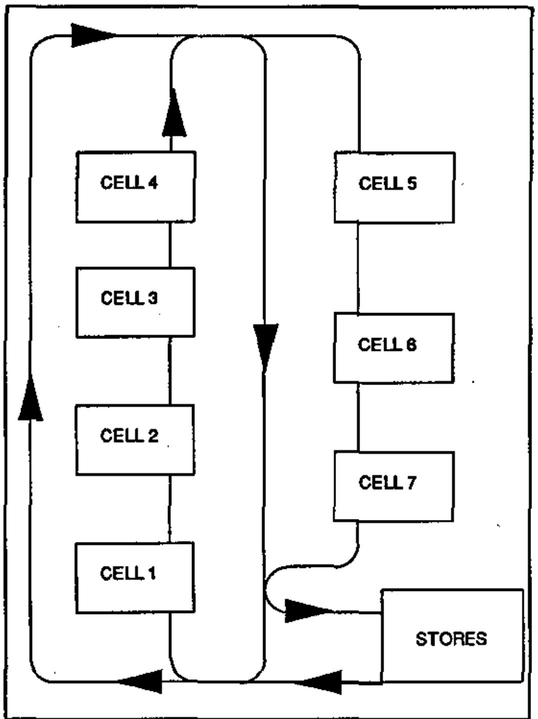


Figure 3.8 | HOLSET MULTI-CELL FMS | LUT-FMS RESEARCH GROUP

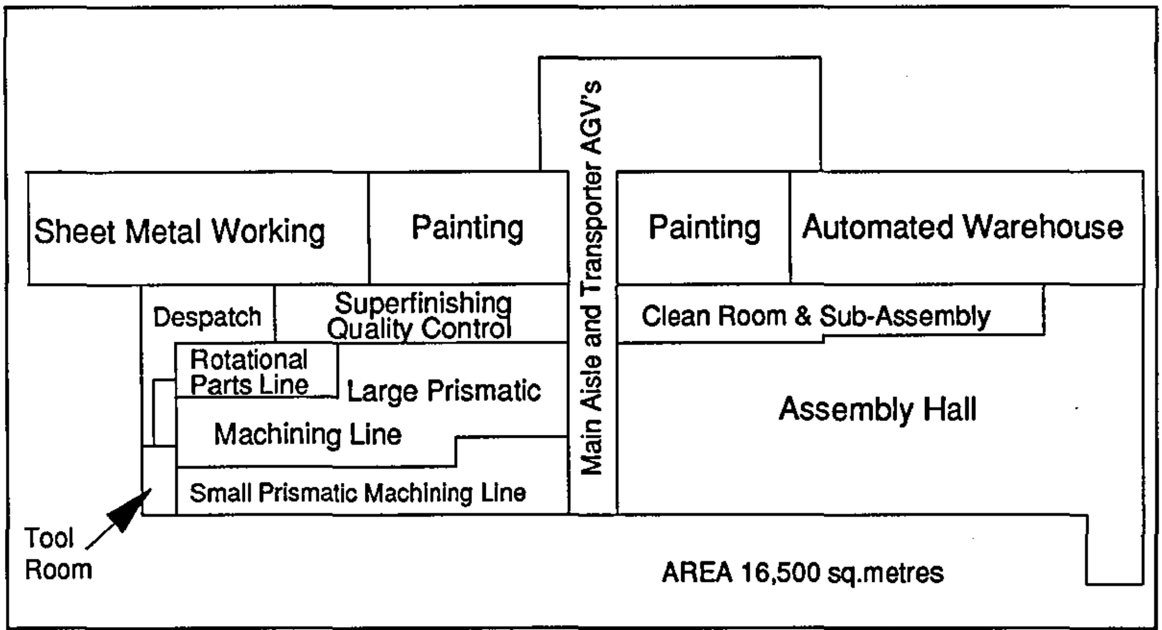


Figure 3.9	YAMAZAKI WORCESTER MULTICELL FMS [ref. 189]	LUT - FMS Research Group

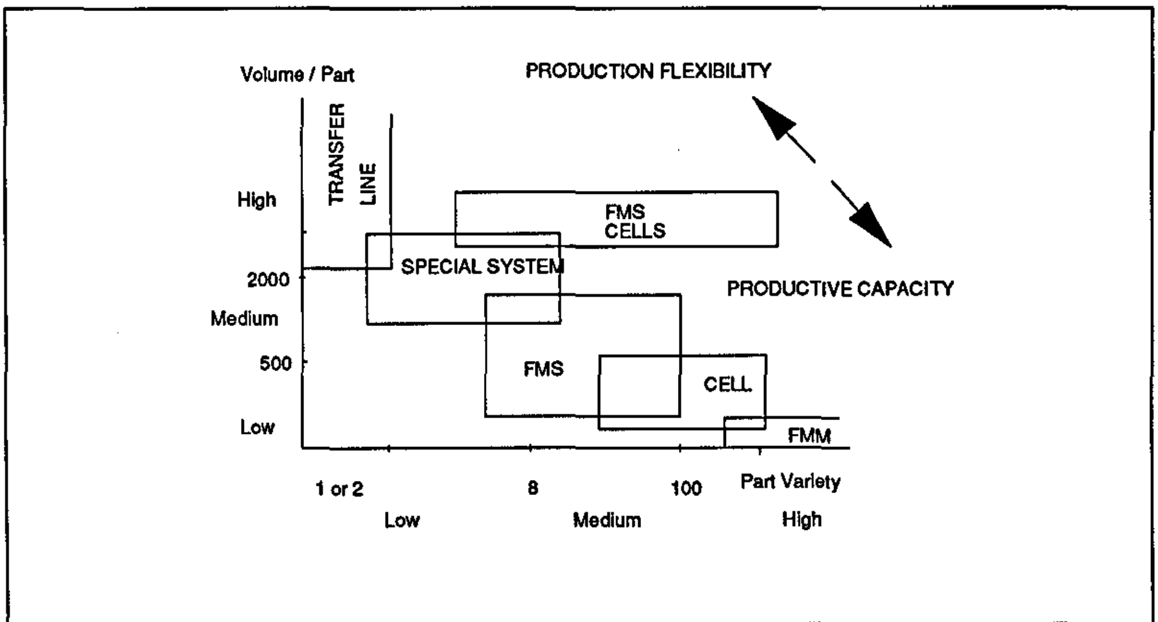


Figure 3.10	MANUFACTURING CONCEPTS - FMS CELLS (MULTICELL) [ref. 161]	LUT - FMS Research Group

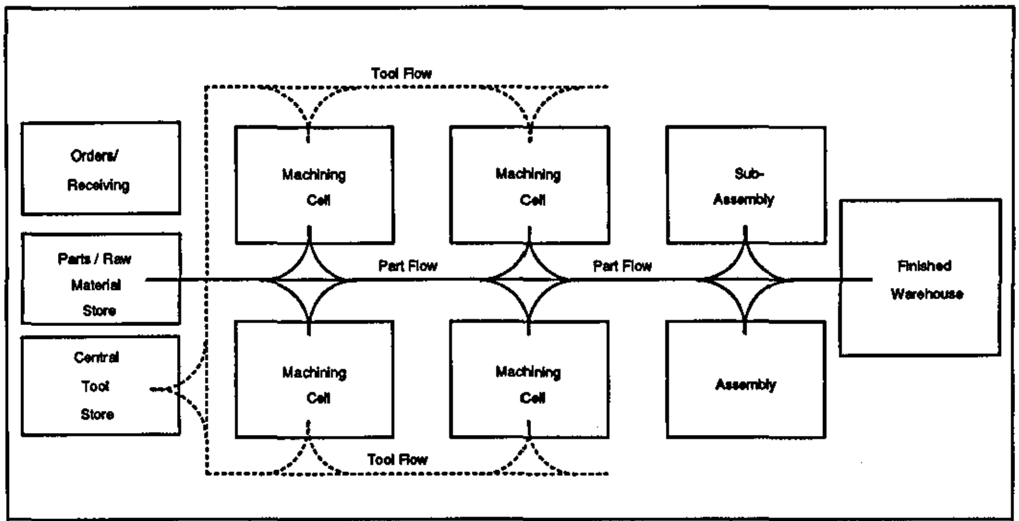


Figure 3.11	TYPICAL ELEMENTS OF A MANUFACTURING AREA [ref. 248]	LUT - FMS Research Group

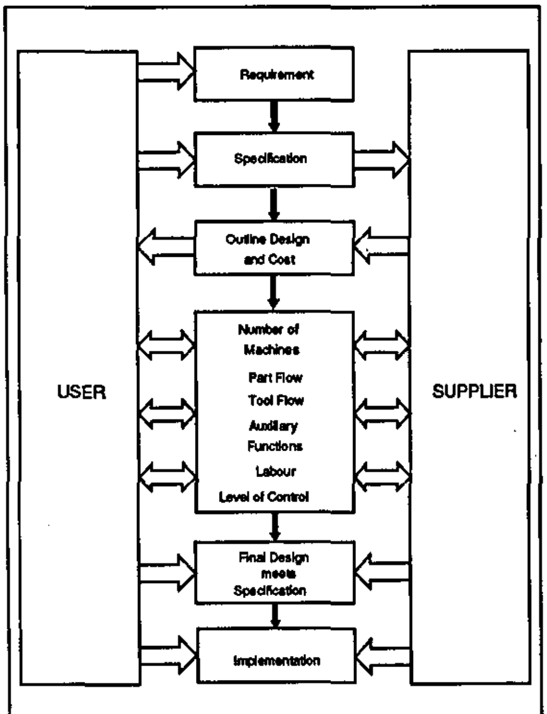


Figure 3.12	USER / SUPPLIER INTERACTION IN MANUFACTURING DESIGN [ref. 248]	LUT-FMS RESEARCH GROUP

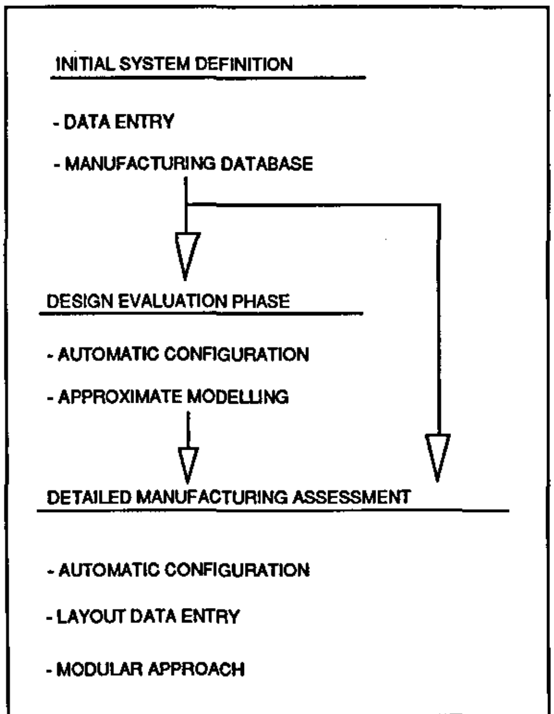


Figure 3.13	OPERATIONAL STRUCTURE [ref. 248]	LUT-FMS RESEARCH GROUP

Chapter 4:
THE MAJOR ISSUES IN TOOL MANAGEMENT FOR FLEXIBLE MACHINING INSTALLATIONS

4.1 Introduction

The issues, subdivided into the pertinent technological issues of how to store, handle, transport and load the tools; and the managerial issues of how to best organise the supply of tools are discussed in this chapter.

4.2 Factors Affecting the Rapidity of Tool Change

The number of cutting tools in a medium size FMS, or any manufacturing system operating with minimal manning, can easily run into thousands. Therefore, to achieve an uninterrupted machining cycle, tool set-up, change, and tool magazine load/unload should take place outside the machining cycle. Stand-alone machining centres generally: have the disadvantage of a limited tool storage capacity of between 24-60 tools (the number of tools required by each machine will often exceed the capacity of the built-in tool changer); only work unmanned for one or maximum two shifts; undergo manual changing of the complete set of tools for each new batch of workpieces; and undertake external presetting or readjusting of tooling in a separate tool facility. Thus, some means of augmenting the tool supply is required. The current trend is to move away from these stand-alone machines to more advanced tooling systems which can either expand the tool store locally or supply the machine from a remote centralised tool store, or both. These systems are usually characterised by automated tool handling, transfer and control strategies to satisfy the requirements of *flexible machining* to run unmanned or minimally manned.

Automated tool flow, storage, retrieval, loading and unloading presents a real challenge to the FMS system designer in choosing the right level of automation and a tooling system configuration to suit the needs of the FMS (146,171,294). This advanced technology does not in itself solve problems, it is how, when and where this tooling systems technology is used that matters. Planned for and carefully implemented, this technology is a fundamental building block in a long-range management strategy for profitability and growth (318).

4.2.1 Tooling System Factors

The factors involved in the automation of the tool flow are:
- a tool transfer network
- centralised and/or decentralised tool storage facilities
- automated tool exchange mechanisms
- a tool refurbishment facility
- a control/operational logic for managing the technological, analytical and managerial activities

(a) Tool Transfer: Tool transfer is mostly between individual machining stations and one or more tool storage or refurbishment facilities. Tool transfer may be accomplished either by using the workpiece transfer system or a separate tool transfer system as in the Citroen Meudon (19) and Makino Atsugi (220) installations. With a large number of tools in use (upto several thousand per month), in the larger installations, the potentially disastrous possibility of unsuitable transfer devices must be protected against. The method of transport and the means of transfer of tools to the machine can substantially affect the response time for a tool demand from the machine to be satisfied which in turn can influence the machine utilisation. A choice has to be made from a number of alternatives depending upon the nature of the tool flow and the machining installation under consideration. The chosen method of tool transfer will depend upon the number of tools required, per part on each machine, and the diversity of tool families together with their rate of usage.

(b) Tool Storage, Exchange Mechanisms: The selection of appropriate tool storage facilities, their location and exchange mechanisms presents a real challenge to the designer. The choice will influence the effective and economic management and operation of the installation, *figure 4.1*. If tools are to be changed manually, than using the largest possible tool magazine would be best, however, if automated tool transfer between stores is available, then smaller magazines would be sufficient. Several approaches to tool storage are evident: local expansion can be simple using an auxilliary tool store and transfer device, or modular expansion of the existing tool store, or even whole magazine changing may be possible. These approaches increase machine flexibility but can also significantly increase the capital tied up in tooling. An alternative is to link machines in a cell with an associated Secondary Tool Stores (STS), or even several cells to a Central Tool stores (CTS). This can be achieved in a variety of ways and minimises the total tool holding at the same time as maximising system flexibility. Ancilliary tool storage facilities can thus vary from tool-rack (matrix) arrangements to auxilliary tool-chain/drum systems to an independent secondary tool store supplying a cell via dedicated tool transporters, overhead conveyors, etc.

(c) Tool Refurbishment: Tool refurbishment is a company specific activity and as such, subject to management policy with regard to in-house or sub-contracted tool refurbishment. Replenishment of tool stocks should be handled in an orderly and timely manner according to predefined criteria. Decisions pertinent to refurbishment and presetting of the tools is fundamental to the administration of the tool flow and there is a requirement for proper planning procedures. These procedures may be assisted or automated using any suitable commercially available inventory control software.

(d) Control Logic: Complex control logic is involved in the operation and management of automated tool flow systems to ensure the appropriate tools, prepared and in a usable condition with their associated data, safely and reliably at the right location when needed so as to minimise unnecessary tool changes (66). In order to do this there has to be a balance between the cost of the system selected and the saving it will achieve in reduced machine idle time due to inappropriate tools, tool data or decision strategy; increased utilisation of tool life and a reduction in tool inventory. Computer modelling is thus essential for the selection and analysis of the above factors, in order not to nullify the benefits of automated tooling systems (49).

4.3 Tool Management and Supporting Technologies

Tool storage, transfer, handling and control requires careful analysis and planning for each individual case in order to meet user-specific requirements. It is precisely in this area that many as yet unexpected productivity reserves exist (21,110,276). The selection of the right tooling system category (see chapter five) to suit particular applications depends upon the production volume, shifts in work patterns, the selection of machine tools of modular design (system machines) or stand-alone machines (204,227) , see chapter three, the influences of market developments, and manufacturing strategies on the long-term planning period selected. Tool storage can be either *centralised, decentralised,* or *decentralised and centralised.*

Decentralised tool storage, *figure 4.2,* has gained much importance recently. Using this type of tooling system, all the tools required for a machine or system are stored directly on the machine, i.e. all the tools needed for a particular range of workpieces are stored *on-site.* Large linear surface magazines like the Mazak Tool-Hive (see chapter two) are ideal for this application and can accommodate several hundred tools. This assumes that all the tools required are continuously accessible, but problems may arise in tool utilisation efficiency, which is normally lower than in the case of centralised tool storage, and risk of tool contamination which may effect accuracy and machine availability. These systems are generally less flexible, less costly and easier to control.

Centralised tool storage, on the other hand, provides for making tools available to the entire cell or installation, *figure 4.3* . Central control and highest possible tool utilisation are achieved, as well as good linking facilities to tool preparation and presetting. Other benefits to be gained from the use of centralised systems are increased machine utilisation because tool change is mechanised and takes place during actual cutting time; reduced tool costs because each tool is fully utilised up to the end of its useful tool life; reduced number of tools as each machine has free access to the common tool storage; smaller batch sizes and the possibility of using the part transportation system for the transfer of tools. These systems tend to be complex to control, of high cost and suffer from relatively long journeys to the individual manufacturing points. Correct tool loading is essential in these *open* systems. Direct access to a central tool storage facility means that parts can be machined in a continuous process where the number of tools required exceed the capacity of the machines primary tool storage. In this system computer controlled tool re-supply can take place as and when required (57).

Decentralised and centralised tool storage together in a system can largely eliminate the disadvantages and exploit the advantages more effectively. Certain basic and cell-specific tools remain locally *on-site* and others are accessible to all manufacturing points. Typical for this type of integrated tooling system are machines with larger but cost favouring tool magazines fitted to the machines themselves - normally with capacity of up to 100 tools. This ensures that most of the tools are continuously available and at appropriate intervals, the remaining tools can be exchanged in relation to the central or secondary tool store without involving downtimes. A variety of possible configurations for these types of systems is presented by Stute (296).

Within these integrated systems, the support technologies associated with tool management for machining centres are crucial to the implementation of effective minimally manned machining systems. These technologies are developing rapidly and are the subject of many studies (282,292) .

For example, as the number of tools available at a machining centre increases and if unmanned production is desirable, some form of tool identity checking and tool monitoring becomes desirable since the risk of selecting a wrong tool is much higher and potentially disastrous. Various techniques are available for writing, storing and reading the tool code, including ring coding on tool holders, and the use of bar codes and transporters attached to tools, tool holders and magazines (245). Data which can be carried in the tool code includes information on tool type, tool size, tool offsets, tip grade, and the tool geometry. The selected code must be compatible with the coding device and the system requirements. A standard coding system would be desirable as the popular general purpose code, the VDI 3320, is so broad based that it is said to be cumbersome in use. There is little standardisation between manufacturers product codes and as a result several standards organisations are now pressing for action. Eversheim et al at Aachen University have proposed a structure and application of a universal company-independent data bank for tools [109].

Similarly, there are a number of approaches that may be adopted to determine the end of useful tool life. The simplest but perhaps the least effective is to define the end of tool life in terms of the number of components machined or the number of minutes involved in machining. Actively monitoring the tool wear is a more efficient method of determining the end of the useful tool life. Any method adopted must be reliable and effective and allow tool changing to take place at the end of the useful tool life or when unforseen breakage occurs, see chapter fourteen. A number of devices are available that can, to some extent be used for this purpose.

Other important features necessary for these integrated systems include waste (swarf and coolant) disposal, workpiece inspection [114,140,280,325], and where a central tool store is in use, automated tool presetting operations are necessary. The tool presetting operation can be automated to various degrees, from downloading of data from a manual station into the software stores of a tool management system, to completely automatic presetting where the presetting device reads the tool code, then runs through a programmed presetting routine to update the tool offsets in the coding device.

Fundamental to unmanned operation and in parallel to the above features is the requirement that the machining cell should be able to monitor itself. Tool verification, through increasingly sophisticated feedback devices and systems will go beyond sensing the presence of a tool, to include the ability to determine whether the tool is capable of delivering optimum results, and even to systems where the workpiece itself is monitored on-line for dimensional errors. The use of probing technologies where the results are fed back to higher levels for analysis as to cause and subsequent actions are also required [60,200,328].

The engineering and the organisation of the tool management within these integrated systems, as described, can only be implemented by data combination in individual interacting computers. It is essential that the data combination is not only organised horizontally but also vertically, as the demand for complete machining with the shortest possible times necessitates a vertical permeability of all the relevant manufacturing information, such as the required production figures, delivery dates, etc., at all levels. This requires increased data communication between the design and planning functions and between the central data bank and the lower manufacturing levels. This conceptual formulation will provide an interface hierarchy to the central data processor [319].

Thus, full implementation or putting together of an automated tooling system and applying it to a particular situation presents a considerable problem for a majority of manufacturing industry. This is exacerbated by the fact that nearly every system will be different and there are therefore no general solutions. These systems, not unexpectedly, are expensive and involve a degree of risk [238]. As with many areas of automation, trade-offs have to be considered between what is technically possible in tooling systems technology and what is commercially available, see chapter five. The choice of approach is determined by the present and anticipated volume of production, the variety of the product range, and the flexibility of response to market needs. This level of complexity in tool handling requires a framework for the analysis, selection and evaluation of a suitable flow network, transfer and control strategies. Analysis by modelling is the obvious route to approach this problem as experimentation with actual hardware is prohibitively expensive and alterations are difficult to implement. A computer aid to provide support in this systems-thinking approach to tool management is thus necessary for fast, effective and economic network design, management and operation.

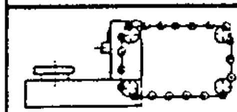
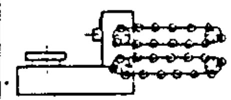
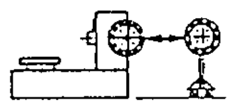
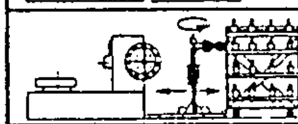
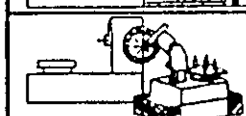
tool storage and transport		storage capacity per machine tool	time fraction per tool change over	bound capital for tools in the manufacturing system
	One machine-integrated circulating magazine	40 - 100 tools	large	large
	Two machine-integrated circulating magazines	60 - 120 tools	small	large
	interchangeable disc-magazines	20 - 40 tools	medium	medium
	successive interchange of single tools from a stationary auxiliary magazine	20 40 tools	none	medium - small
	automatic interchange of single tools with mobile industrial robot	20 - 40 tools	none	small

Figure 4.1

AUTOMATIC TOOL STORAGE AND TRANSPORT AT MACHINING CENTRES [ref. 295]

LUT - FMS Research Group

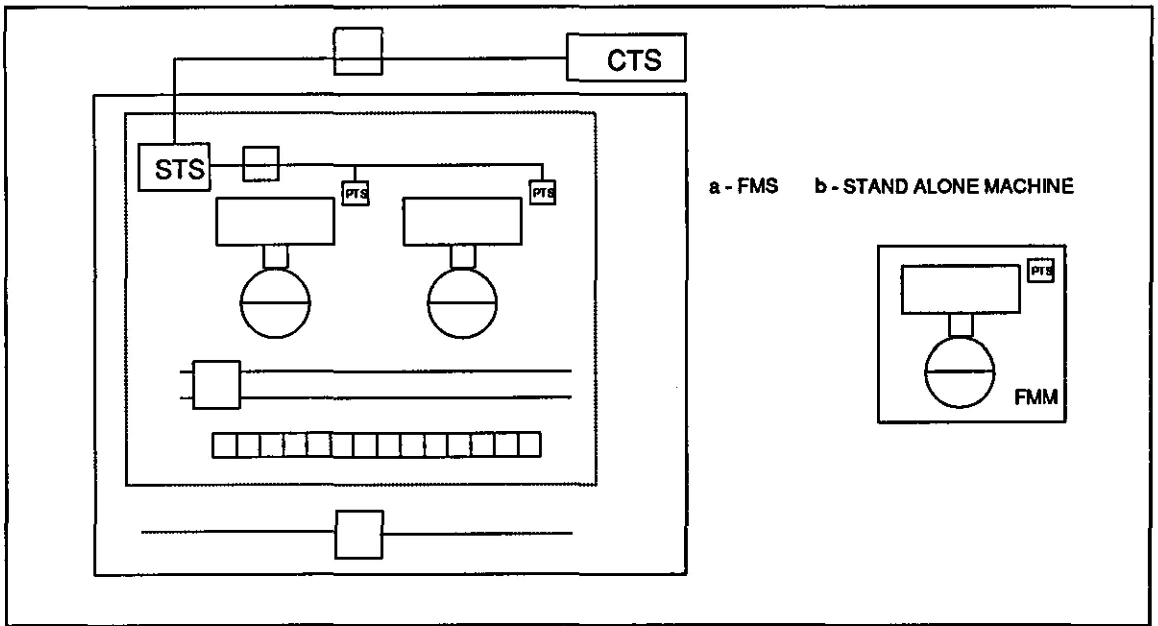


Figure 4.2 DECENTRALISED TOOL STORAGE [ref.227] LUT - FMS Research Group

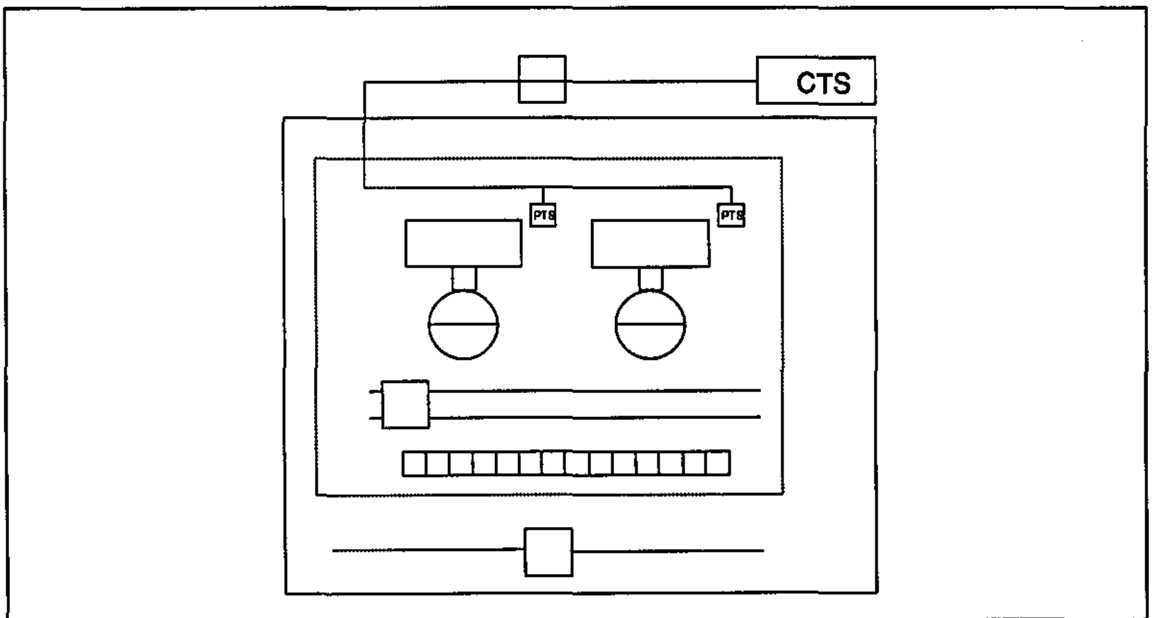


Figure 4.3 CENTRALISED TOOL STORAGE [ref.227] LUT - FMS Research Group

Chapter 5:
CELL TOOLING SYSTEMS
FOR THE MANUFACTURE OF PRISMATIC PARTS

5.1 Introduction

A structured approach to tooling systems is presented in this chapter, based on the survey of current tooling systems in chapter two, in order to guide a system designer through the maze of available options. This structured approach is developed for different types (categories) of tooling systems, used in the manufacture of prismatic parts, according to complexity, capacity, design interest and functional value. The categories provide a backcloth against which any tooling system may be identified, operating strategies selected, and the chosen network evaluated using the computer aids described in subsequent chapters. The categories thus map out all the technical solutions so that they can be adequately represented within the algorithms. This chapter describes this first stage in the methodology for the design and operation of tooling systems. A discussion of the *state of the art* with respect to tool flow systems used in flexible transfer lines and turning centres is presented in the literature survey.

5.2 Categories of Tooling Systems

The state of the art with regard to single, multi-spindle and multi-tool head machining centre technology can be described by a hierarchy of technical levels, where each level can be categorised according to the following characteristics:

a) the level of automation or functional value
b) design interest
c) capacity
d) type of storage medium; and
e) exchange mechanism

5.3 The Levels of Automation or Functional Values

Three levels (categories) of automation or *functional value, figure 5.1*, are apparent and are referred to in the text for convienience by an alphabetic symbol as follows:

[A] - This is the simplest form of tooling system found on stand-alone machining centres. The tooling system consists of a localised tool magazine or PTS (Primary Tool Store) and a mechanism for tool exchange between the tool magazine and the machine spindle(s).

[B] - This is an intermediate form of tooling system with a more sophisticated design used to augment the PTS capacity. These ATS (Auxilliary Tool Store) systems feature huge capacities in automatic or semi-automatic supply and storage of tools with minimal space requirements. This kind of tooling system not only enables long, unmanned stand-alone operation periods to be achieved, but is also capable of being linked with other machines to form cells.

[C] - This is a more advanced tooling system used in large scale or cellular installations. They are a more economic and effective alternative to the ATS system. This system employs an STS (Secondary Tool Store) at a cellular level with the tools being transported to the machines using a dedicated-tool or shared- tool/workpiece transportation network.

5.4 Tooling System Features

Special features of design interest, capacity, magazine type, transport and exchange mechanisms are described for each of the functional values as follows:

5.4.1 Category A - Manual Tooling Systems

The particular features with regard to this type of system are the categories of design, the basic forms that the localised storage may take and the capacity of the PTS.

(a) Sub-Categories of design: Three design categories are evident in these systems. These are denoted as follows:

The Single PTS : The standard single integrated primary tool store systems are readily described in the respective manufacturers literature and are not discused in detail here. This PTS is usually in the form of a standard tool - drum, - chain, - disc, etc., incorporated into the machine tool design.

The non-standard integrated PTS is a novel approach to increasing the number of tools held at the machine level in a confined space. Several designs have evolved. One machine worthy of mention here is the Makino MC series of machining centres [221,222]. This machine has a drum type PTS with capacities for 30, 60, 99 or 120 tools. The tools are arranged in upto 4 concentric circles. Tools in any of the multi-circles can be readily accessed by the spindle via an integrated automatic tool changer or ATC.

Machines with Two or More Integrated PTS's : Solutions with two or more integrated PTS have evolved to enlarge the capacity of the single PTS. These magazines accommodate a large number of tools and tools may be loaded into one magazine when the other is in use, reducing downtime occasioned by the replacement of tools. Several approaches are evident, many being based on a tool-chain type of PTS. The KTM Fleximatic FM100 is an exception with two 60, 120, or 180 tools capacity drums and twin pallet shuttle [76]. The Mandelli Regent series of machining centres [17] provide other examples of such machines, with a double chain for a total of 120 tools.

The Mori Seiki machining centre [123] is another example. Above the normal 60-tool chain is a 40-tool chain for smaller tools such as drills. There is a small arm which hangs down from within the route of the small chain. It picks up the small tool and articulates outward before extending to the lower chain to install the tools into a holder. Ex-Cell-O [5] with its four banks of 32-tool chain magazines that can be shuttled in and out as needed under computer control provides another example.

Another novel method for increasing the tool availability is by employing cassetes of tools. OKK [125] has demonstrated a machine which has three stands to carry tool cassettes. Each cassette is a vertical tool carrier of Z-section, so that it can hold two vertical rows of six tools. Each machine has immediate access to 24 tools.

Interchangeable PTS's : The forementioned design categories tie up a large local tool inventory, are very costly and the time spent in manual tool replacement remains excessive and results in the same machine idle times. An advancement is to include the interchangeable PTS's which may either be localised around a particular machine or interchanged with any other tool magazine in the system. This sub-category has evolved to enable a large numbers of tools to be made available quickly. The designs range from one or more back up magazines through several-tier magazine systems. A deviation from the circular interchangeable magazine is the rectangular crate design also used as a transportation and storage medium. These designs are not very popular as they tie up considerable tool inventory, are complex to control, and may interfere with the workpiece transportation system. These designs need to be implemented as a total concept and not phased in with stand-alone single PTS machining centres which may be supplied by different machine-tool manufacturers.

The main idea behind this concept is that the PTS on a machining centre can be completely exchanged with a fully set up replacement. An example is provided by the Hulle Hille nb-h 70 machining centre [216], equipped with two disc magazines, one either side of its spindle. The right hand disc has room for 24 standard tools, whereas the left hand disc is intended for special and duplicate tools and can be automatically exchanged with any of the three replacement discs. The four interchangeable discs each have capacities of 23 tools which gives a total tool capacity of 116.

The Yamazaki Machining System (YMS) installed at Minokamo, Japan [11,44,124] is slightly different in concept to the Hulle Hille machine as it has only one 'working' disc magazine, which can be automatically exchanged with any one of four replacement discs. Each disc has a capacity of 30 tools giving a total disc capacity of 150 tools. Other machines in this category would include the Marwin Automax machines, the Okuma machine design concept, the White Consolidated (WCI) machining centre and the KTM FM200, see chapter two.

The transferable disc system is intended for situations where rapid changes of many tools are necessary. This situation occurs in a typical FMC where one or two machines need to be capable of carrying out different types of operations in order to process the part. However, a design such as the Hulle Hille nb-h 70 machining centre [216] which has one fixed disc for standard tools and four interchangeable discs for special tools is likely to be most efficient with regards to tool duplication.

(b) PTS types: Various magazine types of different complexities are found in practice. The basic forms are illustrated in *figures 5.2 to 5.4 inclusive* and include the following :

- star-type turret head
- crown-type turret head
- disc-type magazine
- drum-type magazine
- chain-type magazine
- drum-type magazine or turret head for multi-spindle heads
- chain-type magazine for multi-spindle heads
- mixed-type chain or drum magazines
- multi-circle drum magazines
- matrix-type magazines
- pallet-type of magazine for multi-spindle heads

Smaller machining centres are normally equipped with the drum or disc type of tool magazine. Usually these types of magazines typically have a capacity of 20-60 tools limited by the diameter of the magazine. User experience has shown that this is inadequate for many machining tasks, and since retrofitting has not been possible because of the relatively high cost and more importantly downtime, the trend has been towards tool chain designs. These chain-type magazines can accommodate a relatively large number of tools and can made with different shapes. Alternatively a large number of tools may be accommodated in a compact space in a single PTS using a multi-circle type magazine. The advantage of this type of magazine is the fast tool search and exchange times.

5.4.2 Category B - Auxilliary Tool Store Systems

ATS systems, sometimes referred to as semi-automated tooling systems, usually employ the same basic forms of magazines as the PTS. Very much in evidence are the matrix or rack type and tool chain designs, although the capacities of the magazines tend to be very much larger than that which can be contained in a single PTS.

Of particular interest in this type of tooling system is the exchange mechanism which transfers the tools from the ATS to PTS and back. These exchange mechanisms, *figures 5.5 and 5.6*, include :

- overhead gantry systems
- shuttle mechanisms
- robotic exchange
- gripper exchange

Examples of these category B systems include the Normalair-Garrett(NGL) FMC [26,102,173] at Crewkerne in Somerset which consists of two KTM 560 machining centres, each equipped with drum magazines with capacity for 40 tools, and the Fritz Werner DFZ630 duplex cell [108,116,187] which features an overhead gantry tool change robot transferring tools between the 40-tool magazines on two four-axis machining centres and a bed of movable storage racks behind the machines.

5.4.3 Category C - Secondary Tool Store Systems

STS systems may feature huge capacities for tool storage and require particular designs. These usually are of four basic types and are as follows:

- paternoster type
- multi-disc type
- multi-chain type
- rack or matrix type

STS systems supply a number of machines at a cellular level and thus require sophisticated networks for the flow and exchange of preset tools between the STS and respective PTS's and ATS's, and between these cell-based stores and a central tool store (CTS) or multi-cell systems.

These transportation networks may either be dedicated to the movement of tools or shared with the movement of the workpieces. The exchange mechanisms usually employed on these networks include those used in ATS systems and are as follows:

- overhead gantry systems
- shuttle mechanisms
- robotic exchange
- gripper exchange
- conveyors-type
- guided vehicles

This type of integrated tooling system provides fully automatic supply of tooling to the machines, although loading and unloading of tools at the machine level may be either automated or manual as is evident in some systems. This concept is similar to that of the Auxilliary Tool Store except any one ATS is not specifically intended for any specified machine.

Examples of category C systems include the TOS Olomouc plant [305,306,329,330,331] developed by the VUOSO Research Institute of Machine Tools and Machining in Czechoslovakia which uses an original and very versatile tool management system, and the Citroen Construction Mecaniques (CCM) [8,19] FMC at Meudon which consists essentially of three Graffenstaden 5 axis machining centres an automatic Tool Room with capacity for 600 tools.

The Makino plant at Atsugi, Japan [10,23,220] constructed using the most up-to-date technology, the Leyland Bus turn-key installation at Farrington, and the 'Small Parts' FMS installation at British Aerospace, Preston, provide further examples.

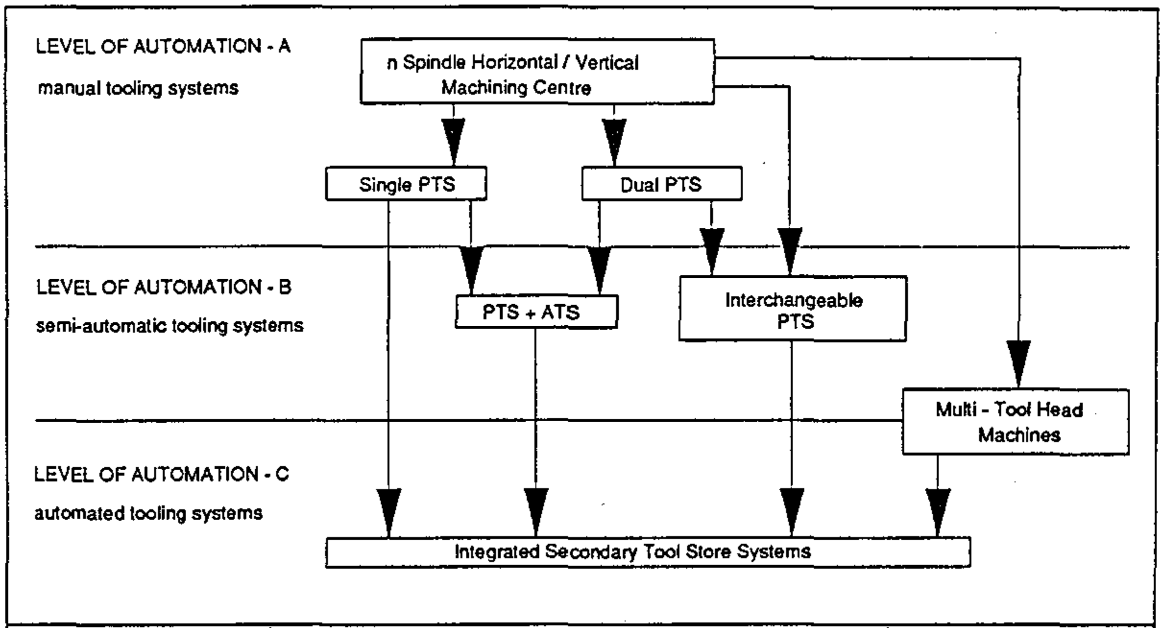


Figure 5.1 | PRISMATIC CELL TOOLING SYSTEMS - THE GENERIC FORMS | LUT - FMS Research Group

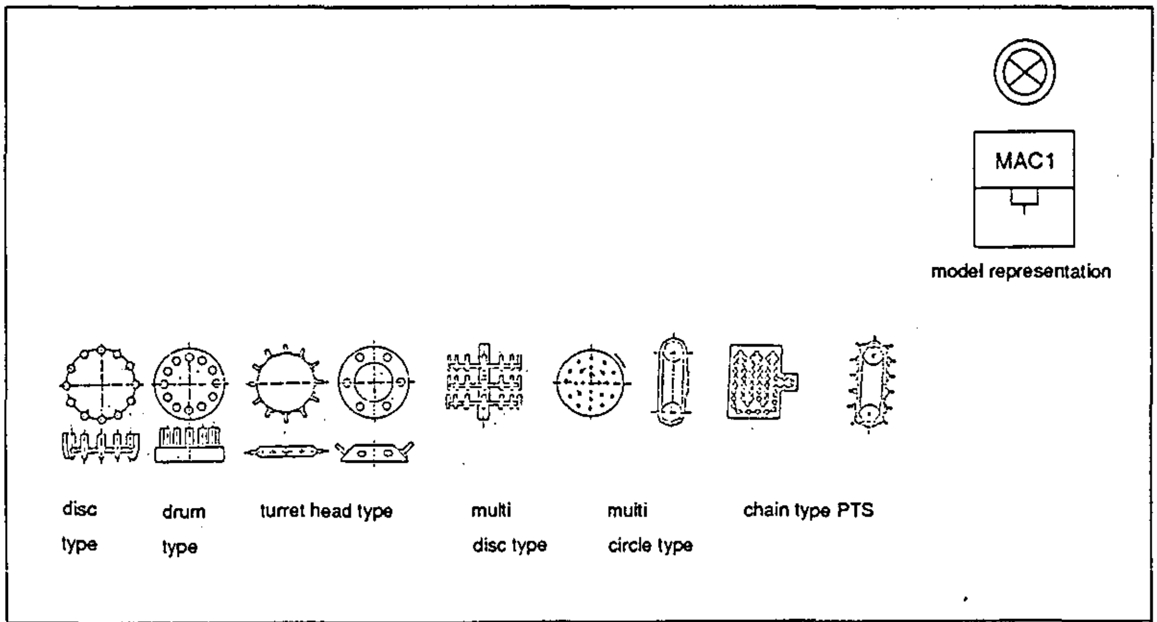


Figure 5.2 | CATEGORY A - SINGLE PTS | LUT - FMS Research Group

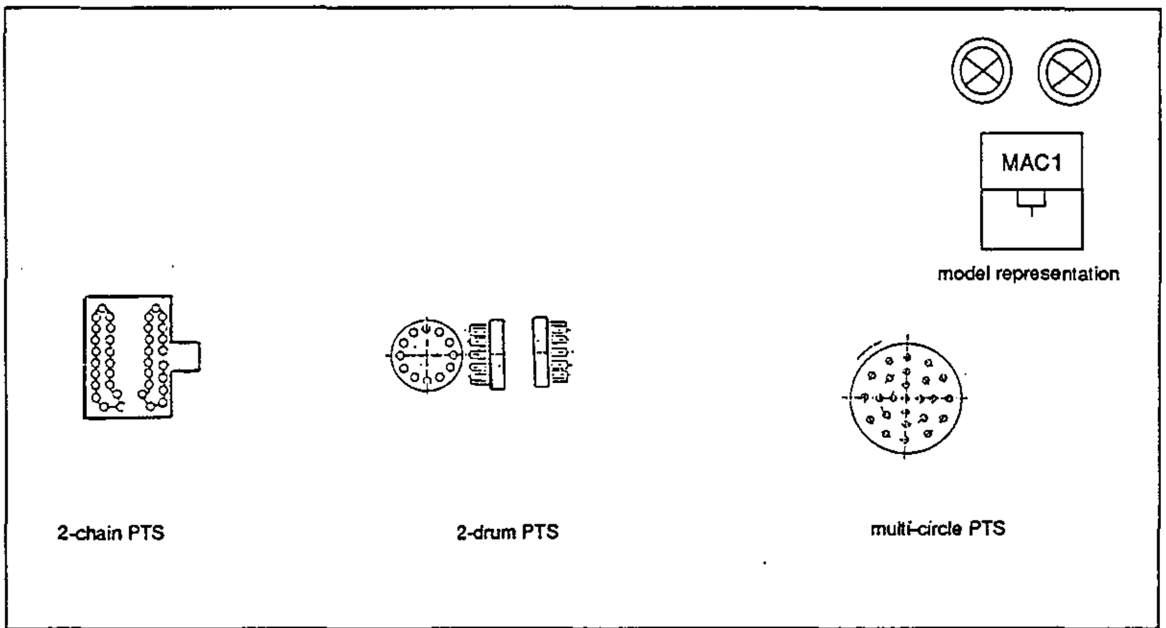


Figure 5.3 | CATEGORY A - TWO INTEGRATED PTS's | LUT - FMS Research Group

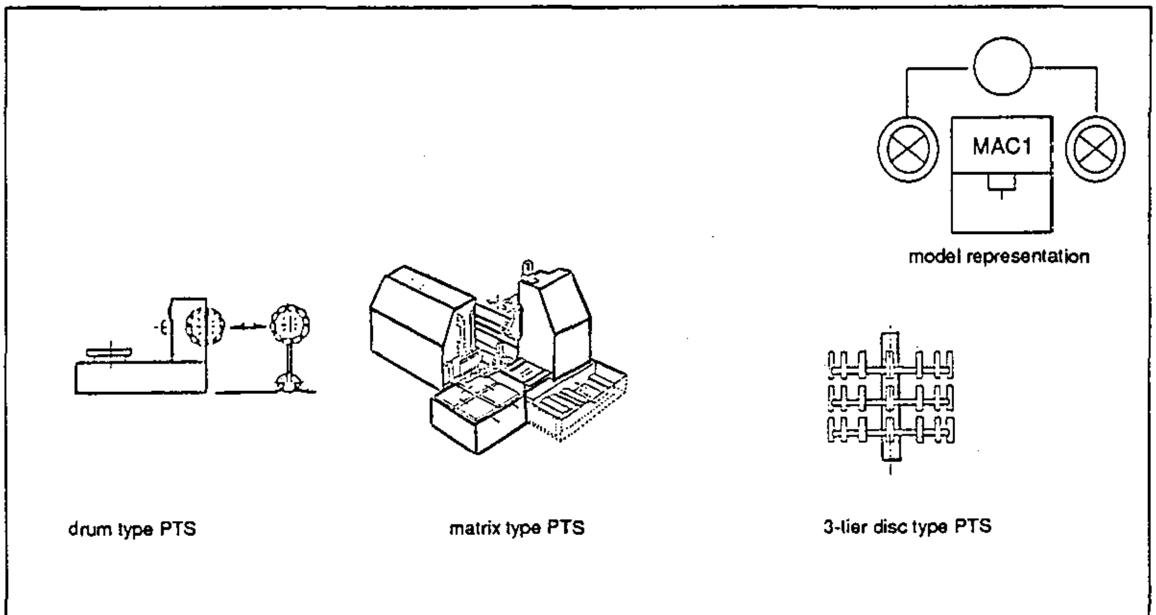


Figure 5.4 | CATEGORY A - INTERCHANGEABLE PTS | LUT - FMS Research Group

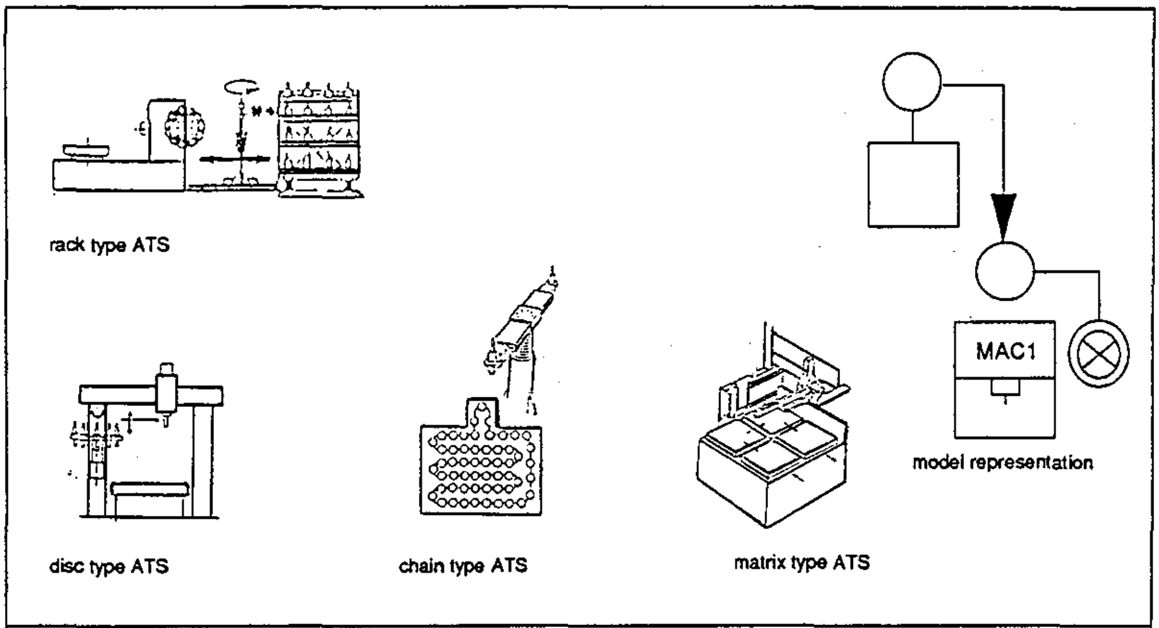


Figure 5.5	CATEGORY B - ATS SYSTEM	LUT - FMS Research Group

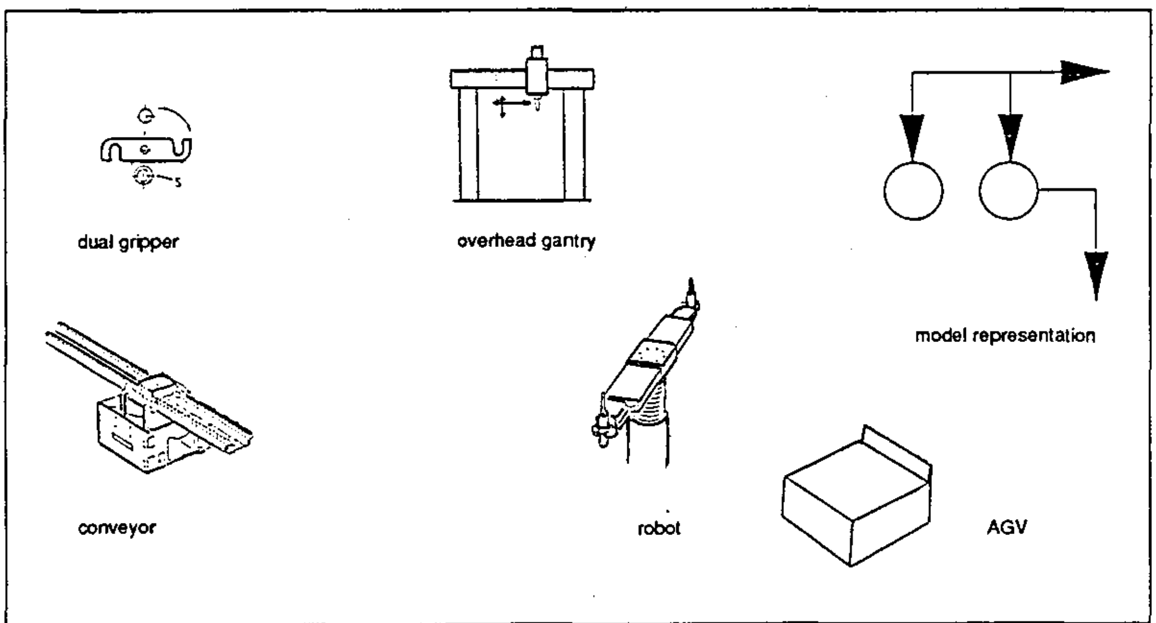


Figure 5.6	TOOL TRANSFER DEVICES	LUT - FMS Research Group

Chapter 6:
A STRUCTURED REPRESENTATION OF TOOL MANAGEMENT

6.1 Introduction

A formal structure, encompassing the categories of tooling systems described in chapter five, is developed to represent tooling system configurations for either cellular or multi-cell manufacturing systems. This sets the framework for the single cell and multi-cell models which are discussed in subsequent chapters.

6.2 An Overview of Single Cell Tool Management

The typical cellular tool management system is responsible for a wide range of activities within the cell. The fundamental responsibility of the management system is to ensure that the appropriate tools necessary for the processing of the orders are provided, prepared and in a usable condition, with their associated data, safely and reliably at the right location, when required so as to minimise unnecessary tool changes. This form of tool management system is governed by the component types that are to pass through the system i.e the sytem is considered to be demand-driven. The basic demand for the processing of components (based on push or pull technologies) is generated via an MRP, OPT, JIT [248a,248b] or similar system. The demand, based upon a time horizon, is then scheduled by a 'system manager' to the cell in the form of machining lists.

The heart of the management system is the tool list which is derived from the machining list, the starting point and controlling factor of all the cells' activities end events. The machining lists, at the highest level, consist of order numbers, due dates, priorities and required quantities. The machining list is subdivided into partial orders (individual workpieces) and is stored in the form of order waiting queues or work schedules. These schedules exist for every machine in the cell, and specify the sequence of operations for a particular workpiece, and the required tool sequence (the tool list). The tool lists not only determine the schedules for tool transfer and tool changing but also the gross tool requirement. A net tool requirement is established by examining tool store contents for the appropriate tools which have adequate residual tool life; and introducing new tools where necesarry, to service the machining lists (see chapter fourteen). The generated tooling requirement is placed in the tool room, which is responsible for supplying the required tools. The organisation of the tool room (see chapter twelve) to manage these required tools depend upon the facilities supplied and the manpower used.

As orders are being processed, the currently completed number of workpieces is recorded and updated. The consequences of these completed workpieces on the lists is an indication of which tools are no longer required or can no longer be used due to reaching their life limit. This in turn activates the tool transfer schedule and new tools may be introduced into the system. This continuous process of supply and storage of tools provides very effective tool management system control, and may also permit manual establishment and/or modification of the order waiting queue. In this way it becomes possible to give urgent orders preference with the introduction of the associated new tool lists.

The tool management system thus concentrates on maintaining a dynamic inventory of all tools in the cell, their size, type, number and location; and on improving tool forecasts and warnings of tool changes, reducing delays in the system and improving the reliability of tool information, *figure 6.1*.

6.3 Levels of Tool Flow Automation

A hierarchy of levels of tool flow automation may exist at a cellular level. A generalised tool flow network for a single cell is shown in *figure 6.2*. Any tool flow network may be described by the inclusion and specification of the modules shown. Each of the levels is assigned a functional value or category of either A, B or C as in chapter five. Each of these levels of tool flow automation has its own focal point of tool supply: In category A the focal point is the PTS which is supplied with tools manually according to the production requirements; In category B, the focal point is the ATS, which is supplied with tools manually whereas the exchange of tools between the ATS and PTS is automated; In category C the focal point is the STS which supplies a number of machining stations via an automated cell tool transport network. These categories of tool flow automation provide the basis for the algorithms (see chapter seventeen) implemented within each of the three computer models (see chapter eight) which have been developed to correspond to each of these levels.

6.4 Tool Management for Category A Systems

This is the lowest level characterised by stand-alone machines, equipped with an integral PTS. The tool supply to the Primary Tool Store (PTS) is dependent upon whether the workpieces are machined as part families or in batches. If families of workpieces are machined, all tools including redundant tools are accommodated in the PTS. If batches are machined, the batch-related tools may be loaded into the PTS while machining of the previous batch is taking place. All standard tools used for different batches remain in the PTS. Thus the duration of unmanned operation is dependent, in both situations, on the design category, the capacity and the type of PTS.

When the tools have reached the end of their predetermined life or have exceeded their tool life limit, they are transferred or removed at specified intervals into a transportable device, which in due course may be changed with one containing new tools. This loading and unloading of tools is dependent upon the design category and the rules implemented at this level (see chapter thirteen). In the case of a single PTS, the machine may have to stop to allow tool loading and unloading unless tool exchange is possible during the machining cycle. In cases other than that of a single PTS, the tools may be loaded or unloaded into the inactive PTS without downtime. The downtime occasioned by this manual replacement of tools is therefore a function of the number of tools to be replaced and the design category. In this form of tooling system the overall tool management is localised and normally carried out by the machine tool control system.

6.5 Tool Management for Category B Systems

The tool flow in this intermediate semi-automated system operates as though the stand-alone machine (automation category A) has another integrated PTS. This closely resembles the two or more integrated or interchangeable PTS design categories in *category A*. Tools are transferred, loaded and unloaded manually into the ATS until the capacity is reached. At appropriate intervals, tools are exchanged between the Auxilliary Tool Store (ATS) and a PTS by means of the exchange and transfer mechanism. Thus, a continuous supply of tools may be achieved enabling the machine to operate unmanned for a much longer time as the capacity, is typically much larger than that of a single PTS. Hence, the machining of a range of workpieces which may require an extremely large number of tools is possible.

6.6 Tool Management for Category C Systems

This cell level tooling system is usually found in a multi-machine FMC. ATS's are not normally present in this cellular tool flow system. The Secondary Tool Store (STS) is the main supply point for the cell's machines and is usually linked to the PTS's by a cell tool transportation network. Tools are transferred from the STS to the PTS's by means of the tool handling device. These tools may be moved individually, in kits or in sets according to the type of STS. Tools which are no longer required by the PTS or have reached their tool life limit are removed from the PTS and exchanged with the new tools. The removed or worn tools are transferred back to the STS to await transfer to a Central Tool Store (CTS) depending upon the cell operating rules.

The overall tool management of this system is controlled by the cell computer, which will issue instructions about which tools are no longer required and cause them to be unloaded from the PTS (see chapter thirteen). The cell computer will also schedule the supply of new tools from the STS to a respective PTS just before the machining of the current batch of workpieces has been completed (see chapter twelve), thus ensuring continued uninterrupted operation of the machining cycles. The tools or whole magazines of tools, dependent upon the design category of the PTS, are normally exchanged with those tools present in the PTS or even the whole PTS may be exchanged between tool changes at the spindle. The tool file for that machine is then updated with the new tool identification codes, offsets and accumulated tool life.

The tool flow between the STS and the PTS is normally semi or fully automated. This bidirectional tool flow may be on a dedicated tool flow network or on a shared workpiece/tool flow network. The tool transfer method will depend upon the scale of the cell, production requirements, and design category of the PTS.

6.7 An Overview of Multi-Cell Tool Management

The tool management discussed here is for a highly automated manufacturing system which includes a number of cells linked to a central supply and refurbishment point, *figure 6.3* . The focus of this form of tool management is the central tool store (CTS).

A bidirectional tool flow exists between the CTS and the various FMC's, *figure 6.4* . The delivery point for the tools from the CTS is the STS. The various FMC's do not normally interact with other except through the CTS. The operating rules for this advanced form of tool management are presented in subsequent chapters.

6.8 Central Tool Store

The central tool store deals primarily with the activities involved in preparing the tools for the cell production schedule in a timely manner (see chapter twelve). It does not normally interact directly with the individual machines in the installation, but through a cell secondary tool store.The main activities which take place in the central tool store are:

(a) to receive tool requirements for different machines, jobs or batches

(b) advance preparation of tools and fixtures to support scheduled production including presetting, tool assembly build-up and grouping tools into kits for transfer to individual machining cells

(c) assessing disposition of the tool assembles which have been returned from the cells

(d) teardown of the tool assemblies which require refurbishment and storing the reusable tool assemblies in appropriate locations

(e) responding to unexpected tool requests due to sudden tool breakage

(f) maintenance of relevant tool characteristics and tool usage data for future reference, reporting and inventory control

(g) replenishing tool stocks in an orderly and timely manner according to predefined criteria.

The flow of tools through the central tool stores would generally be as follows: Tools would be stored in a prepared state in numbered locations in the store. Prior to this, the tools will have been set on a pre-setting machine, which accurately measures the length and radius offsets of the tool, and send them directly the executive computer. The offsets are used by the machining centres for the accurate machining of components. On receipt of tool warnings from the executive computer, tools would be assembled by reference to location numbers, in sets for each machine. These sets would contain the set tools required to process the components at the machining centre. Tools which are returned to the central tool stores are assessed. Worn or damaged parts are replaced or reground, and the tools set in the presetting machine to the required offsets and stored with other usable tools. The presetting function is essential and has the responsibility of mounting the tools in their holders, or any other clamping device [61], to fit the machine on which the operation will be performed. Once the tools are preset, the combined unit (tool and mount) are identified by a special code designated to the system and stored in numbered locations.

If the executive computer requests a tool which is not prepared in the tool room, than that tool will have to be assembled from its constituent items. Therefore a comprehensive tool stock control facility must be available, which shows the tool items required for each tool assembly build-up and where they are located. This should form an integral part of the overall tool management system. The ability to respond automatically and quickly to scheduled tool requirements as well as unexpected tool requests, necessitates the use of an automated storage and retrieval (ASR) system. Tools may be stored within the system individually or in groups according to the adopted tool transfer and control method. A computer controlled handling device may be used to fetch the necessary tools from their locations and load them into the tool transporter for issue to the cell. This system and handling device is a prerequisite for implementing unmanned machining for one or more shifts, irrespective of the level of automation of the other activities in the central tool stores.

Recording of relevant tool data may be automated using bar codes and code readers, or any other data entry method. Recent developments in computerised tool management systems have provided the technology for the automation of the tool room and tool refurbishment facility as discussed above. In the past the organisation of the tool room was simply regarded as an inventory control problem. The traditional techniques of inventory control are based on a one time issue of items, this is not the case in the central tool stores because not only may the tools be reused but decisions and strategies are necessary as to whether the tools should be repaired, re-sharpened,inspected, recalibrated or scrapped. Satisfactory outcomes of these decisions are demanded from these systems that can clearly only be obtained through modelling. Additionally, decisions to purchase tools, and invoke inventory control measures can be assisted or automated using any of the commercially available software (29,107,136,164).

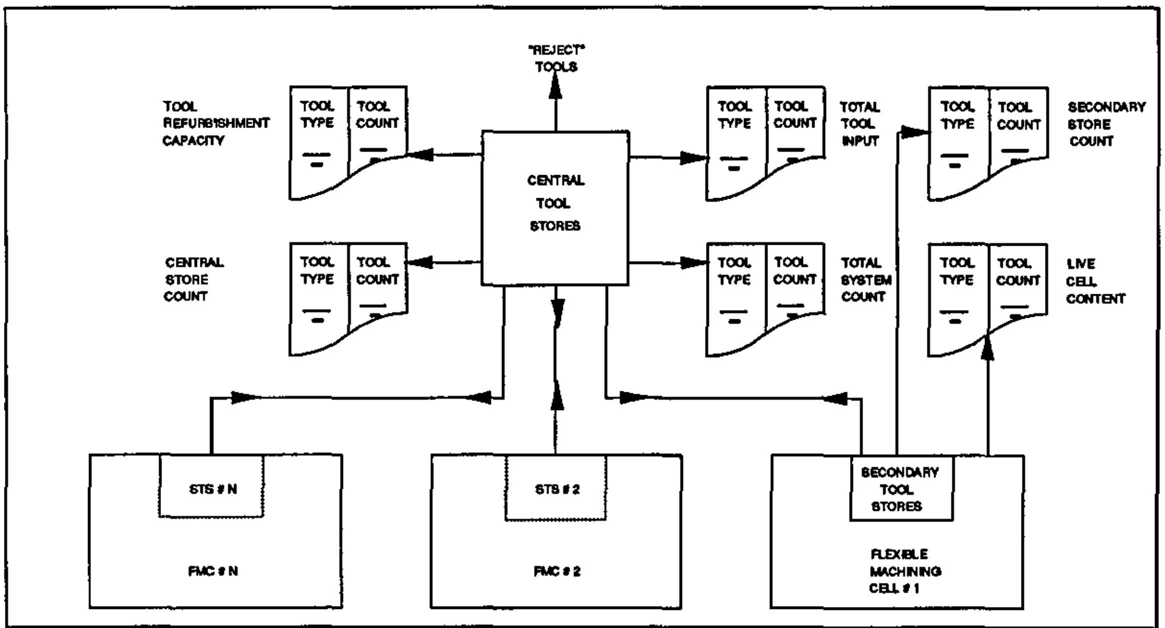


Figure 6.1	TOOL MANAGEMENT DATA REQUIREMENTS	LUT - FMS Research Group

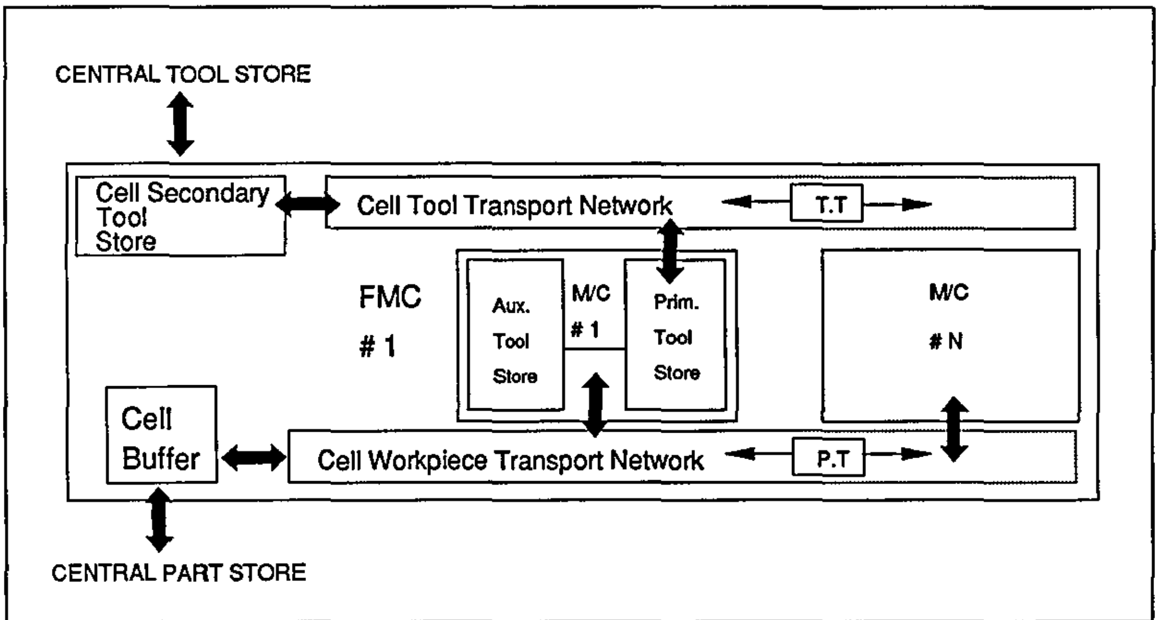


Figure 6.2	SINGLE CELL TOOL AND WORKPIECE FLOW	LUT - FMS Research Group

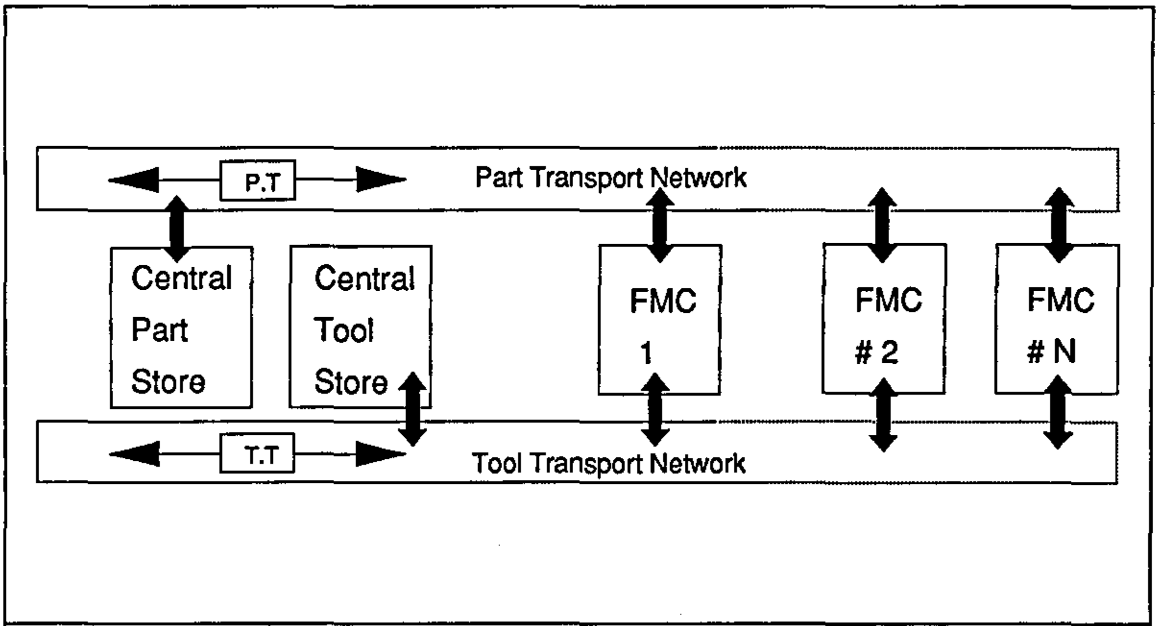


Figure 6.3 — TOTAL PLANT TOOL AND WORKPIECE FLOW — LUT - FMS Research Group

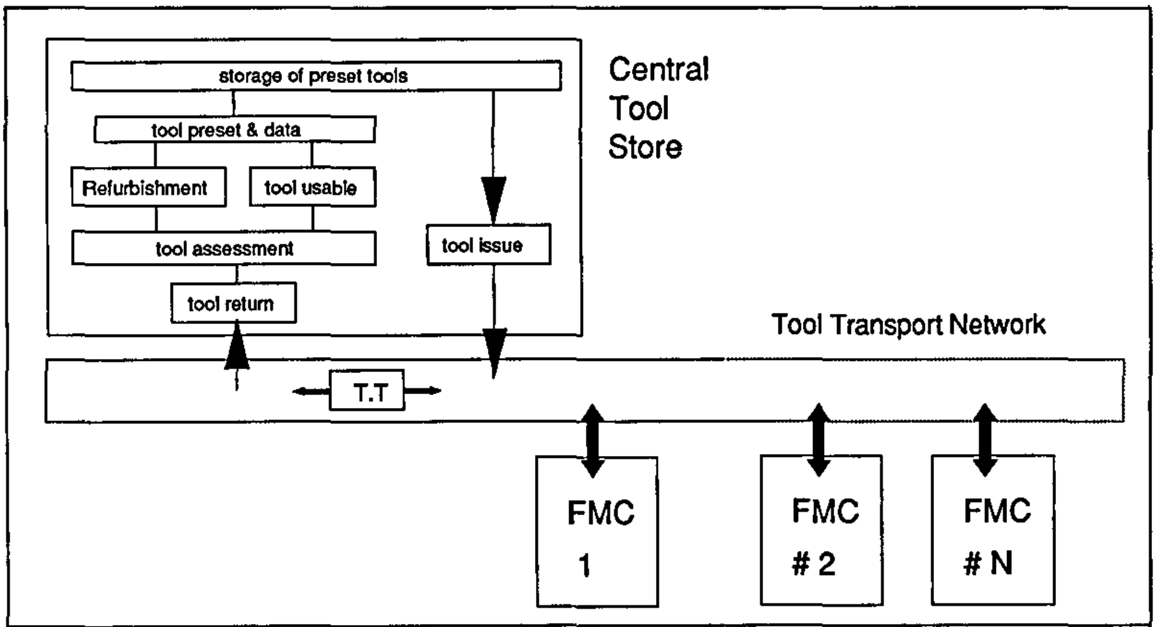


Figure 6.4 — TOTAL PLANT TOOL FLOW — LUT - FMS Research Group

Chapter 7:
ACTIVITY FLOW NETWORKS
IN TOOL MANAGEMENT

7.1 Introduction

The reader is introduced in this chapter to the flow of activities, the event chain and the decision structure or links between each module or node in the formal representations developed in the preceeding chapter for the single cell and multi-cell manufacturing systems.

7.2 The Role of Activity Flow Networks in Tool Management

The activity flow networks serve as the infrastructure for the design and operation of tool flow systems. The activity flow networks are based on the current and anticipated technical solutions. They permit tool management systems to be decomposed into the elemental activities which occur at and between the major tool stores, cells and work buffers.

It is essential to describe these activities and the functional relationships between these activities as this provides a setting for the selection of a tool management strategy, operating and decision rules described in chapter ten through thirteen. The flow or network of activities is best described functionally in terms of routes and subroutes. The routes detail the logical flow of tools around a machining installation and the subroutes define options available for each respective route. These subroutes provide the decision structure for the cell and machine level rules discussed in chapters twelve and thirteen. The networks are based on the generic representations developed for the levels of automation in chapter six and are the basis for the general and strategic algorithms presented in chapters sixteen and seventeen.

Two major networks are described. The primary or cell network links the secondary tool store (STS) to the respective machines' primary tool stores and the secondary network links the cell STS to the factory level central tool stores (CTS). The flow of work is only considered at the level of the machining station and thus no network has been specified beyond this level in this research work.

7.3 The Central Tool Stores (CTS)

The modelling activity flow network for the CTS is shown in *figure 7.1* . Two flow directions are shown in the figure, viz. the forward or 'to the CTS' flow and the return or 'from the CTS' flow. Within each of these flow directions several sub-routes are possible. The CTS routes are denoted by α, where :

α = Cell_Number . Subroute_Number

Routes towards the CTS are indexed by $-\alpha$ and routes away from the CTS are indexed with $+\alpha$.

The -α subroutes are :'

- *Subroute #1* : $0 \rightarrow 0$
- *Subroute #2* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 0 \rightarrow 6 \rightarrow 7$
- *Subroute #3* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 0 \rightarrow 9$
- *Subroute #4* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow 4$
- *Subroute #5* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 0 \rightarrow 6 \rightarrow 7 \rightarrow 9$

The functional description for each of the above subroutes, is as follows :

(a) *Subroute #1* : This route is a simple CTS bypass route.

(b) *Subroutes #2, #3, #5* : These routes are followed by worn tools which are returned from the cell STS for refurbishment. At the node succeeding node 2, the on-shuttle station, there is the cart decision point, node 0. The decision is taken at this point as to which tools are to be sent for refurbishment (subject to the number of regrinds allowed and the tool refurbishment strategy, see chapter twelve) which are to be subsequently recycled back into the system, and which tools are to be dissambled and stored at node 9. *Subroute #2* permits the refurbishment and recycling of the tools whereas *subroute #3* does not. *Subroute #5* allows the refurbished tools which are not immediately required to be stored at node 9.

(c) *Subroute #4* : This route is followed by tool transporters which perform simple tool transfer back to the CTS, according to the STS tool retention strategy, i.e in situations where the maximum worn tools limit for the STS is reached or exceeded. Any tools awaiting transfer to the cell, at node 8, are loaded and the tool transporter returns to the cell STS. This loading of tools is subject to the selected central tool provisioning strategy.

The +α subroutes are as follows :

- *Subroute #6* : $0 \rightarrow 5$
- *Subroute #7* : $7 \rightarrow 8 \rightarrow 4 \rightarrow 0 \rightarrow 5$
- *Subroute #8* : $9 \rightarrow 8 \rightarrow 4 \rightarrow 0 \rightarrow 5$
- *Subroute #9* : $4 \rightarrow 0 \rightarrow 5$

These 'CTS to STS' subroutes correspond to the 'STS to CTS' routes and effectively complete the closed loop system. The functional description for each of the routes is :

(a) *Subroute #6* : This route corresponds to subroute #1 and completes the CTS bypass, back to the cell. This route is followed by idle carts or carts which are queueing for load and/or unload assignments.

(b) *Subroute #7* : This route is taken by the tools which have been refurbished and are immediately recycled back into the system. These tools wait in the queue, at node 8, for a transporter. They are then loaded at the off-shuttle, at node 4, and returned to the cell STS, subject to the tool transporter availability constraints.

(c) *Subroute #8* : Tools are stored in a prepared state in numbered locations in the CTS, at node 9. Prior to this, it is assumed that since the model is demand-driven, that the tools have been assembled and preset with the required offsets. On start-up, on request, and according to the central tool provisioning strategy, itself subject to the cell tooling list, the necessary tools await transfer, at node 8. These tools are then loaded, at node 8, and transferred to the cell STS. The tools which have been refurbished, *new* tools or the cell stored tools, may be transferred together depending upon the selected tool management and tool assignment strategies in force.

(d) *Subroute #9* : This is the common exit route followed by all the preceeding route categories.

7.4 The Cell Secondary Tool Store (STS)

The activity flow network for the STS tool load and tool unload stations is shown in *figures 7.2 and 7.3* respectively. Each of these respective networks, like the CTS flow networks, has positive 'to the cell STS' and negative 'from the cell STS' subroutes. The STS routes are denoted by β, where :

β= Destination_Machine_Number . Subroute_Number

Routes towards the STS are indexed by $-\beta$ and routes away from the STS are indexed with $+\beta$.

The STS Tool Load Station, $-\beta$ subroutes are :
- *Subroute #1* : $0 \rightarrow 3$
- *Subroute #2* : $0 \rightarrow 1 \rightarrow 2$

The functional description for each of the above subroutes, is as follows :

(a) *Subroute #1* : This route is a STS load station bypass route. This route is used by the idle or unassigned tool transporters or those transporters that have not been flagged to the STS.

(b) *Subroute #2* : This route is used when a transporter request flag is set up by a machine requesting tools from the STS. This request is subject to the cell tool transport, transporter selection, and tool transporter availability operating rules.

The STS Tool Load Station, $+\beta$ subroutes are :
- *Subroute #3* : $7 \rightarrow 5 \rightarrow 4 \rightarrow 2$
- *Subroute #4* : $6 \rightarrow 5 \rightarrow 4 \rightarrow 2$
- *Subroute #5* : $2 \rightarrow 3$

The functional description for each of the above subroutes, is as follows :

(a) *Subroutes #3, #4* : These two subroutes are the determinants for the other two routes, in that they determine which tools are put into the queue for loading. The tool issue strategy, discussed in chapter eleven, will determine whether subroute #1 or #2 is used. *Subroute #1* is for the issue of tool kits with node 6 acting as the tool kitting creation mechanism and *subroute #4* is used for loading of single tools irrespective of the kitting criteria in force. Preceeding nodes 6 and 7 is the point where the tools which have been delivered from the CTS, with respect to the cell tool list are stored. The tools are stored in numbered locations in this storage area. The tools are assembled, by reference to their location numbers in kits or transfer *packages* according to the machining list or schedule for the particular machine requesting the tools. This is dependent upon the tool management and tool assignment strategy specified for the cell, see chapter ten.

(b) *Subroute #5* : This is the main exit route followed by all loaded and assigned transporters.

The STS Unload Station, -β subroutes are :
- *Subroute #6* : $0 \rightarrow 3$
- *Subroute #7* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 4 \rightarrow 5$

The functional description for each of the above subroutes, is as follows :

(a) *Subroute #6* : This route is a STS tool unload station bypass route, used by idle or unassigned tool transporters or those tool transporters that have not been flagged to return to the STS.

(b) *Subroute #7* : This route is used for tools which have been returned from a particular PTS, subject to the tool transporter availability. The decision made is whether the tools are to be retained in the STS or returned to the CTS for refurbishment, in which case this route will link up with the $-\alpha / 0 \rightarrow 1 \rightarrow 2$ section of the CTS subroutes.

Tools may be returned to the STS as kits, or as single tools. In either case, the tools are stored in the STS as single tools. The storage point at node 5, corresponds to the storage point, preceeding nodes 6 and 7, in the STS tool load station network.

Only one positive subroute is available in this category and this is represented as $2 \rightarrow 3$. This subroute is followed by tool transporters that have completed their assigned unloading of tools. The cart or transporter may then proceed to either of the positive subroutes for the STS tool load station, i.e the transporter could result in an *idle* state as the unloading of tools into the STS would signify the end of its assignment loop, or it could pick up another assignment flag. The assignment loop for the transporter can be described as follows :

(a) Flag STS -β subroute for loading tools.
(b) Load tools.
(c) Flag STS +β subroute for machining station.
(d) Flag STS -β subroute for unloading tools.
(e) Unload tools.
(f) Select idle or assigned state.
(g) If assigned state, go to (a).

7.5 The Machining Station

The activity flow network for the machining station is more complex than the previous networks. This is particularly so, because the machining station, in this instance, a machining centre, is the interface between the part and tool flow networks. All the preceeding networks do not consider the movement of parts as the material transportation system is not logically represented within the modelling. The movement of parts (pallets) is considered to be direct and to occur in a negligible fixed time. This implies no transporter blockages or delays or other hindrances are allowed.

The total activity flow network for the machining station is shown in *figure 7.4* . This network is subdivided into two major networks, viz. the tool flow and the part flow networks. A similar notation to the STS networks is used, but with opposing arithmetic signs.The machining station routes are denoted by δ, where :

δ = Destination Machine Number . Subroute Number

Routes towards the machining station,and away from the STS, are indexed by $+\delta$ and routes away from the machining station, and towards the STS, are indexed by $-\delta$. Routes for the tool flow network are prefixed with 'T' and those for the part flow network are prefixed with the letter 'P'.

7.5.1 The Machining Station - Tool Flow

The $+\delta$ subroutes are :
- *Subroute #T1* : $0 \rightarrow 0 \rightarrow 0$
- *Subroute #T2* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 0 \rightarrow 0$
- *Subroute #T3* : $0 \rightarrow 1 \rightarrow 2 \rightarrow 0 \rightarrow 3 \rightarrow 4 \rightarrow 0$
- *Subroute #T4* : $0 \rightarrow 0 \rightarrow 3 \rightarrow 4$
- *Subroute #T5* : $2 \rightarrow 7$
- *Subroute #T6* : $7 \rightarrow 6$

The $-\delta$ subroutes are :
- *Subroute #T7* : $0 \rightarrow 5$
- *Subroute #T8* : $4 \rightarrow 0 \rightarrow 5$
- *Subroute #T9* : $7 \rightarrow 4$
- *Subroute #T0* : $6 \rightarrow 7$

Subroutes #P1, #P2, #P3 and #P4 of the part flow network are defined as being equivalent to the positive or 'away from the STS' subroutes *#T1, #T2, #T3 and #T4* of the tool flow network. A fifth part flow subroute, *subroute #P5*, is defined as : $2 \rightarrow 6$.

Subroutes #P6 and #P7 for the part flow network are defined as being equivalent to the *#T7 and #T8*, negative or 'towards the STS' subroutes for the tool flow network. An additional subroute defined as *#P8*, is specified as : $6 \rightarrow 4$.

The functional description for all the above routes, indexed as + or - δ is as follows :
(i) *Subroute #T1* : This is, as in the previous networks, a bypass route for the unassigned or assigned transporter flagged for other machining stations.

(ii) *Subroutes #T2, #T3, #T4* : *Subroute #T2* is used by those transporters which have been flagged to deliver tools from the STS. These tools may be delivered in kits or as groups of single tools, see chapter eleven. *Subroute #T4* is used by those transporters which have been flagged to pick up worn or unnecessary tools from the PTS and deliver them back to the STS. *Subroute #T3* is a combination of *subroutes #T2 and #T4*, in that the transporter is flagged not only to deliver tools to the primary tool store (PTS), but also to pick up tools and return them to the STS. If the kit issue strategy is employed, this would imply that the tool transporter would deliver a *fresh* kit to the machine and pick up an *old* kit. This would also be dependent upon the number of primary tool stores on the machine and the PTS tool retention strategy. If single tool transfer is employed then, depending upon the presence of worn tools, the transporter would either follow a part of *subroute #T3*, i.e $2 \rightarrow 0 \rightarrow 3 \rightarrow 4$, if worn tools were present in the PTS or a part of *subroute #T2*, i.e $2 \rightarrow 0 \rightarrow 0$, if there were no worn tools to pick up for return to the cell STS. This function is obviously dependent upon whether there were tools to unload into the PTS in the first instance.

(iii) *Subroutes #T5, #T6, #T9, #T0* : *Subroute #T5* is the basic loading of the tool magazine from the tool transporter contents. Tools are placed in the tool magazine according to the selected tool insertion strategy and within the confines of the chosen exchange device. The procedure for loading of oversize tools is quite different. Every tool when placed in a particular compartment in the PTS is included in the machine file with references to the pocket number, tool number, tool life details, etc. The pockets are thus cross referenced with the *individual tool number* (ITN). When an oversize tool is encountered that requires free space on either side of an alloted compartment, these empty compartments are labelled with the negative of the integer ITN. The exchange of tools between the magazine and the spindle and vice versa are represented in *subroutes #T6 and #T0* respectively.

Each PTS can be considered to be divided into three areas : a storage area, a worn tools area and a free area. The size of each of these areas is determined by the tool requirement for the specified machining period, the selected tool management strategy and the tool issue strategy. If a tool-oriented tool-kit issue strategy is selected then the whole of the tool magazine would be designated a storage area, as the whole kit would need to be exchanged each time the selected part mix changes. If a single-tool issue strategy is selected then four divisions of the PTS would exist. The fourth division, for standard tools would overlap with the storage and free areas. A similar principle of operation is used for the workpiece-oriented tool management strategy. This is further discussed in chapter eleven.

Tools are thus loaded via *subroute #T5* into the storage area and/or the standard tools area and unloaded, via *subroute #T9*, from the worn tools and/or storage areas dependent upon the fore-mentioned operating strategies. The number of tools, their positions, and status in each of the four areas is available to the user via the output interrogation modules. This form of tool management reduces the tool changeover and tool loading times involved whenever a part mix change is initiated. Tool life is actively monitored at the machining station by updating of the files and logging the accumulatedtool life for each tool in the tool data files.

Before an operation is started, a check is made to see if the tools for that operation are present in the PTS, and whether sufficient tool life is available to complete the operation. When the operation is started the additional tool times for that operation are incremented to the appropriate accumulated tool life record. If there is insufficient tool life, a flag is set up requesting tools from the STS. On completion of the operation, the modelling ensures that tools to be withdrawn are placed in the worn tools or transfer area of the PTS after their respective use and that the tools still required for subsequent machining operations are deposited in the storage area. The provisioning of the respective area, by *indexing* of the PTS array takes place parallel to machining time. The *removal status* of a tool, see chapter twelve, is automatically issued as soon as data on an impending job change is available. This leads to the *exchange list* being established, in which the tools to be moved and/or the tools additionally required are listed, with due account being taken of the remaining tool lives after completion of the current job. The inclusion of this operating principle not only sorts out the tools to be removed but is also higly desirable for manual or automated tool changing and delivery.

(iv) *Subroute #T8* : This is the main exit route used by all the transporters which have picked up the tools from the worn tools area as determined by the preceeding subroutes.

(v) *Subroute #T7* : This route is used by all the preceeding subroutes and is normally towards the STS.

7.5.2 The Machining Station - Part Flow

The part subroutes mimic the tool subroutes in principle of delivery to and collection of pallets from the machining centre. Of particular importance are *subroutes #P5 and #P8*. These are the loading and unloading of the pallet onto and off the machining centre respectively. These load, unload, arrival, and interarrival times of the pallet will determine the schedule for the tool transfer network. The duration of the pallet on the machine, and its indexing will depend upon the part assignment and operation assignment strategies, see chapter fifteen. The selected strategy will determine the tool indexing and the exchange lists for the primary tool store. This is where the two networks interface. The parts are assumed to be readily available from a predefined store, travel to the machine in a predetermined time (negligible for this purpose) and arrive at the machine at a specified time (usually just after the required tools are deemed to be available in the PTS). These times are known in advance of the modelling. The parts are then returned via one of the subroutes to the notional parts store.

7.6 The Multi-Cell Activity Flow Network

The multicell activity flow network can be considered as the global model, as each cell within the configuration when modelled will consist of a secondary tool store and a number of machining stations, represented by the forementioned activity flow networks. The central tool store is the only unique entity which supplies a number of these cellular networks. The multicell network is thus analogous to a cell where the central tool stores is represented by a *STS* and each cell is represented by a *machining station.* The determined subroutes are thus identical with the exception that the routes are denoted by γ, where :

γ = Destination_Cell_Number . Subroute_Number

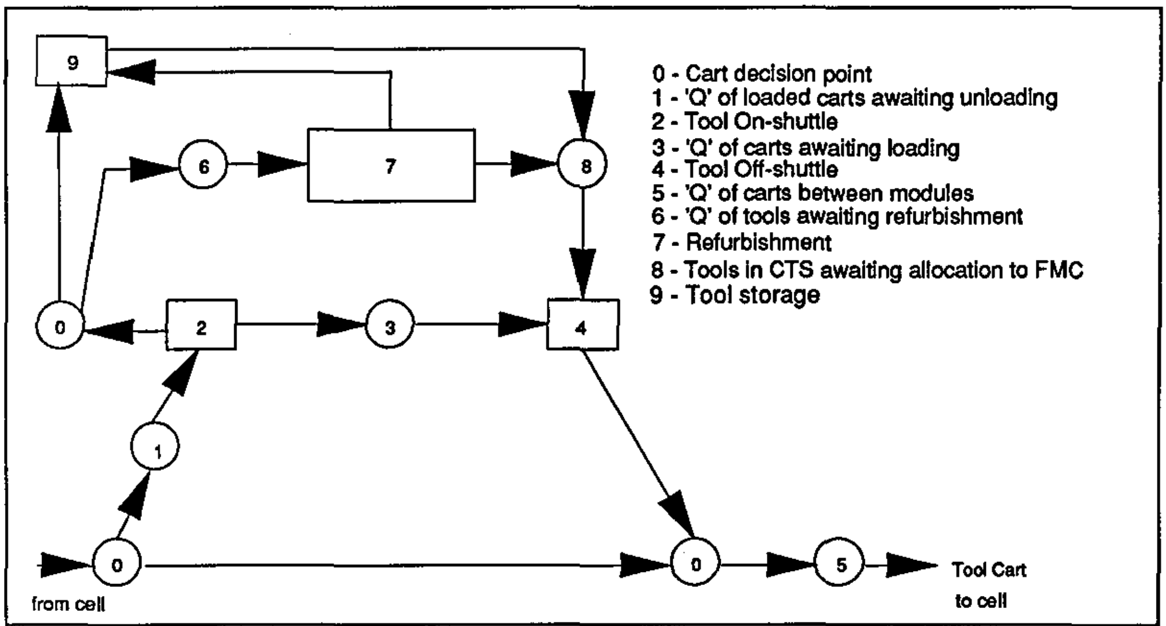


Figure 7.1	ACTIVITY FLOW NETWORK - CENTRAL TOOL STORES	LUT - FMS Research Group

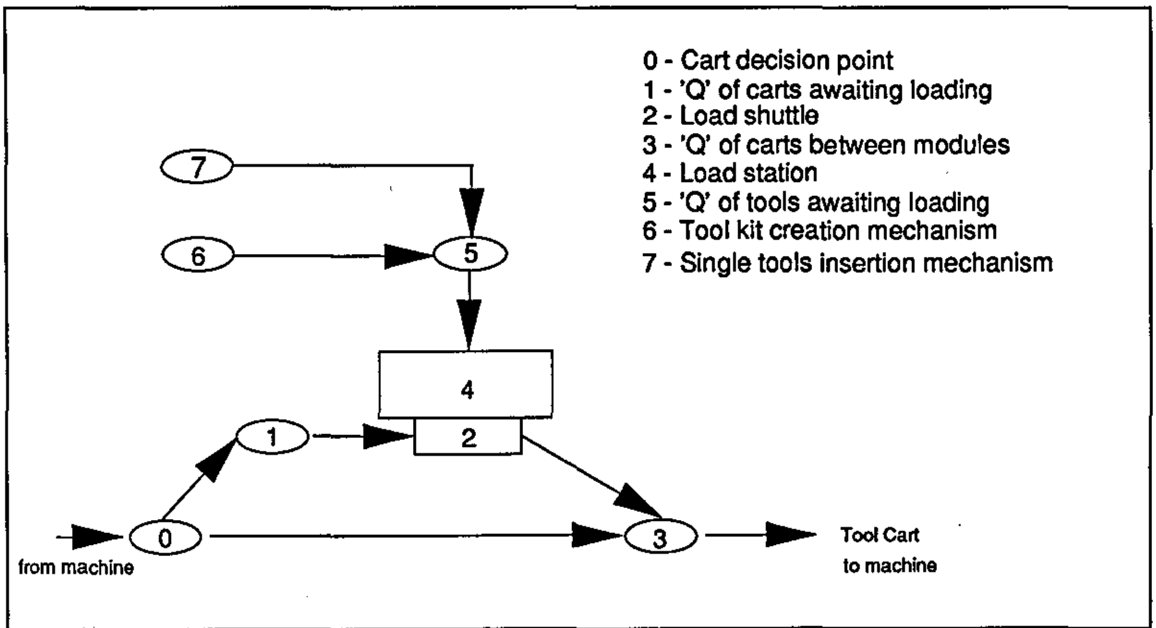


Figure 7.2	ACTIVITY FLOW NETWORK - CELL SECONDARY TOOL STORE TOOL LOAD STATION	LUT - FMS Research Group

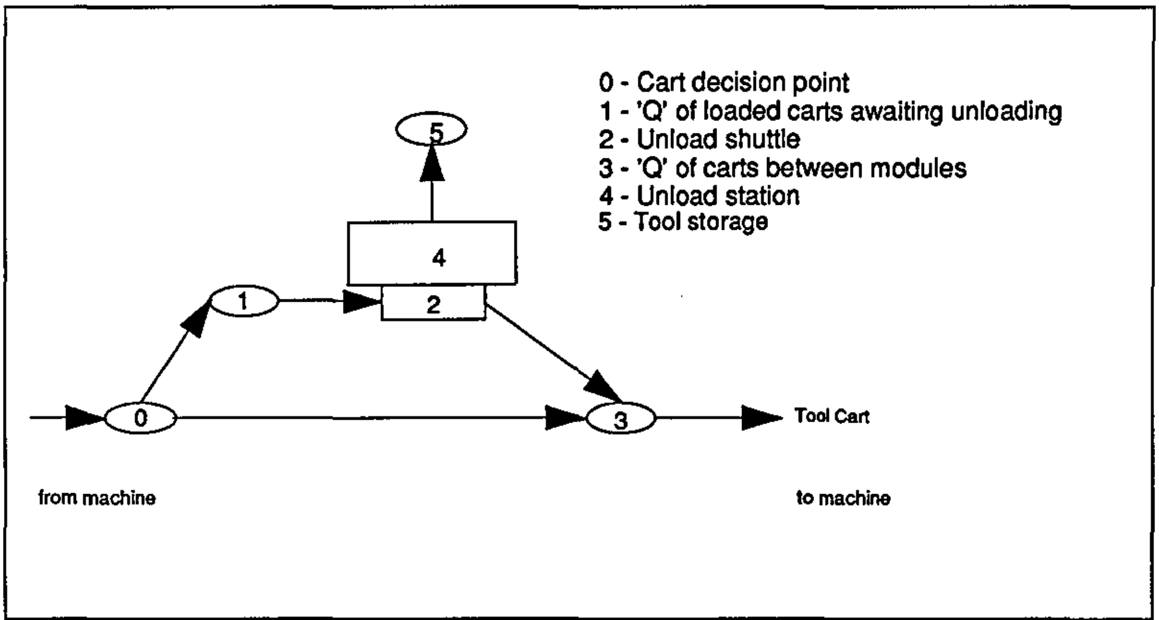


Figure 7.3	ACTIVITY FLOW NETWORK - CELL SECONDARY TOOL STORE TOOL UNLOAD STATION	LUT - FMS Research Group

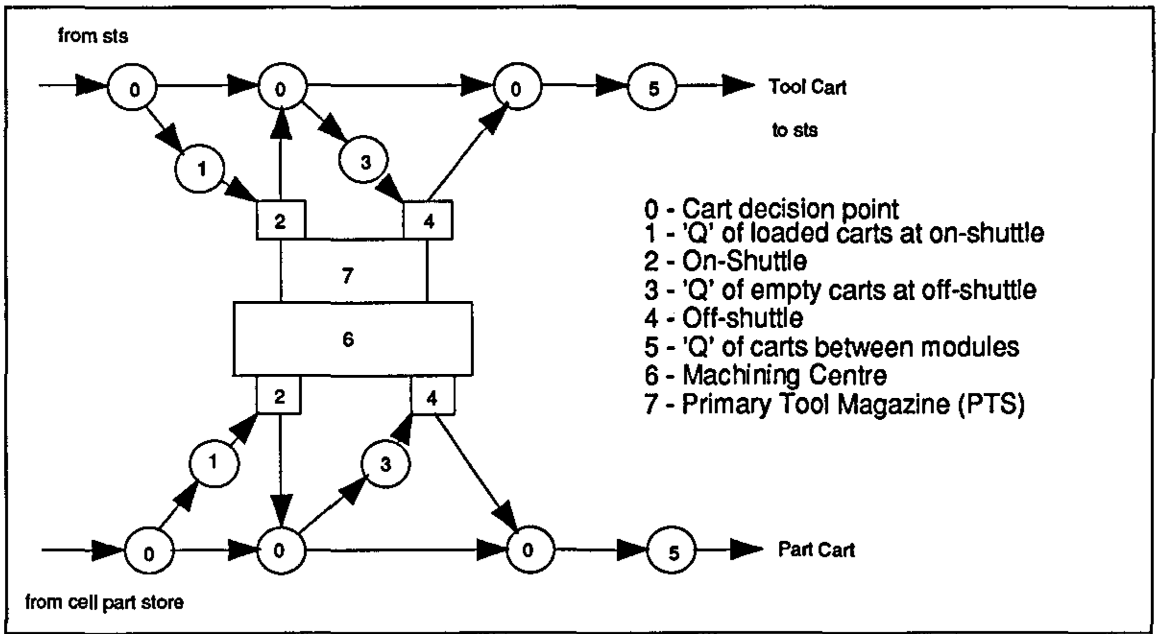


Figure 7.4	ACTIVITY FLOW NETWORK - MACHINING STATION	LUT - FMS Research Group

Chapter 8:
A DESIGN FACILITY FOR TOOL MANAGEMENT IN FLEXIBLE MACHINING INSTALLATIONS

8.1 Introduction

An overview of the scope and the structure of the facility developed for the design and operation of tool management systems in flexible machining installations, is presented in this chapter. The development of this design facility, based on the technical solutions available at the time, has had a strong influence on the specification of the rules and strategies described in subsequent chapters. An in-depth view of the prototype software which includes an user interface, datafile support, general and strategic algorithms, and an output module in parallel to a computer assisted cluster analysis module is reported in chapter eighteen and in appendix two.

8.2 Background

The research represented in this thesis has emerged from project work on rules and strategies, to provide tool management solutions for long or short term manufacturing tasks, and the production of prototype software.

The design facility, shown in figure 8.1, is aimed at providing a powerful design and forecasting tool for tool management, as an aid to cell management, which could either work alongside a currently operating cell-oriented tool management system or be used to assess tool flow solutions within a cell or total factory environment.

The models which are at the heart of the design facility, are embedded within a user interface based on a conversational 'soft-key' approach now commonly found in machine tool controllers employing automatic programming functions, see figure 8.2. This user interface is split within the design facility into an interactive program, which allows interactive data insertion supported by information within the external manufacturing system datafiles, and into an interrogation program which allows the user to interactively query for particular outputs generated by the modelling which is based on the generic and strategic algorithms presented in chapters sixteen and seventeen.

8.3 The Computer Models

The design facility is currently mounted on an extended IBM pc-AT configuration shown in figure 8.3. The detailed specification of this configuration is reported in appendix two. The design facility centres on three models which are derived from the structured hierarchical representations of tool management presented in chapter six and the categories described in chapter five. The prototype tool management software for prismatic part manufacturing systems, shown in figure 8.4, thus offers a stand-alone machine model, a cell model and a factory or multi-cell model which reflects the trend in flexible machining towards cellular manufacturing systems, see chapter three.

The prototype software, described in chapter fifteen and validated through case studies in appendices three to five, permits powerful tool flow solutions to be achieved and the rules and strategies, presented in chapters ten to fourteen, to be assessed at cell level, but is only capable of limited modelling of the multi-cell network configurations as decribed in chapter seven. The prototype software ceilings out at cell level due to the entity restrictions imposed by the hardware and software configuration which is now working at the extreme operational limits. The software is to be transferred onto a more powerful SUN 386i workstation. This workstation with its capability for multi-windows, faster processing and enhanced capabilities will render the restrictions placed on the current IBM configuration as 'primitive' and will permit the full potential of the software to be realised at factory level.

A preliminary transfer of the software onto the SUN 386i was undertaken and the result was a decrease in run time by some 25 times and a vast capability for handling a large number of data entities. The transfer was undertaken after major modifications were effected to minimise or eliminate some of the initial shortcomings with the present configuration, thus confirming that this is the way forward, see chapter nineteen and twenty-one.

The modelling system is dedicated to the sole algorithmic representation of tool flow systems. This is in stark contrast to the many available simulators which are work flow dominated (see chapter two). A limited number of situations do exist where it is necessary to consider the dual flows of work and tools. This is currently being examined in a complementary research programme [239].

The prototype software available for modelling of tool flow in cylindrical parts manufacturing systems [332], figure 8.5, covers the same ground but the distinction is drawn with the modelling of live tools and the more complex automation at machine level.

8.4 The User Interface

The input structure for the prismatic parts model is closely related to the specification of a tool flow network for a specified level of automation and is based on the use of interactive data insertion, described in chapter eighteen and in appendix two. The networks considered, described in chapters six and seven, include a tool transport network interlinking a hierarchy of tool stores, coupled with tool exchanges, automated or otherwise, at the machining stations, so as to allow the movement of tools around a flexible machining installation, including the central tool stores and refurbishment facility.

The user interface is based on the software design now commonly found in machine controllers which employ conversational automatic programming functions. The essence of this conversational language is the ability to prompt and assist the user in the design and operation of tool flow systems, leading him through the required steps by asking the necessary questions in the correct sequence and indicating the correct key to press.

The user is led through the hierarchical data input structure via the menu driven software. The user is asked to specify the manufacturing system parameters, to describe the configuration, the machines, the transporters, the tool stores and the tool handling system. The selection of decision rules, see chapter ten to fourteen, and the part routings determined by the external scheduler, see chapter nine, complete the input process.

All the computer models are data-driven and are supported by an interactive database. The database which contains information on machines, tools, parts and configurations allows the user to retrieve data, and to interactively input this information via the user interface. Alternatively, the user can compile input data on an IBM pc or compatible, in their own factory, using their own database management system. This data may be translated into ascii files, which may or may not include prescheduled work lists, which may then be transferred via floppy disk to the design facility. An interface which enables this transfer and data handling to be carried out is incorporated within the user interface and described in appendix two.

8.5 The Modelling Capability

Considerable detail involving complex relationships between system elements has been built into the modelling through the use of rules and strategies. The intention of this detail is to reproduce as accurately as possible the real operating tasks to be performed within the manufacturing system, see chapter sixteen.

The modelling has the ability to record considerable amounts of user specific data on the operation of tool flow systems within each constituent machining cell. The design facility offers solutions to problems within tool management systems, not only to the technological problems of how to store, handle, transport and load the tools; but also to the analytical and managerial problems such as when and where to schedule tools and how to best organise the supply of tools and their information. If this generated data is subjected to proper analysis, it can be used together with the users own experience to improve or design the overall performance and operation of a total factory tool flow network. The influence of tool life can be more accurately predicted, and thus tool changes and tool inventory levels can be forecast at greater time spans and with greater confidence and speed. The modelling also allows alternative designs and operating rules and strategies to be explored, see chapter eighteen.

The tool flow modelling could be used in either of four ways. Firstly, the model could provide detailed output on tool flow for a prismatic part manufacturing systems' performance in machining a given short- or longer-term manufacturing task. Secondly, the model could provide summary outputs of performance for either long or short-term manufacturing tasks or to evaluate an existing or proposed tool flow network. Thirdly, the modelling results and particularly the results from the CACA module could act as an interactive front-end to the Emulator providing a starting point for work and tool flow emulation or alternatively to verify the tool flow network performance for an already emulated part flow network.

The model could also be used in a more novel manner to model a mixed facility where machining centres and turning centres are present either in *hybrid* cells or where a prismatic parts cell is in parallel with a cylindrical parts cell. In both cases modelling of such facilities would be more appropriate for a long term evaluation, followed by detailed modelling using either the prismatic model to evaluate the machining centres and the associated cylindrical parts model [332] to test out the acceptability of lathe solutions and to fine tune the system performance. In this category of model usage, the lathes would be represented in a limited form as machining centres. Thus by varying emphasis on the rules and strategies the model could not only be forced to behave in the expected manner from the modelling of stand-alone stations to the multi-cell configuration but also to model in the longer term, a mixed facility. The results from modelling of such a hybrid are the same as for the general prismatic system modelling but where applicable, separate results may be specified for the turning centres. The results include tool transfer schedules, throughput times for respective machining lists, the tools transferred, the tooling requirements, tool life analysis, the transient capacities and forecasts and finally the utilisations.

The prototype software has the scope for modelling large single cells (upto fifteen machines). An eleven machine cell case study was sucessfully undertaken for one of the collaborating companies. The restriction imposed is the number of maching activities that can be handled in any one modelling period. The modelling of over 2000 activities imposes a severe restraint on the system and the computing run time may extend over a couple of days. The imminent transfer of the software onto the SUN 386i will ensure that realistic cell modelling can be completed in run times in the order of three hours.

8.6 Loading and Scheduling

Some basic loading and scheduling functions necessarily complement the current total tool management package to provide a balanced prototype facility and cover the influences of short range scheduling, see figure 8.6. Much of this work, described in chapter nine, has been undertaken in collaboration with a parallel research programme and is fully desribed therein [332]. The schedule necessary for this research work is obtained in the form of a short range schedule generated by an *external production scheduler* or from a prescheduled work list. The objective is to construct an ordered *machining list* for each machine. The *internal production scheduling* is the dynamic phase of the assignment process and attention is devoted to scheduling tool changes required by the machining lists efficiently, according to the selected tool management and system operating strategies, see chapters ten to fourteen. The method employed, described in chapter nine, uses simple set theory and a user-selected decision rule to select an activity from a machining list to schedule to the machines.

The use of this approach has proved to be effective and adequate in all the cases examined and in the determination of a minimum and actual tooling requirement. The determination of this minimum tooling requirement (MTR) has proved to be an essential part of the modelling. The MTR based on the short range schedule, management of tool life and the rationalisation of tool usage in the machining lists (see chapter fourteen and seventeen) pinpoints particular tools which should be duplicated and indicates possible tooling configurations and loading for each of the major stores. Although the MTR provides a good starting point for the modelling, the actual tooling requirement is dependent upon the dynamic behaviour of the machining system and the internal production scheduler which is not taken into account in the MTR module.

8.7 Computer Assisted Cluster Analysis (CACA)

Initial efforts in tool-oriented tool management have culminated in the development of the CACA module. This module, included within the overall suite of prototype software, see figure 8.7, is directed towards specifying tool packages for each machine with or without sister tools. The CACA module gives the user the option of rapidly configuring and reconfiguring tool cluster sets for each machine without going through the rigours of full scale modelling. The module permits optimum tool cluster set configurations for changes in batch sizes, maximum permissible tool life and different tool life specifications. CACA has potential for assessing manual tooling systems and for determining fixed or resident tools to be held in tool magazines, particularly in the new single tool transfer systems. Used in a workpiece-oriented tool management environment CACA has added advantages particularly in the determination of revised short-range work-to schedules. These schedules in turn may be fed as input to the workpiece-oriented models for the more detailed assesment of tool flow systems. This cluster analysis technique may thus either have a competitive status to the internal scheduling algorithms, see figure 8.6, or complement them in operation as discussed in chapter eleven. This technique is not only suitable for the selection and deployment of work and tools but also has potential for the assignment of fixtures.

8.8 The CACA Module

The CACA module, figure 8.8, has been developed using a widely available industry-standard spreadsheet package, viz. Lotus 123, see appendix two. The software is user friendly and prompts the user to specify part and tool types based on a work-to list. The end result is a minimum tooling requirement for preferred tool cluster sets which may or may not include sister tooling. This requirement may then be used to generate revised work schedules. Alternatively, the effects of changes in order requirements, tool life and maximum permissible tool life values on tooling configurations may be observed.

The CACA module has proved to be popular among the companies collaborating in this research and has applicability to a number of situations in highly automated and manually supported installations. The configuration of this module lends itself to relatively easy integration within other suites of software such as the Emulator, factory control systems and distributed schedulers. Its greatest potential is realised in situations where tool management requirements can be explicitly situated and can assist in situations where there is a requirement for efficient utilisation of plant.

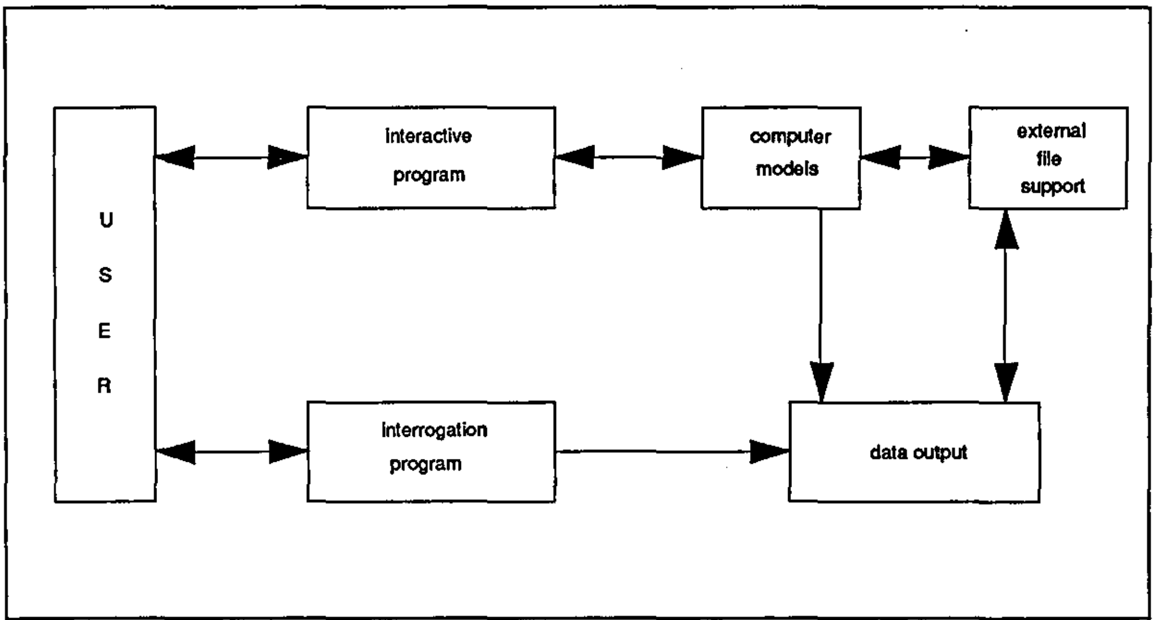


Figure 8.1 | TOOL MANAGEMENT SOFTWARE CONFIGURATION | LUT - FMS Research Group

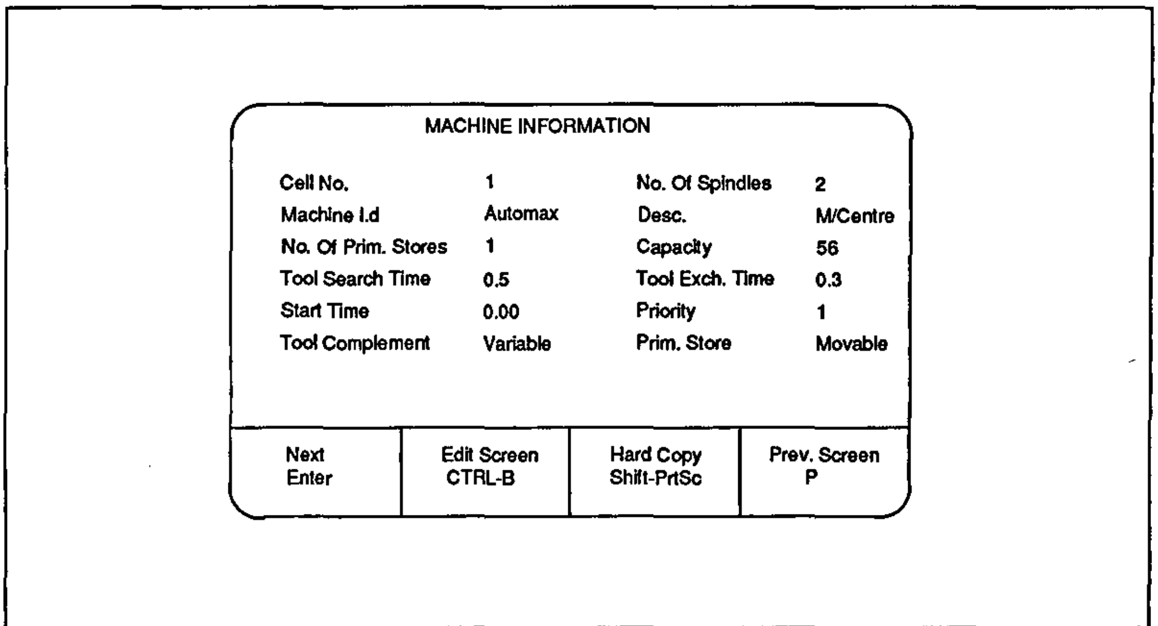


Figure 8.2 | A TYPICAL INPUT SCREEN | LUT - FMS Research Group

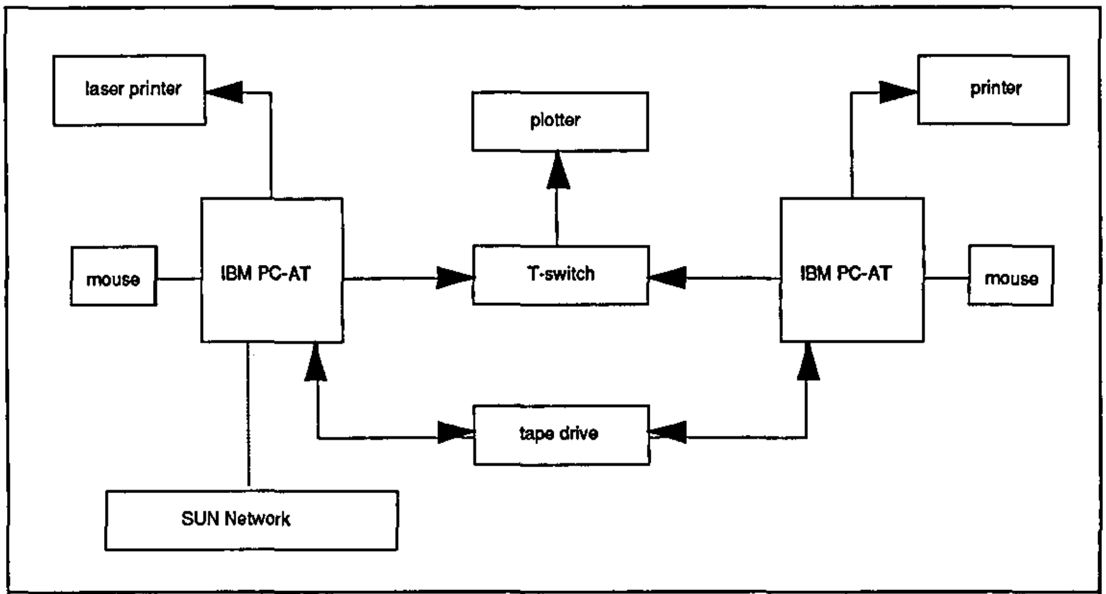


Figure 8.3	TOOL MANAGEMENT HARDWARE CONFIGURATION	LUT - FMS Research Group

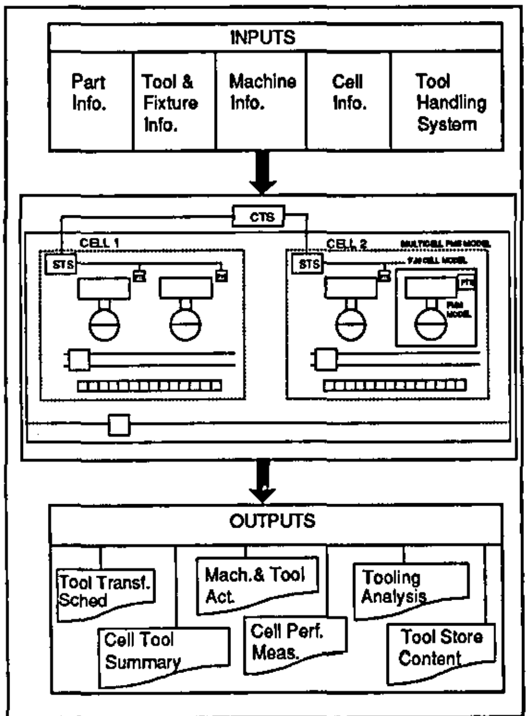


Figure 8.4	WORKPIECE - ORIENTED TOOL FLOW PRISMATIC PARTS MODEL	LUT-FMS RESEARCH GROUP

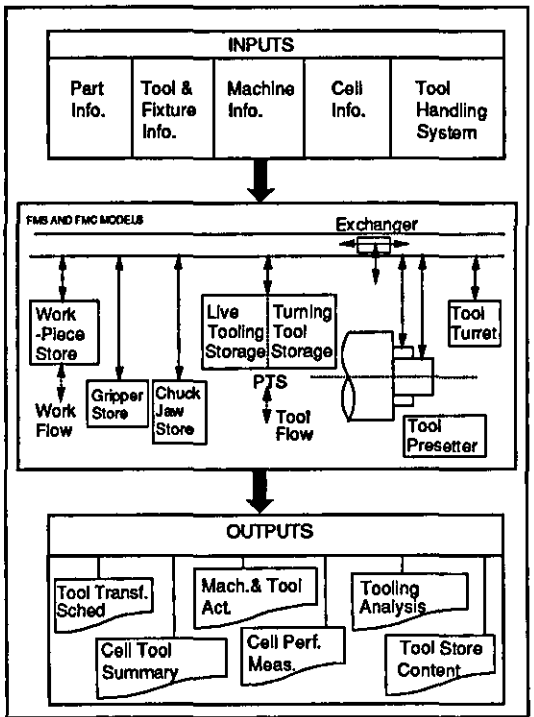


Figure 8.5	WORKPIECE - ORIENTED TOOL FLOW CYLINDRICAL PARTS MODEL	LUT-FMS RESEARCH GROUP

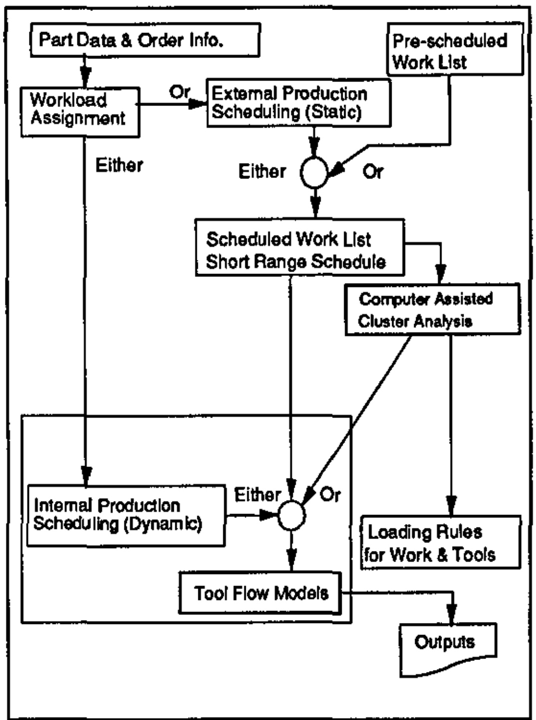


Figure 8.6 | INTEGRATION OF SCHEDULING | LUT-FMS RESEARCH GROUP

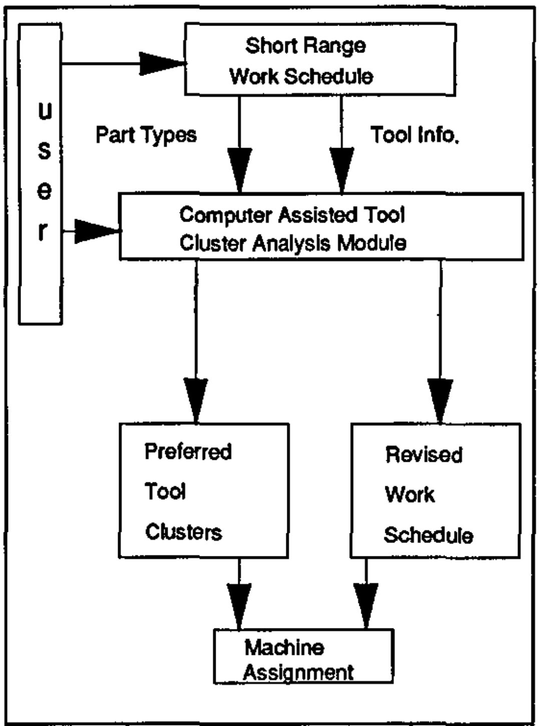


Figure 8.7 | TOOL - ORIENTED CACA MODULE | LUT-FMS RESEARCH GROUP

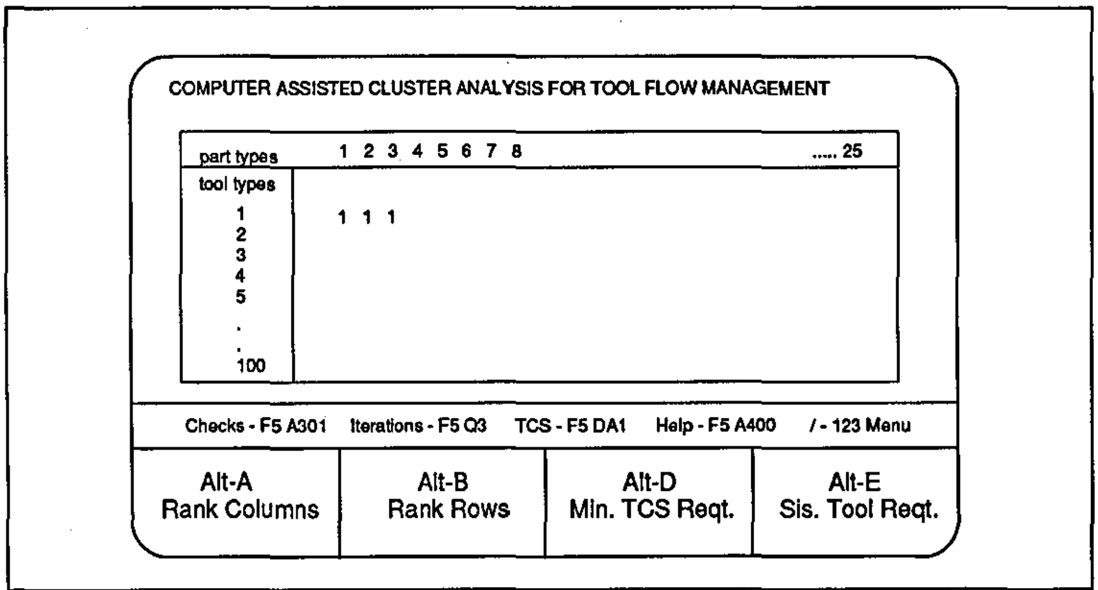


Figure 8.8 | CACA MODULE - INITIAL ROC MATRIX | LUT - FMS Research Group

Chapter 9:
LOADING, SCHEDULING AND SEQUENCING OF WORK AND TOOLS

9.1 Introduction

The most important goal of any tool management system is to have the right tools on the appropriate machines at the right time - with the minumum of human intervention. Some basic loading and scheduling functions, necessary for the effective design and economic management of the activity flow networks, consistent with the aims in the previous chapter, are discussed with a view to providing a balanced prototype facility and to cover the influences of short range scheduling. This chapter is thus devoted to the work required in the user interface other than that required for the modelling algorithms.

9.2 Loading, Scheduling and Sequencing

The loading problem can be simply and generally stated as the assignment of operations and the required tooling of the scheduled part types among the machines subject to the technological and capacity constraints of the cell. This problem has been studied by many researchers using a variety of methods ranging from complex integer programming problems to simpler heuristic algorithms (see chapter two). In general, it has been stated that any solution to the loading problem must comply with certain constraints, viz. : each operation and its associated tools must be assigned to at least one machine; an operation can be assigned only to those machines capable of performing it; and the tools required for the entire set of operations assigned to any machine must not exceed the capacity of the tool magazine of that machine.

Tooling is thus, a major consideration in these decisions and various aspects of part scheduling under tool availability constraints have been considered and illustrated with reference to particular manufacturing systems. No optimal formula has yet been proposed but what is apparent is that the problem is one with many parameters. Most of the scheduling algorithms are geared towards *category A* installations (see chapter five), with manual tool changing and as such the migration of tools is not usually considered, hence, the capacity of the tool magazine clearly becomes a constraint. Many installations now employ sophisticated tool management strategies and automated tool transfer is now an integral part of these auxilliary, *category B*, and secondary, *category C*, tool store systems. Another assumption frequently encountered is that the tool magazines are fixed and not removable. Current developments in machining centre technology render this assumption invalid in particular cases, such as the *Hulle Hille* and *Automax* machining centres (see chapter two).

Tool life and tool rationalisation are also very rarely considered within the scheduling function and it assumed that duplication of tools is permissible, i.e new tools are assigned each time a batch is assigned to a machine even though those tools may already have been loaded on that machine; thereby resulting in more tools assigned to a machine than needed which in turn reduces machine capability. Tool lives are often assumed to be the same irrespective of the types of batches and the machines to which they are assigned. Finally, each manufacturing system tends to have its own individual characteristics and therefore results related to one system may not be valid generally.

No attempt is made in this thesis to develop optimal scheduling and loading rules, but general algorithms are employed to maximise the effeciency of the workpiece-oriented modelling. A module has been developed in this research work which has the ability to bridge the gap in schedules which do not consider the tooling and tool flow explicitly. This computer assisted tool clustering module, discussed previously and in chapter seventeen, has the added potential for selection and deployment of tools and for the scheduling of work in a workpiece-oriented environment.

Loading, scheduling and sequencing in the modelling is a two-step process, *figure 9.1* . The first step comprises of the *external scheduling process* and the second step is the *internal scheduling algorithms* employing the *next step* scheduler. The external scheduling process has been developed in close collaboration with a parallel research programme which describes in greater detail the algorithms, strategies and functioning of this process [332]. The process attempts to provide a balanced workload and production mix for a respective manufacturing period, resulting in a short range schedule.

9.3 The External Scheduling Process

The *external scheduling* stage is the machine loading phase where the parts to be machined are assigned to the machine in some selected sequence, according to specified loading rules. The objective of this stage is to construct an ordered *machining list* for each machine and a file of part routes through the system, this in turn is the major input to the *tool requirement module, figure 9.2* .

Two options for *external scheduling* are made available to the user. First, is the input of a *prescheduled machining list* for each machine. The prescheduled list is as a result of an external scheduler. Each part which the system will be required to produce will have its own *work list* or lists, and each *work list* is given a number and stored within the model. When the machining sequences are determined, each *work list* is selected and allocated to the machine in a predetermined schedule, upto the specified available machining capacity of the machine. The machine will then service this *machining list* (collection of ordered or sequenced work lists) provided that the tools are available. This option allows all the possible machining sequences (work lists) to be stored in the model, and the order (machining lists) in which they are assigned to the machine to be changed. It is possible to delay the start of one work list until another list on another machine has finished. This will allow the movement of one part to several machines.

The *work list* includes a list of the operations needed on each part, the machine or machine group to which it may be assigned and its duration. For each operation/sub-operation there is a list of the tools required and the cutting time of each tool. This *tool list* is the heart of the tool management system and is the focus of attention in the internal scheduling stage. The *prescheduled machining list* can also be considered to be the interface between the modelling and other schedulers. A standard data file format for the prescheduled lists has been specified. This link can and has been used for the transfer of pertinent data output from the *Emulator* module of the LUT-FMS suite of design software which is the subject of a parallel research programme. In this instance, the tool flow modelling, will function as a module within the overall configuration of the design software. Data can also be imported from other external schedulers, or even from the results of simulation studies [112], in the form described above. The method of communication is via ASCII formatted files.

The second option available for *external scheduling* is the *production scheduler, figure 9.3*. The objective of the production scheduler is to create the *work lists* and subsequently the *machining list* for each machine. The inputs to the production scheduler are extracted from the *Part File, Machine File,* and user specified available machining capacity. The production scheduler is supported by built-in heuristic priority dispatching rules. Two such rules have been selected, but no preference is expressed as the user may select from a menu of options, the particular rule that suits his installation. In the context of studying a system, providing that the priorities of specific parts as opposed to part types, are not important, then simple priority rules are almost as effective as any other method. The rules incorporated include the *SOT* (Shortest Operation Time) and *EST* (Earliest Start Time) rules. The inputs required for use of these rules is a *job file* that describes the entire set of jobs appearing over the course of the modelling and which cross references the *Part File*. It is necessary to specify each parts' operations, which may vary among part types or remain fixed, and the machine(s) assigned to perform the machining.

The part types or orders are split up into pallet loads upto the specified pallet capacity. From now on these pallets may either be considered independently or in a *batch* of pallets relationship. The pallets are assumed to be readily available and of the correct type. Additionally, the palletisation is considered to occur before and not during the modelling. The pallets are assigned to the machines with the least workload and in accordance with the alternative machines specified for the first uncompleted operation. Successive pallets for all orders are then assigned to the machines in a similar fashion. There is a facility for assigning pallets which are part of the same original order, or to assigning residual uncompleted operations to the same machine. This bias is user selectable. Pallets and operations are assigned till either all pallets have been assigned or all available machining capacity, either specified globally for the system or individually for each machine or machine group, has been exhausted. The resulting workload (work lists) for all the machines are then sequenced using a simple priority rule to obtain a prescheduled machining list for each machine.

Delay values have been imposed on the process to prevent machining and transport overlaps between machining lists and to reduce machine idle times for reasons other than tool starvation. This sequencing of work lists into a machining list allows all pallets which constitute an order or a sub-order, if other constituent pallets have been assigned elsewhere, to be aggregated into a cluster thus enabling more efficient tool assignments to the machine. This option allows greater flexibility than is available for the prescheduled machining lists.

The splitting of an order into several batches further allows the exit and entry or re-entry of split or partly processed batches in the manufacturing facility. The use of this batching strategy, dependent upon pallet capacity and type is also necessary when tool storage capacity limitations do not allow all the desired parts to be machined in a facility at one time. Occassionally, balancing the workload on the machines may be so difficult that batching is required. Balancing the workload on each machine tool attempts to maximise machine tool utilisation as well as avoid potential bottlenecks in the system, with the intent of maximising system throughput. Often it will not be possible to balance everything. This is especially true in systems with different types of machines. Balancing can also be difficult where a large number of tools are needed for certain parts. The division of work content and tool magazine capacity is crucial. Additionally if parts are required to visit a number of machines, the effect of transport times and the material handling system congestion may need to be considered. This situation is more easily handled by emulation of the system rather than at this premodelling level.

The use of priority dispatching rules within the scheduling process are particularly suitable for use in the transfer of single tools. Other rules which have been incorporated are primarily intended for use with the *tool kit issue strategies* or for the issuing of *tool cluster sets.* Two such rules are the *similarity rule* or the *smallest tool kit first* rule. The *similarity rule* is also applicable to the *modified tool kit concept* or to the *tool cluster set concept.* This rule examines the tools or cluster sets already present in the primary tool store and used for the preceeding part and then accordingly assigns the next part which requires the fewest tools from the secondary tool store, or least tool changeover. This implies sharing of tools across tool kits or cluster sets which is the essence of the modified kit concept and the computer assisted cluster analysis. Use is made of a *similarity coefficient* for this method of part sequencing. This coefficient is determined as the quotient of the common tools present over the total tool requirement. The *smallest tool kit first* rule is simply the sequencing of parts according to the size of the tool kit requirement. No sharing is allowed. Alternatively, the output of the computer assisted cluster analysis may be used to specify preferred tool cluster sets and to suggest appropriate loading and scheduling rules.

An *add-on heuristic rules module* is made available so that the user may incorporate within the software his own specific decision rules for the assignment of jobs to the machines. The means to aid the user in writing these rules are provided, as is a facility for intoducing a *short-term* schedule. The modelling may be interrupted at convienient intervals for the user to input a preferred schedule of parts if so desired.

9.4 Internal Production Scheduling

The loading so far described forms the static part of the scheduling framework of the modelling. The main output of this loading is the determination of the *minumum tooling requirement* for servicing the schedule of part types in the specified manufacturing period, *figures 9.4 and 9.5* . This in turn is an input to the mainstream tool flow model.

The second step of the loading and scheduling process is the *internal production scheduling, figure 9.6* . This is the dynamic phase of the assignment process and attention is devoted to scheduling tool changes efficiently, according to the selected tool management and system operating strategies. This differs from other models in that priority dispatching, *similarity* or *smallest tool kit first* rules are employed for scheduling tool kits or single tools, rather than evolving a scheduling method which assumes that tool changes are an immutable constraint. The method employed here uses simple set theory and a user-selected decision rule, similar to those employed at step one, to select an activity from a *machining list* to schedule to the particular machine. This selected activity determines the *tool list* to be transferred to the machine. Any conflict between two activities is resolved by selecting the activity in the *cut set* with the lowest activity number, where every activity number is unique. This method of scheduling the *next step, figures 9.7 and 9.8* , eliminates the possibility of two machines or part types requesting the same tool at the same time from a common tool store, as the activity which satisfies the scheduling criteria is selected first and thus, that machine receives the demanded tool. This process is performed sequentially for each machining stage on each machine and operates satisfactorily within the modelling framework. The *next step* scheduler could be made to operate across several machines simultaneously if multi-processing is employed. This is outside the framework of this thesis but consideration has been given to incorporating this facility within the *Emulator*.

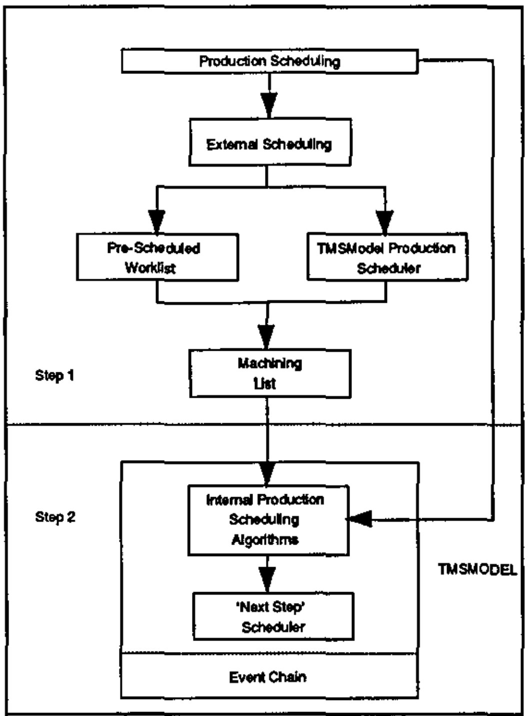


Figure 9.1 | PRODUCTION SCHEDULING FOR THE TOOL FLOW MODEL | LUT-FMS RESEARCH GROUP

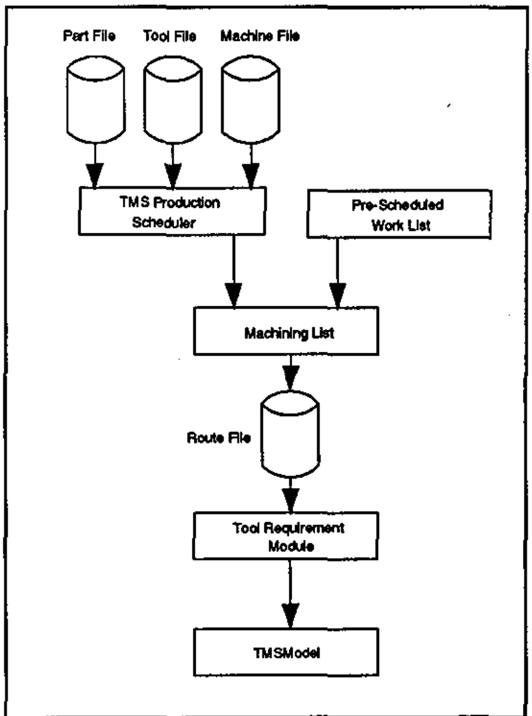


Figure 9.2 | THE ROLE OF EXTERNAL PRODUCTION SCHEDULING | LUT-FMS RESEARCH GROUP

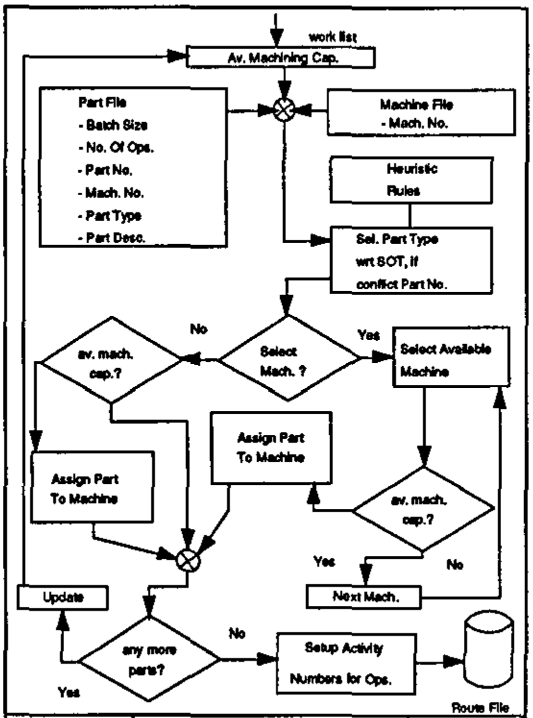


Figure 9.3 | LOGIC FLOW OF PRODUCTION SCHEDULER | LUT-FMS RESEARCH GROUP

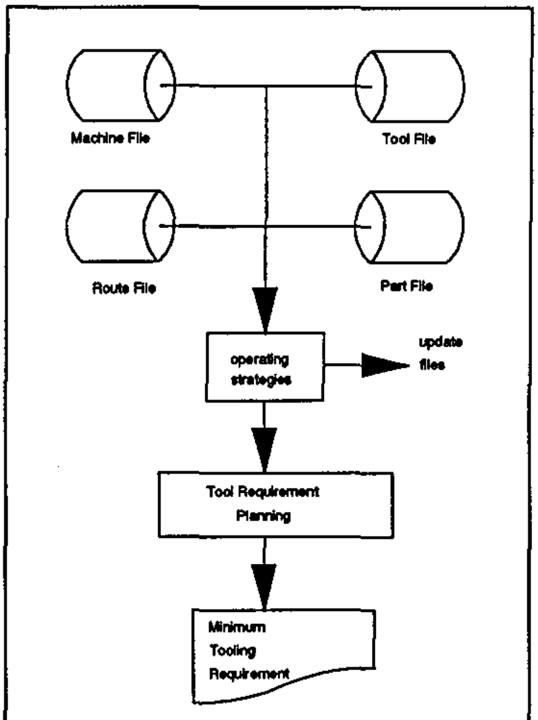


Figure 9.4 | TOOL REQUIREMENT MODULE | LUT-FMS RESEARCH GROUP

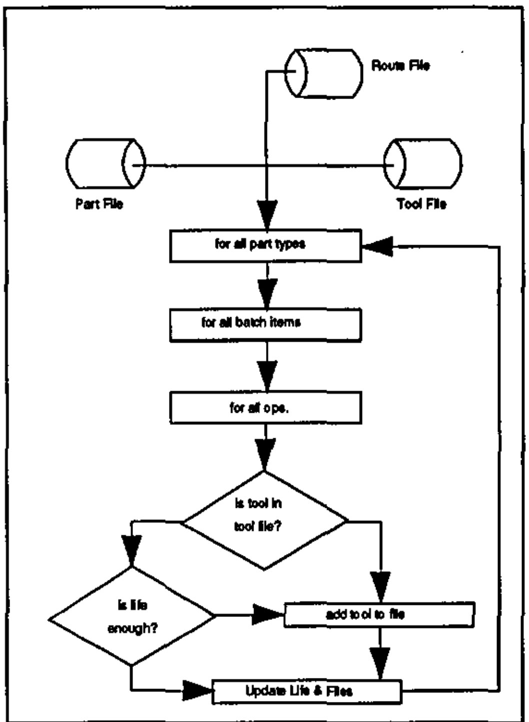


Figure 9.5 | LOGIC FLOW OF TOOL REQUIREMENT MODULE | LUT-FMS RESEARCH GROUP

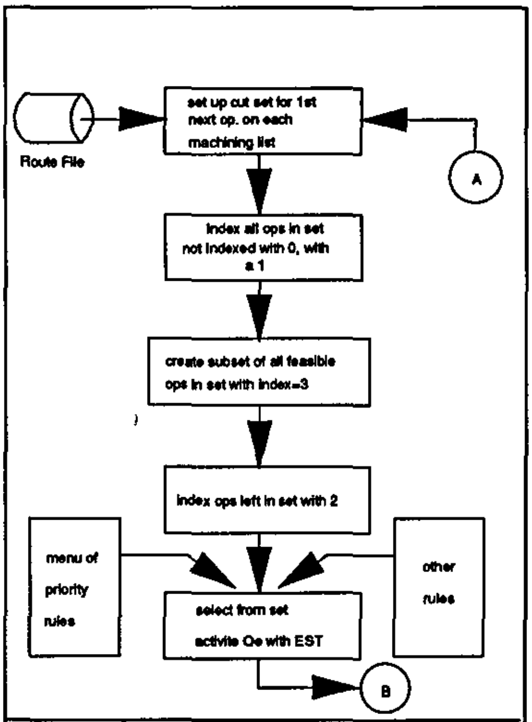


Figure 9.7 | THE 'NEXT STEP' SCHEDULER | LUT-FMS RESEARCH GROUP

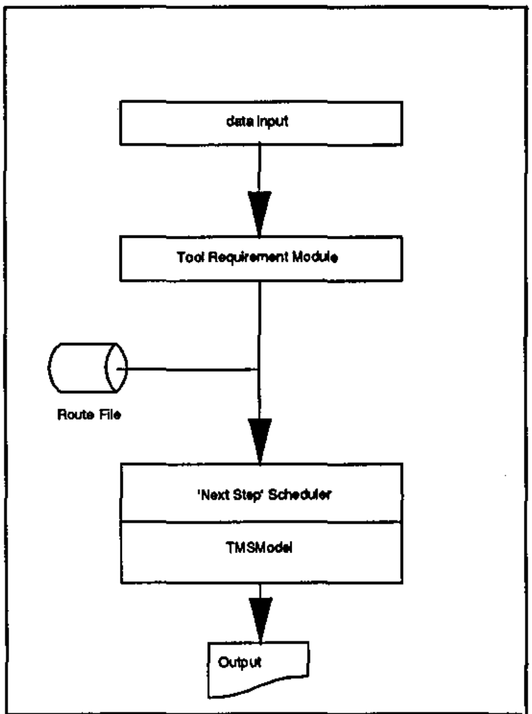


Figure 9.6 | THE ROLE OF INTERNAL PRODUCTION SCHEDULING | LUT-FMS RESEARCH GROUP

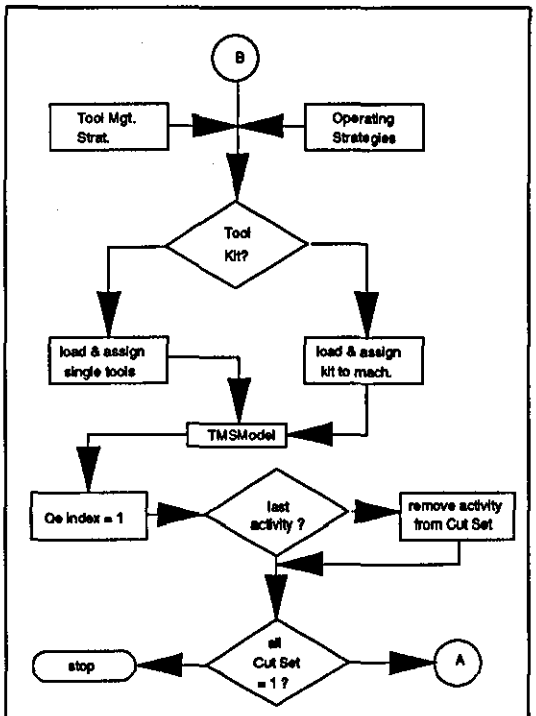


Figure 9.8 | 'NEXT STEP' SCHEDULER Cont'd | LUT-FMS RESEARCH GROUP

Chapter 10:
STRATEGIES FOR HIGHER LEVEL TOOL MANAGEMENT

10.1 Introduction

This chapter introduces the reader to the categories of tool management strategies available for cutting tool provision. The role and functioning of these strategies in relation to the major features, cost and the number of captive tools in the system is examined, at levels above the individual machine tools.

10.2 Tool Management

The essential role of tool management is the timely scheduling of tools to satisfy a short to medium term manufacturing task. Two strategies for this provision of cutting tools are evident : *workpiece-oriented* or *tool-oriented.* Within each of these categories a number of variations exist.

There are seven major factors involved when considering the form of tool management system to implement or replace in flexible machining installations. These are total tool inventory, cell tool requirements, the transport function, the tool flow solution, the production volume, the part mix and last but not least the cost, *figures 10.1 and 10.2.*

The total tool inventory is by far the most important factor, as it is the substantial reduction of this inventory that most tool management systems seek to achieve. The efficiency of a tool management system is often judged against the number of captive tools in the system versus the cost of holding and maintaining this inventory. The number of captive tools at cell level particularly within the cell STS is the major factor in determining the total tool inventory and the cost of the solution. In some cases this cell tool inventory is kept high to minimise tool exchanges between the cell and the higher level CTS as is the case in the 'Small Parts' FMS at British Aerospace [48]. In other cases the inventory at cell level is kept lean with fast transport to the machine tools and the tool room. This latter situation found at the Yamazaki Worcester installation [189] not only provides a cost effective solution at cell level but also at factory level, as the one STS is concurrently available to a number of cells via a tool 'highway'. Thus the number of captive tools at cell level is often a function of the level of tool flow automation or mechanical option chosen for tool provision.

The transport function especially between the cell STS and the central tool store is also a major feature of any tool management system. The pattern of supply and return of tools is of particular importance. A number of solutions exist resulting in either irregular, periodic or regular patterns of supply. These solutions some of which are cheap but clever and others which are more expensive in hardware often reflect the level of software control inherent in the installation. Generally, the more expensive the hardware solution the less sophisticated is the control system. Yamazaki is now one of the leading lights in this area with its evolution in system design from hardware dominated solutions in its Japanese plants to the software dominated solutions implemented at factory level for tool control.

The tool flow solution adopted or selected for flexible machining installations also reflects the form of tool management required. This is discussed in detail in the next chapter. The solutions adopted range from kitting through to the issue of single tools under the workpiece-oriented technique and from the issue of tool cluster sets to tool packages under the tool-oriented techniques. The selection of tool flow solution bears a direct relationship to the pattern of supply and return of tools within a cell and thus on the selection of strategy within either of the two tool management techniques. A number of tool management strategies either evident in practice or found to be a logical option are categorised below.

10.3 Workpiece-Oriented Strategies

The workpiece-oriented approach considers the case where the machines are supported with tools related to the actual orders, i.e the manufacturing system is said to be demand-driven. A tool rationalisation algorithm is applied to reduce duplication of the tools not only within the primary or machine-based store, but also within the overall manufacturing system. Tool disposition using this approach requires greater planning to determine tool demands, but guarantees maximum availability and flexibility of tools in the system. In many cases these workpiece-oriented techniques produce a satisfactory solution to the tool flow problems, but in some cases where the system is not explicitly driven by the work or where there is competition of priority in the flow of work and tools, *figure 10.2*, expensive and inelegant solutions to the tool flow task might result.

10.4 Tool-Oriented Strategies

The *tool-oriented* strategies are targeted to respond to the need for workpiece processing and routing flexibility and in situations where there are many diverse workpieces produced, unlike the *workpiece-oriented* strategies, where the number and type of tools is determined from the machining requirements of a workpiece spectrum introduced over a given scheduling period. These strategies are particularly suited to situations where *dynamic scheduling* is practiced and in situations where it is necessary to rework the production schedule due to machine breakdown, unavailability of material, etc., or in situations where there are difficulties in scheduling; frequent tool changes; many different types of tools, fixtures and programs to manage; many operator set-ups and special schedule situations as in the case of a critical part. This is in contrast to the *workpiece-oriented* strategy where there is an assumption that a set of workpiece types will visit particular machines with a high degree of certainty. Two variations of this strategy are apparent. Although the majority are not demand driven, a few exist such as the tool clustering strategy where an initial workpiece-demand or work list may be used to generate the tool complements.

10.5 Categories of Tool Management Strategies

10.5.1 Complete Duplication Strategy

This is the simplest strategy most closely resembling the tooling philosophy in the now obsolete job shop, *figure 10.3* . This strategy simply provides a copy of each tool needed for each operation on each batch visiting the machine. This ignores the fact that possible sharing of tools in consecutive batches can reduce the tooling inventory and tool handling particularly between the cell STS and the factory CTS. The problem of control is minimised at the expense of excessive tooling inventory at the cell STS and the machine PTS. The flow of parts is fixed in such a manufacturing system and the tools in the primary tool store may remain unchanged for a considerable length of time [303,304]. This *unlimited and as needed* strategy only becomes a sensible strategy with a high volume / low part mix application. Tool management control problems are reduced to complete replacement of tool kits or magazines as required. This strategy of complete change of tools at the end of a batch is practiced at the British Aerospace installation [48]. In this installation because of the dual spindles on each machine tool the tools are assigned to suit what is almost a 'batch of two' concept. Applying this strategy means that the manufacturing system is all but converted to a flexible transfer line.

A variation of the *complete duplication strategy* is possible. This variation known as the *bulk exchange strategy, figure 10.4* [96] removes tools when a particular part type or part set is completed, i.e on completion of a scheduled work-to list, and replaces them with tools for another work list. Tools are not necessarily duplicated for each operation. This complete change at the end of a work list or shift is in contrast to the complete change of tools at the end of a batch. This strategy is practiced in many of the Cincinnatti Milacron installations [63].

10.5.2 Limited Duplication Strategy

The *limited duplication strategy* offers an improvement on the bulk exchange strategy in relation to excessive tool inventory, *figure 10.5* . This strategy is more progressive in that it attempts to recognise common tooling between workpieces or several part batches in a *frozen schedule* [63] . Tools which are so identified are not duplicated in the tool magazine for each workpiece type. This strategy thus has a tendency to lessen the total tool inventory. The tool magazine is serviced only once at the beginning of the work list, so all the tools must be accommodated in the primary tool store or in an auxilliary tool store. At the end of the work list, a new set of tools for the next work list is loaded. The tool management is slightly more complicated than the previous strategy, and so is the mechanical design of the tool flow network. From the outset this approach of limited duplication requires having larger capacity tool magazines (generally 80-140 tool capacity) and a lower provision for differential kits but permits a higher variety of parts to be machined and can thus be considered to have a lower tool inventory and to be more appropriate for irregular batching environments. A variation on this strategy is employed in the Werner and Kolb QTC system where the delivery of these differential or partial kits is undertaken via cassettes [232] , although this system does not sit comfortably in any one category as the machines are designed to move from one tool upto sets of tools. This system may also be included within the tool-oriented category. The limited duplication strategy can be viewed as a variation of the complete duplication strategy for a given work list as opposed to an individual workpiece type.

The strategies so far described relate mainly to stand-alone machining centres and manual tooling systems, categorised as A (see chapter five). The following strategies are more suitable for automated tool flow systems of system categories B and C (see chapter five) and are thus able to substantially reduce the tool inventory.

10.5.3 Continuous Replenishment Strategy

Migration of tools at the completion of a workpiece type takes the concept one step further than the previously defined strategy; fixed part flow is not required in such a scheme. In this strategy the scheduled period is not affected by the tooling capacity, *figure 10.6*, available on the machines. As workpiece types are completed several tools may become candidates for removal from the primary tool store. Their removal permits the loading of tools required for other workpieces. This strategy substantially reduces the tool inventory through the concept of sharing of tools. In effect, therefore, tools are provided, replenished and recirculated to machines continuously as required by the work lists and not periodically for example at the end of a batch, shift or work list. However, the decision logic concerning the set of tools to leave the primary tool store becomes more sophisticated as some of these tools may need to be reloaded at a later time. Tool mix and tool provisioning can only be determined by modelling. This decision could affect the number of tools handled. The primary trade-off is between a satisfactory low tooling inventory and enforced under utilisation of machines through tool starvation because of the ability to move the same tool continuously between machines and thus although sharing reduces the tool inventory it may actually increase the waiting times for tools at the machines. This strategy ensures the ability to respond to any unexpected situations which may arise during production. A new logic problem arises - how to tune the manufacturing system for a given production period with the tooling inventory shared by several machines. The ideal composition of a manufacturing system operating under this strategy is a group of machines with identical processing capabilities (303). This strategy is perhaps the most popular and is used in a number of machining installations employing differential kitting or single tool issue options, such as the Vought Aerospace FMS in the USA (6) and the Tos Celakovice FMS in Czechoslovakia (303).

This replenishment tool management strategy places completely new requirements on manufacturing system design - large capacity tool magazines and automated transfer of single tools or differential kits between machines and a secondary tool store are necessary. Such a manufacturing system must be supported by system software where the tool flow must match the machining task.

The Yamazaki Worcester installation (189) employs this strategy in combination with a strategy for determining the size and composition of the fixed tool complement within a tool magazine. Thus each of the machines possesses a fixed tool complement which is continuously replenished with single tools on a just-in-time basis. The application of this strategy in this situation is unique because not only is the strategy operational at cell level but also at factory level due the fact that the STS is concurrently available to a number of cells.

A variation of the continuous replenishment strategy is in effect a combination of this strategy and the limited duplication strategy in that continuous replenishment is employed until the end of a work list and then replacement is effected as for the limited duplication strategy. Although this is a logical option no example has been traced except within the MAST simulator offered by Citroen Industries, where it is offered as an option.

10.5.4 Work and Tool Clustering Strategy

In the Makino Max FMS (91), this *tool-oriented* strategy, figure 10.7, is used most effectively to reduce cost and greatly simplify the tool management. The tooling analysis or *cluster tooling* analyses the operations for each machine in a group, to find *tool families* of parts which can be machined one after another using the same tooling with the same set-up. Operation of the system is designed according to the concept of *tool family scheduling, figure 10.8* [30,35,169]. The tool scheduling system uses the principle of statistical cluster analysis to establish the *minumum set differences* in tooling requirement between successive parts loaded onto each machine. Tool set differences can include not only tool type but also the differential wear per part operation for each location and tool. Automated tool handling requirements using this strategy are usually minimised to the marginal difference between sets on sequentially loaded work in relation to each machine.

This cluster analysis technique regards each operation, part type or process string as having an associated *Tool Set* (TS) required to manufacture the part. The process string is said to encompass part loading, machining and part unloading. Cluster analysis is then applied to obtain the optimum number of tool sets in a given *Tool Cluster Set* (TCS), figure 10.9.

The tool cluster set strategy provides each machine with the flexibility to produce any individual part or batch that is included in the tool cluster set resulting in cost effective work and tool flow. The tooling configuration of any primary tool store is thus managed on the basis of cluster sets and not as single tools. In the event of a broken tool, this form of management system evaluates the remaining tools in the cluster set to make most efficient use of the transport system. Any tool which is approaching or has reached its tool life limit is removed and transported with the broken tool to a central tool storage facility for refurbishment. Use of this strategy requires dynamic scheduling and dynamic machine allocation principles to be employed for scheduling of work.

The functioning of this strategy is illustrated in *figures 10.10, 10.11, and 10.12.* Figure 10.10, illustrates the removal of a tool cluster set after complete machining of a part family in a predetermined scheduling period. The replacement of this TCS with another for a different part family is shown in figure 10.11 . This theory is extended to a single cell and is shown in *figure 10.12* . One TCS is assigned to each machine. This TCS may be duplicated on another machine to cover possible breakdowns and enhance flexibility. Unlike group technology a part family may overlap with another part family in which case a TCS changeover is carried out smoothly and the machine may continue machining with the tools overlapping between both TCS's.

Three important considerations are to be found in clustering : summing of clusters, machine assignment and tool economy. Clusters determined from the analysis may be summed up to form larger cluster sets. This is obviously limited to the magazine capacity. This summing up is not always straightforward as tool types may not need to be duplicated in each cluster and thus the number of sister tools may vary

The assignment of clusters to machines is another important consideration based on one or more of the following factors : flexibility, breakdown, and priority hysteresis. In order to enhance flexibility or to consider the case of a machine breakdown, it may be necessary to duplicate a cluster set at another machining station, thus enhancing routing flexibility and minimising production delays in these situations. These two factors may further complicate the management as the combination of clusters at each machine may then have to be individually considered.

Priority hysteresis [219], provides for system tunability. For example, if a machine is currently configured with a TCS or a combination of TCS's that includes a TS for the highest priority job, where the priority is based on the progress towards a production plan, then as parts are completed on this highest priority job (say, job A), its priority is reduced. At the same time, the priority of a second job (say, job B), not currently being produced is increasing. At a given point in time the priorities of these jobs will become equal and then reverse. Without some form of priority hysteresis, i.e a reversed priority value, the TCS would be changed to produce the now highest priority job, B, until the old job, A, again becomes the highest priority job. This could require another TCS change - back to the original TCS for job A. Obviously, priority hysteresis is used to minimise the number of TCS changes and is based on tool transporter capacity, number of TCS's in the system, required accuracy of delivery date and the commonality between TCS's. The commonality between TCS's is the main focus of tool economy together with the number of sister tools. The commonality between TCS's is advantageous during TCS changeover as continued machining is possible during this activity.

10.5.5 'PERA Programmed Job Planning' - A Restricted Clustering Strategy

This is a similar approach to cluster analysis, *figure 10.13* , but employs a much simpler method. The method is based on *match measures* and *attributes* [30]. The technique is similar to cluster analysis in that tool sets are generated when the *match measures* of the tools to the *work tasks* is equalled.

The attributes consist of primary elements such as faces, secondary elements such as grooves, and quality detail such as surface finish. A set of attributes and their detail together with any interrelationships constitute a work task. The problem of programmed job planning is then to assign a set of tools to a work task so that : there is a best possible match between attribute set for the task and that for the tool, and so that the production costs and the number of tools required for each workpiece is minimised. The basic method for achieving this is a pairwise comparison between attributes of tools and work tasks. The coinciding atributes are called match measures. Thus if the number of match measures equals the number of attributes contained in the work task specification a solution is obtained. No example of an installation using this technique has been found.

10.5.6 'Random Tool Flow' Strategy

This term has been used to label a form of tool-oriented strategy employed at the Tos Olomouc plant [330]. This strategy , *figure 10.14,* requires that identical operations be machined not only on the same pallet but also on the same machine. This system is managed on the basis that for a certain period of time each machine should repeatedly perform the machining of a limited chosen variety of operations until one type of operation is completed within the whole range of available workpieces. Only then can another operation be accepted and aligned into the repeated sequence of chosen operations. This form of management, in the Tos Olomouc installation, minimises the tool transportation time, in this case because of the distributed tooling system network where each of the tool magazines not only serves the adjacent machine but is also available to every one of the eight machines in addition to the secondary tool store, but requires the capacity of the primary tool store to be sufficient to cover the repeated machining of the chosen operation on a particular machine.

10.6 Selection of a Tool Management Strategy

The selection of either the *tool-oriented* or *workpiece-oriented* tool management strategy is system and volume dependent. The workpiece-oriented strategy predominates in one-off and small batch production whereas the tool-oriented strategy is typically found in mass or large batch production systems and when special purpose machines and dynamic scheduling is employed. In some manufacturing systems both type of strategies may prevail. This is now evident in many one-tool robot overhead gantry tool transfer systems such as the Yamazaki Tool Hive Stocker and the Cincinnatti Milacron secondary tool store networks (see chapter two).

The trend is towards a combined tool management strategy which is also suitable to manually supported tooling systems and those highly automated systems with low capacity, low cost, fast and reliable tool transfer systems as described above. These systems are easier to control and co-ordinate as opposed to their counterparts operating under either of the tool management categories. There is some evidence of moves away from dynamic scheduling of tools, pertinent to the tool-oriented tool management strategy, to systems which are prescheduled with tools, and set-up and organised around flexible machining lists. These systems need to be modelled for short range schedules along tool-oriented lines but managed along workpiece-oriented principles.

With a combined tool management strategy it is possible to leave certain basic tools on the machines upto the end of their useful tool lives and to exchange only the variable workpiece-related tools in accordance with predetermined strategies.

This combined tool management strategy effectively emphasises the salient points of each of the strategies described. The selection of different operating strategies then permits the tool flow system to be biased towards either of the tool management categories. Within each category the real decision making is at the micro level where the choice between alternative operating strategies will greatly influence and/or suggest what tool management strategy is appropriate. This *bottom-up* approach to overall strategy selection is less restrictive, than compromising at the macro level and then choosing how to operate the system. This method allows for look-ahead modelling to be carried out without unnecessarily restricting oneself to what system hardware is available, except of course, when modelling is used as an operational rather than as a design tool.

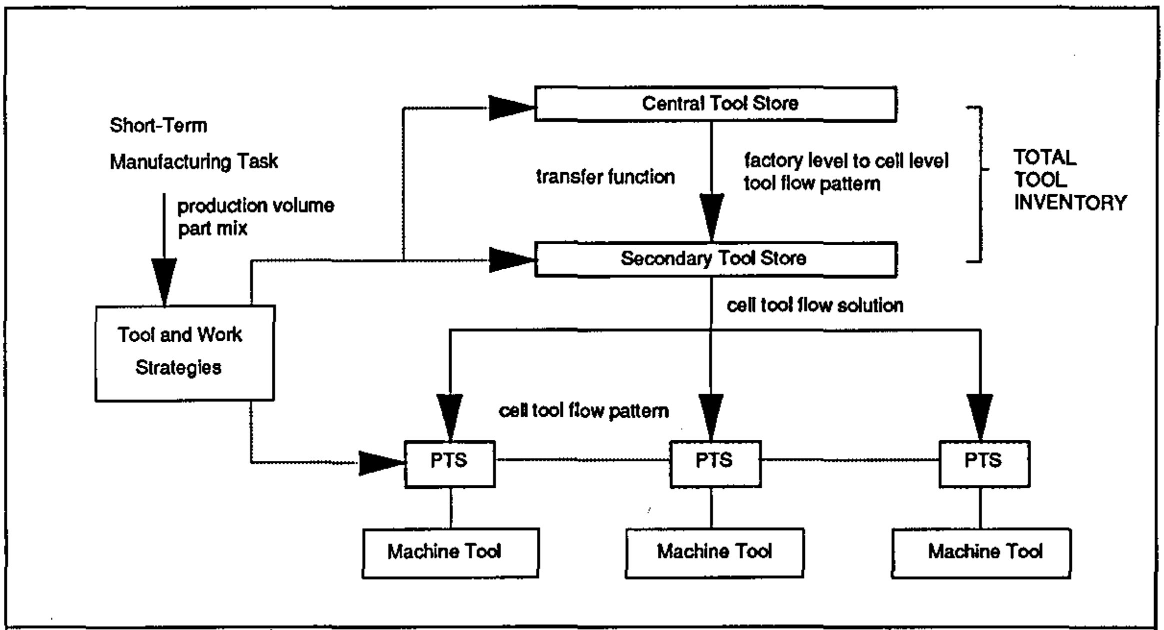


Figure 10.1

FACTORS IN TOOL MANAGEMENT FOR
- TOOL STORE HIERARCHY

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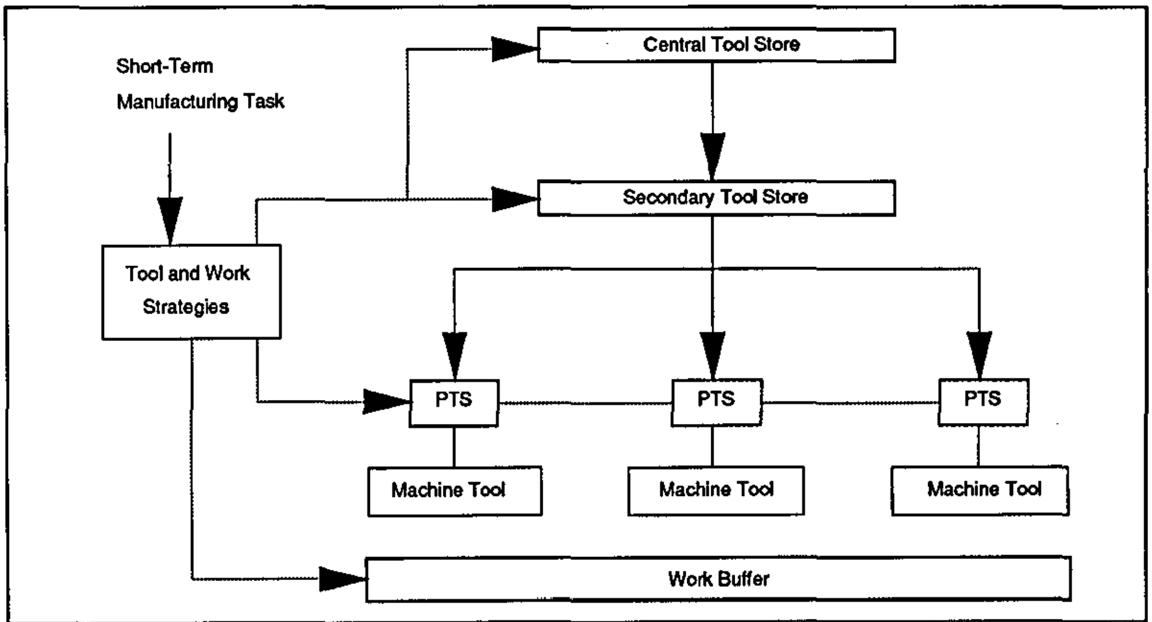

Figure 10.2

FACTORS IN TOOL MANAGEMENT FOR
- DUAL FLOW

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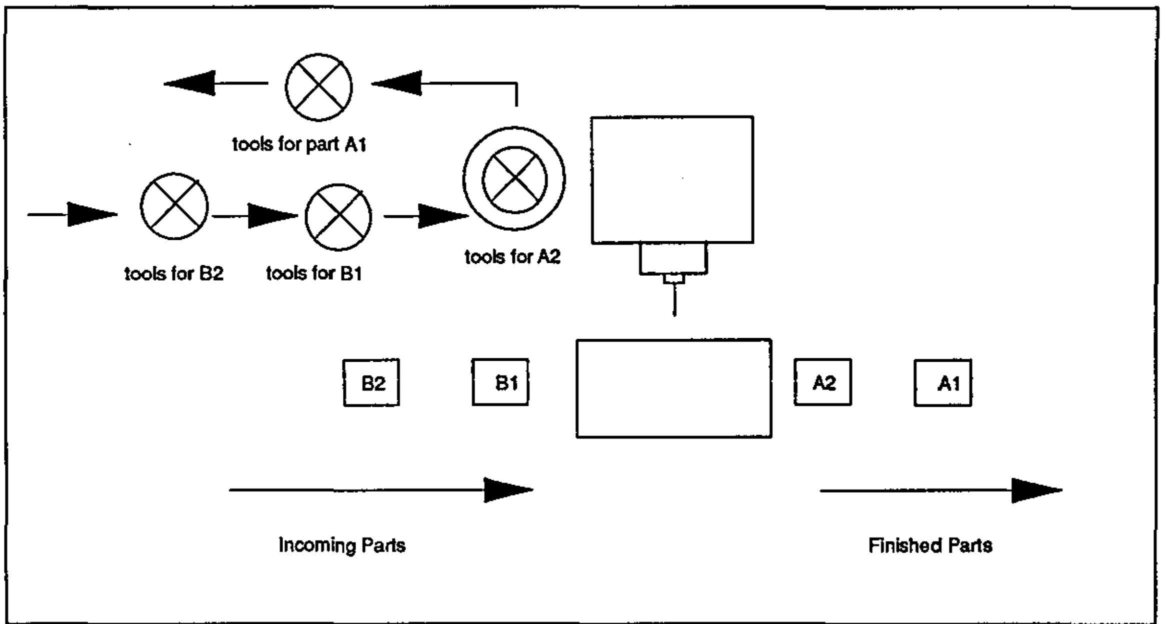

Figure 10.3	WORKPIECE-ORIENTED TOOL MANAGEMENT STRATEGY COMPLETE DUPLICATION STRATEGY	LUT - FMS Research Group

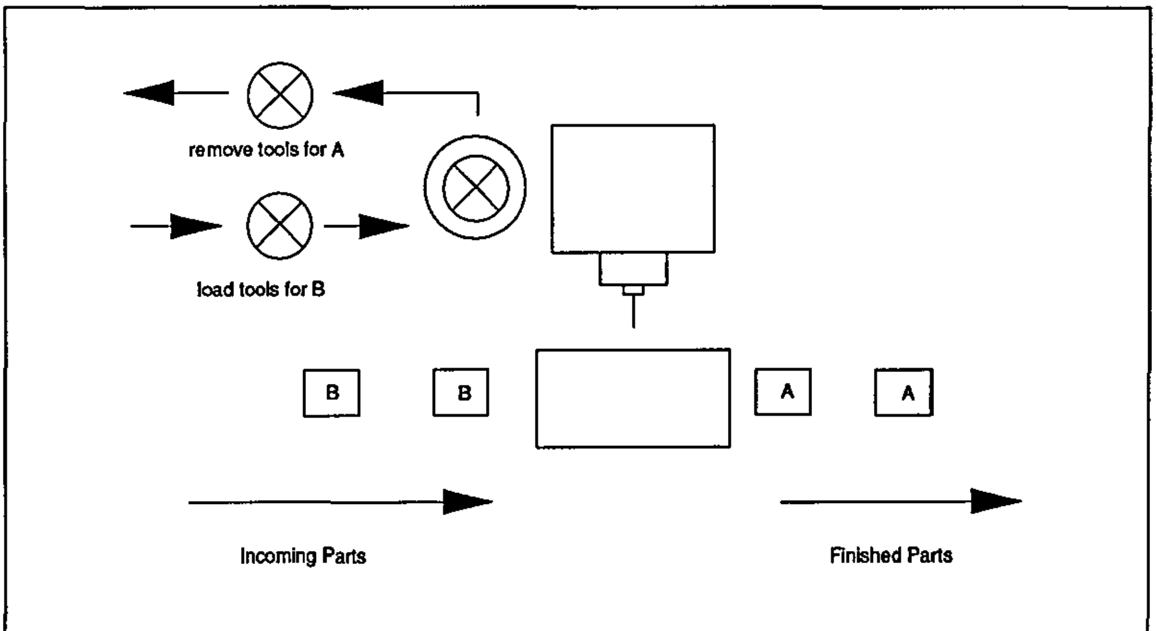

Figure 10.4	WORKPIECE-ORIENTED TOOL MANAGEMENT STRATEGY BULK EXCHANGE STRATEGY	LUT - FMS Research Group

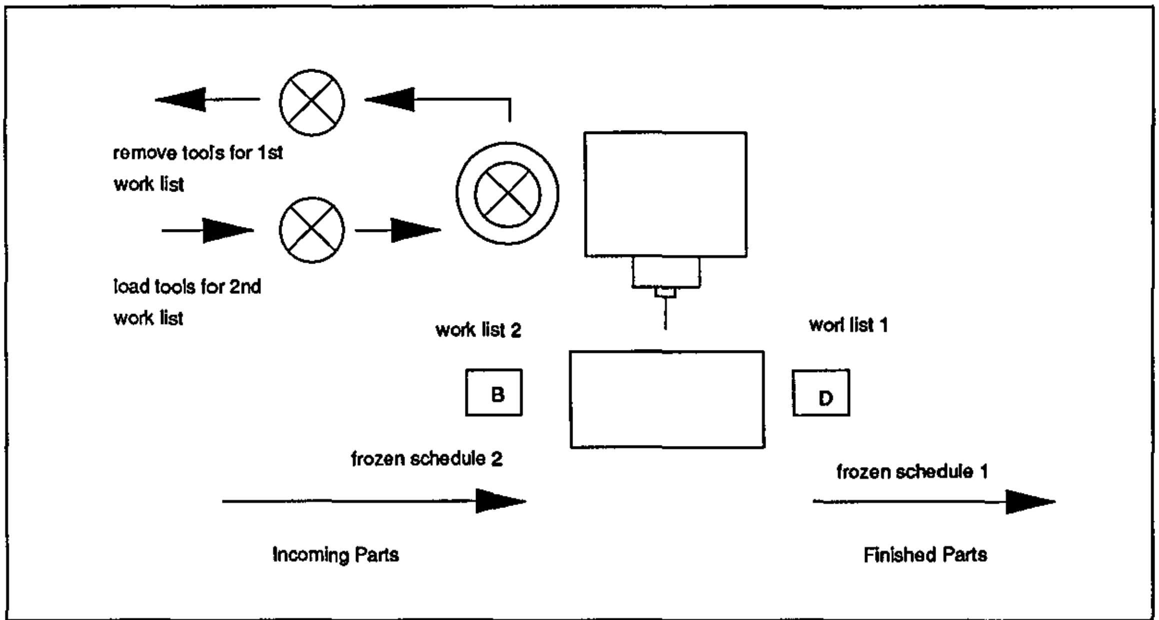

Figure 10.5 | WORKPIECE-ORIENTED TOOL MANAGEMENT STRATEGY LIMITED DUPLICATION STRATEGY | LUT - FMS Research Group

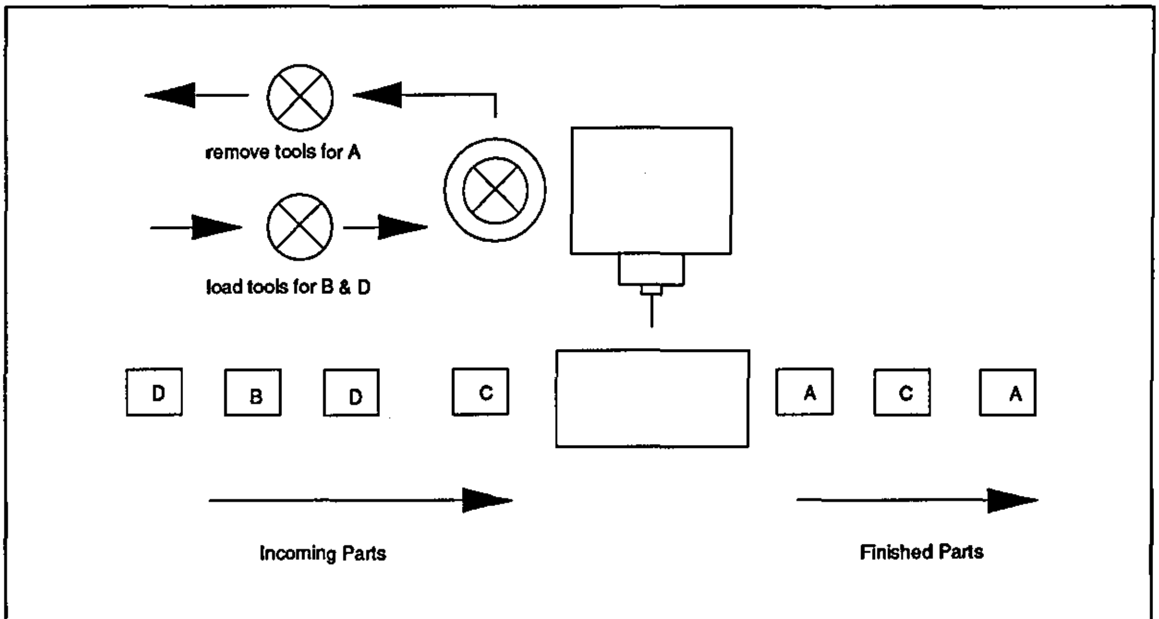

Figure 10.6 | WORKPIECE-ORIENTED TOOL MANAGEMENT STRATEGY CONTINUOUS REPLENISHMENT | LUT - FMS Research Group

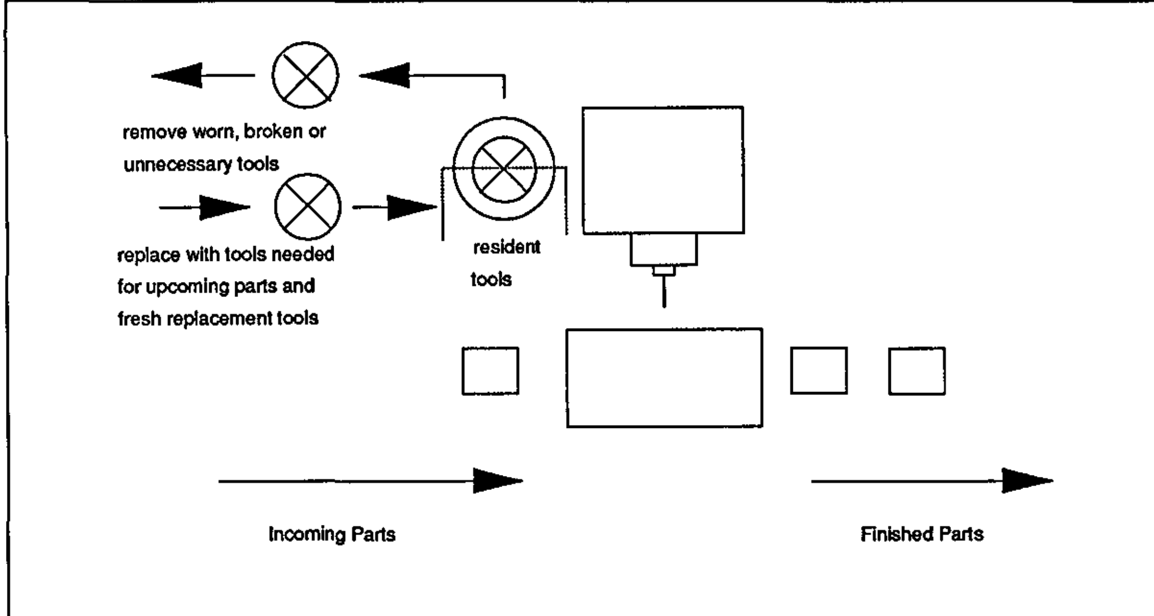

Figure 10.7	TOOL-ORIENTED TOOL MANAGEMENT STRATEGY RESIDENT TOOLS	LUT - FMS Research Group

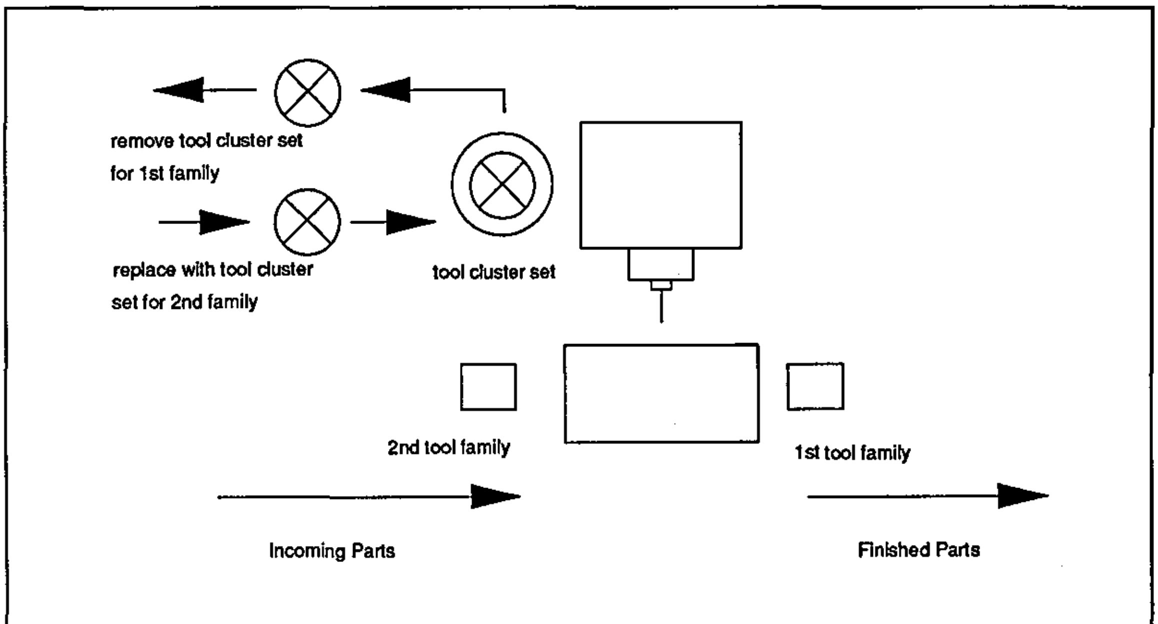

Figure 10.8	TOOL-ORIENTED TOOL MANAGEMENT STRATEGY TOOL CLUSTER SETS	LUT - FMS Research Group

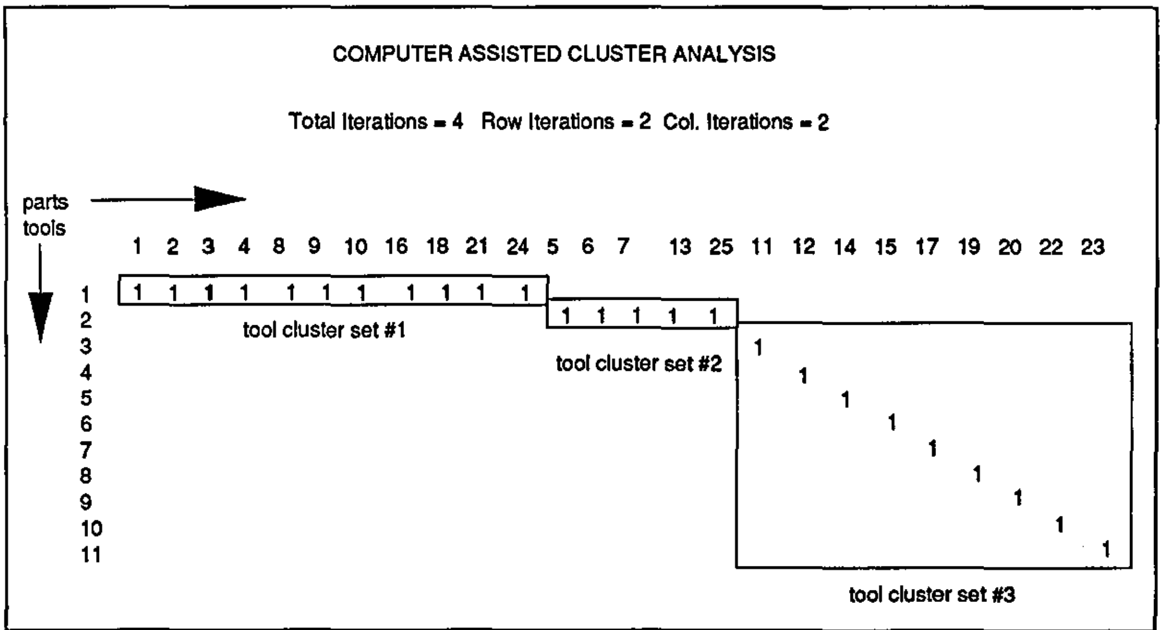

Figure 10.9 | THE CLUSTER ANALYSIS TECHNIQUE | LUT - FMS Research Group

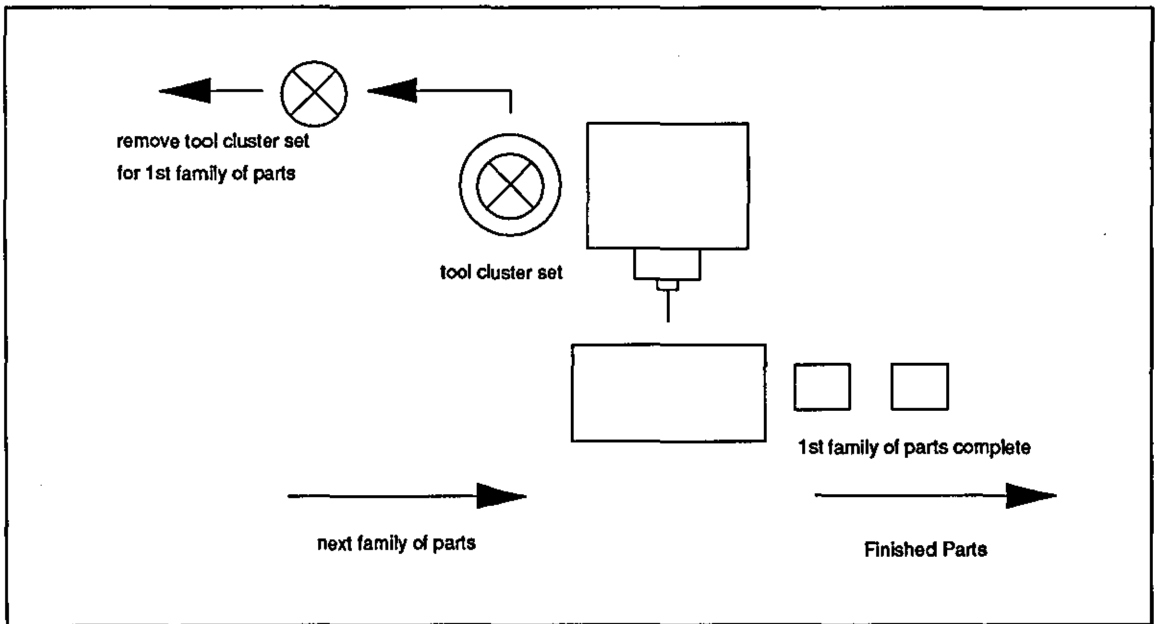

Figure 10.10 | TOOL-ORIENTED TOOL MANAGEMENT STRATEGY TOOL CLUSTER SET REMOVAL | LUT - FMS Research Group

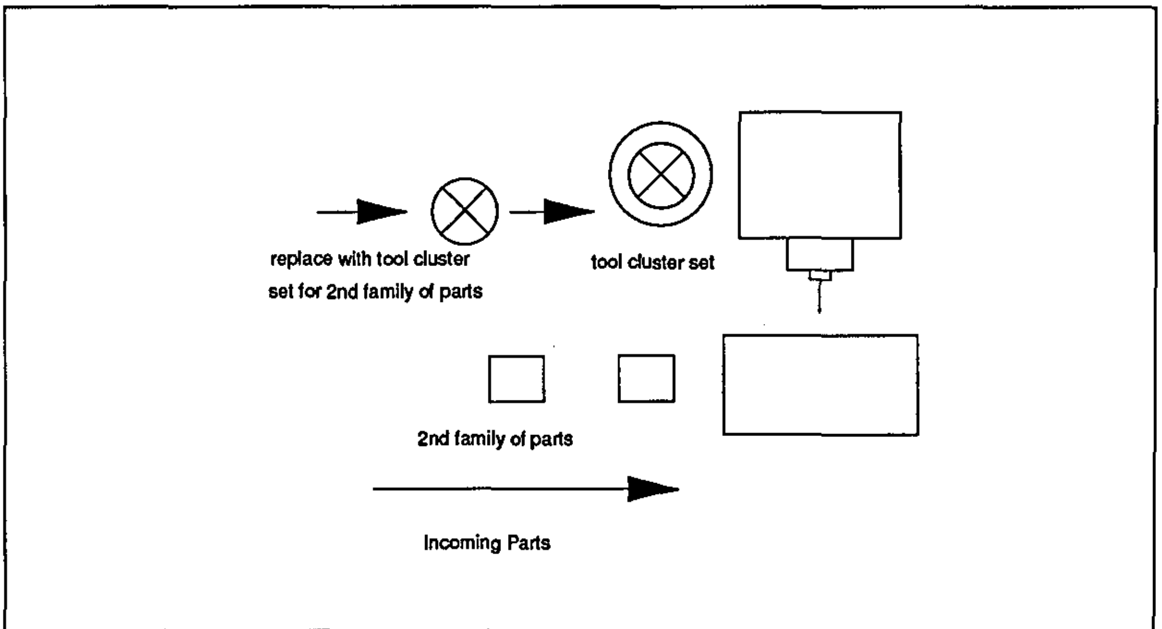

Figure 10.11	TOOL-ORIENTED TOOL MANAGEMENT STRATEGY TOOL CLUSTER SET REPLACEMENT	LUT - FMS Research Group

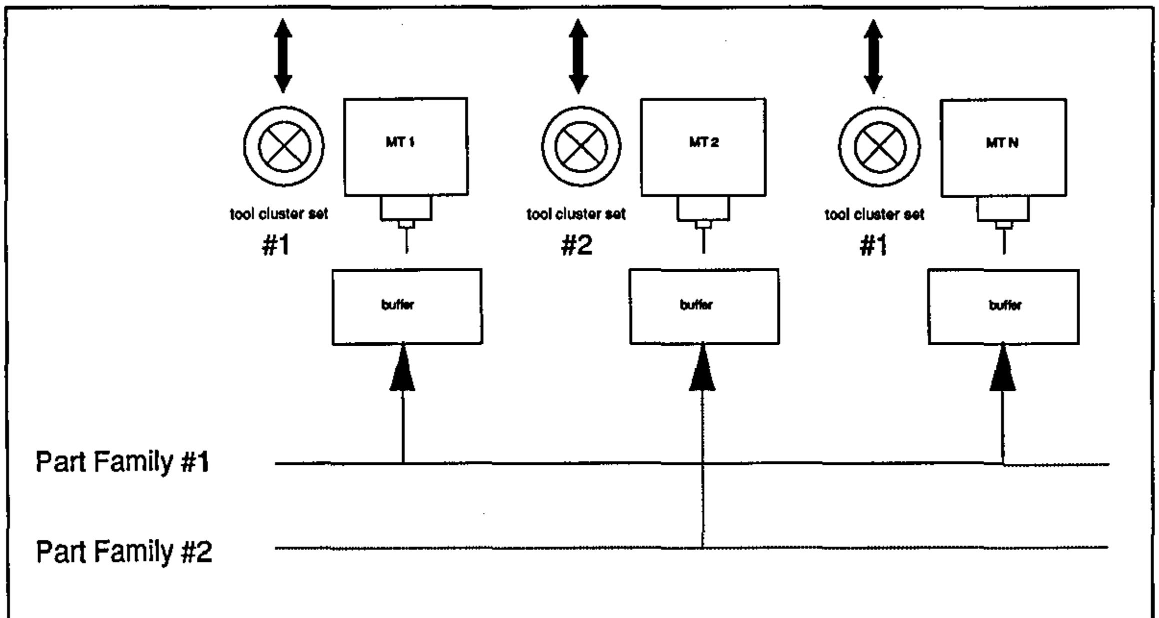

Figure 10.12	TOOL-ORIENTED TOOL MANAGEMENT STRATEGY SINGLE CELL TOOL CLUSTER SET ASSIGNMENT FOR RESPECTIVE PART FAMILIES	LUT - FMS Research Group

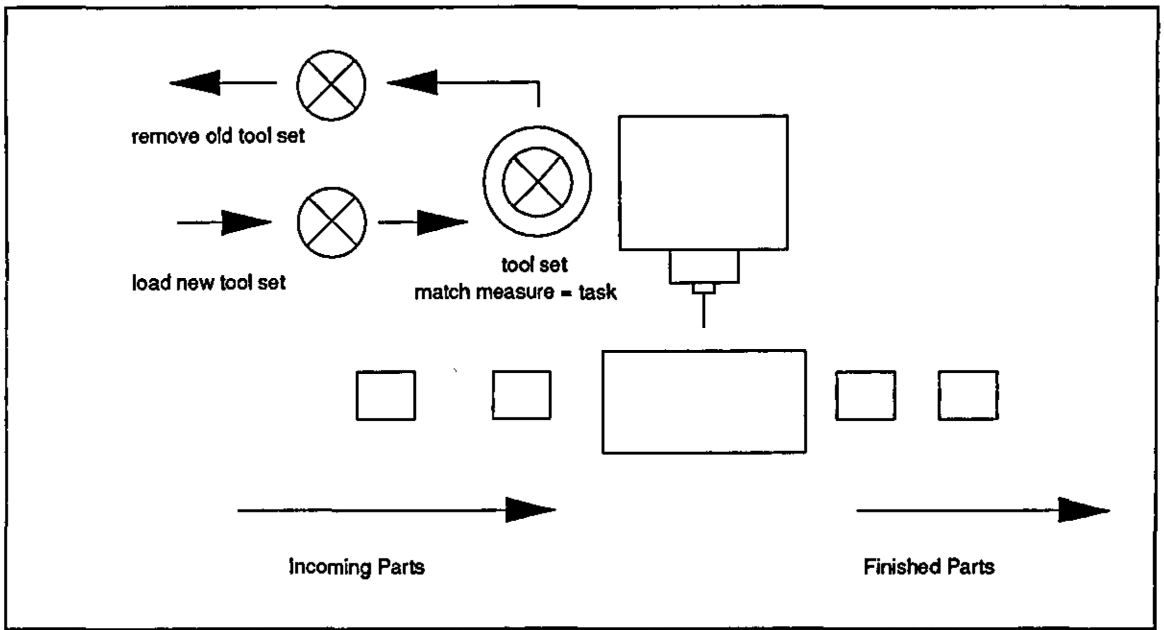

Figure 10.13 — TOOL-ORIENTED TOOL MANAGEMENT STRATEGY
PROGRAMMED JOB PLANNING — LUT - FMS Research Group

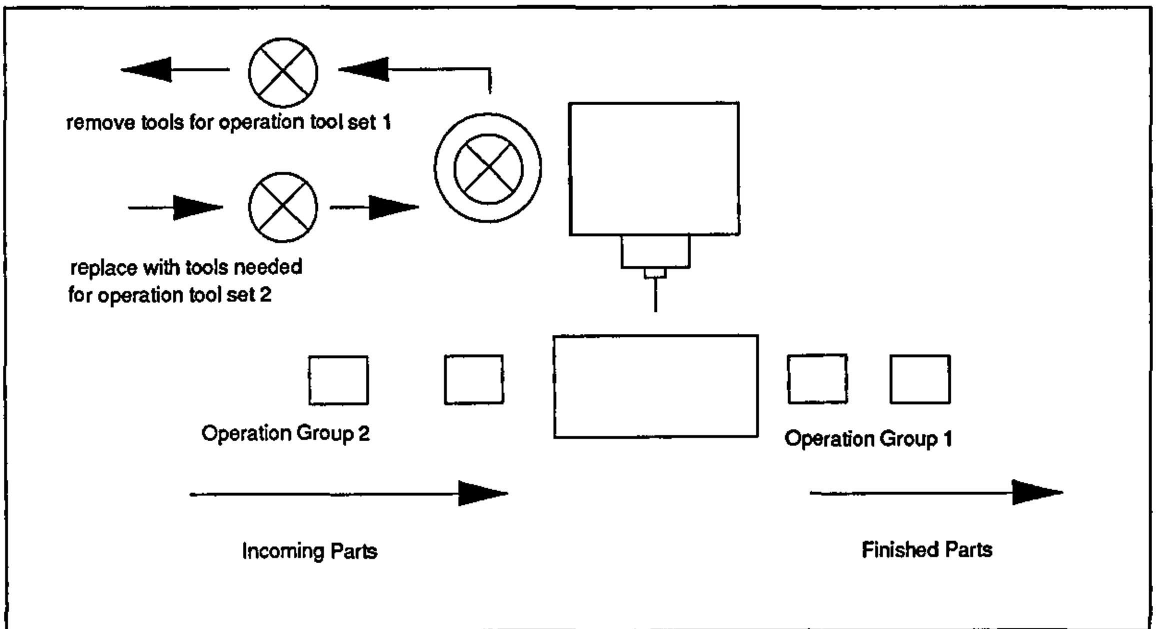

Figure 10.14 — TOOL-ORIENTED TOOL MANAGEMENT STRATEGY
RANDOM TOOL FLOW — LUT - FMS Research Group

Chapter 11:
HIGHER LEVEL TOOL FLOW STRATEGIES

11.1 Introduction

The difficulties encountered in managing the tool flow, point to the need for strategies to deal with specific higher level operational problems, such as tool assignment and tool issue, in the activity flow networks described in chapter seven. Each of these operational strategies and their relationship with the loading and scheduling function (described in chapter nine) and the tool management strategies (described in chapter ten) contibute to a total tool management solution. This framework for a complete solution and the operating strategies themselves are discussed in this chapter. The higher level tool issue strategies also provide the basis for the design and operation of the modelling package described in chapter eighteen.

11.2 A Rule and Strategy Framework

The overall framework to provide a tool management solution to an existing or specified manufacturing system is shown in *figure 11.1*. The first solution phase is to specify or identify the tool flow network appropriate for the manufacturing requirements. The categories, detailed in chapter five, provide a starting point from which other solutions or requirements may be identifed. The second phase involves the careful selection and definition of a tool management strategy which may either already be in existence in some form or to replace the installation with a different system operating strategy or simply to experiment with options available when selecting new or proposed hardware and/or software.

The tool management strategy selected and the configuration, set-up, and functioning of the tool flow activity network (see chapter seven), whether tool-oriented or workpiece-oriented (see chapter ten), will consequently dictate the options available for tool issue and tool assignment from a spectrum of tool flow strategies and rules.

A *bottom-up* approach is applied to rule and strategy selection for each of the building blocks in the hierarchical network of stores (see chapter six). At the lowest level is the machine PTS, where the selection of rules and strategies (chapter thirteen) reflect the machine not only as the interface between the part and tool flow networks (as described in chapter seven), but also as the focal point of the supply, exchange and return of cutting tools. At the cell level STS, an additional set of rules is available to represent not only the flows within a cell but also the flow between cells and between CTS and the machining cells. The cell rules and strategies (chapter twelve) build upon the rules selected at the machine level. The selection of rules and strategies for the higher level CTS provide for the overall control and auxilliary functions such as refurbishment, cell level assignments, etc. The rules and strategies required at each level are illustrated in *figures 11.2, 11.3 and 11.4*.

The integration of the rules and strategies into an overall control or decision structure is dependent upon the emphasis placed on the flow of parts and tools within an installation. Emphasis may either be solely on the flow of parts or on a dual flow of parts and tools. Given a short-term manufacturing task, then in the latter case of emphasis, the rules and strategies selected at the cell level would have to reflect not only the tool activity - event chain but also the activity at the cell's part input and output buffers, *figure 11.5.* In the former case of sole emphasis on part flow, *figure 11.6,* the rules at the machine level would be given prominence as the tool transfer and exchange activities at the STS level would not be the main focus of activity.

In both cases, modelling is required to make possible a more substantial understanding of tool flow problems and the economic solutions for flexible machining installations and explore the relative merits of alternative designs and control strategies for flexible machining ranging from stand-alone machining stations to highly automated multi-machine multi-cell configurations. To this purpose, a spectrum of control strategies for tool assignment and tool issue are presented for the two categories of tool flow management.

The adaptation of the strategies and rules for modelling purposes are examined in chapter fifteen. The resulting tool management solutions for chosen rules and strategies are illustrated via industrial case studies presented in appendices three to five. Tool life management criteria and rules are discussed in chapter fourteen.

11.3 Tool Assignment Strategies

The tool assignment strategy is the heart of any automated tooling system, *figures 11.7 and 11.8* . The ultimate goal in planning and executing this strategy is reducing the distance travelled by the tool transporter, minimising machine idle time, maximising equipment utilisation, and eliminating tool redundancy and duplication. A system may be designed to allocate as many tools as possible to the primary tool store (PTS) and reserve the secondary tool store (STS) for providing replacements for worn or broken tools. This type of operating strategy creates a large tool inventory as tools may be duplicated across several machines. The PTS capacity of the machine needs to be sufficiently large to accommodate all the required tools if the system is to run unmanned. Secondary exchanges are minimised because of the large local tool inventory, flexibility is increased as each machine has a large enough tool set to machine a spectrum of parts, and control is at the machine level in systems which employ this operating strategy.

An alternative strategy is to keep the majority of tools in the STS and transfer them to the respective PTS before a specified machining sequence. The tools are then either held in the PTS, if sufficient capacity is available, or transferred back to the STS on completion of this set of activities. The tools required for the next task are then allocated to the machine and placed in the PTS. This management strategy should effectively minimise the tooling inventory but may require many more secondary exchanges. Some tool duplication may be necessary to avoid conflicting demands on the same tool by more than one machine at any given time.

The two operating strategies described are essentially the two extremes of a continum of possibilities. The optimum system may use parts of both operating methods. The tool assignment strategies are dependent upon the selected tool management strategy and also upon the particular tooling system configuration.

11.4 Tool Issue Strategies

The tool issue strategies bear direct relationship with the tool management strategies outlined in chapter ten. The tool management strategies provide for higher level organisation and tool changeover whereas the tool issue strategies provide for lower level tool set ups. Seven tool

issue strategies are considered, these are :
(a) total tool changeover
(b) tool kitting
(c) differential or modified tool kitting
(d) single tools
(e) tool cluster sets
(f) resident kits, and
(g) functional tool number (FTN) issue

Tool issue strategies (a) to (d) are essentially workpiece-oriented and strategy (e) is tool-oriented. Strategies (f) and (g) are a compromise between the two management strategies.

11.4.1 Total Tool Changeover

This strategy is basically operable when the bulk exchange workpiece-oriented tool management strategy is selected. On completion of a particular spectrum of parts over a given production period, all the tools held in the tool magazine are removed and replaced with tools for the next production frame or work-to list. Tools are loaded, upto the capacity of the PTS, without unnecessary duplication at the start of the manufacturing period. Very little tool flow is evident in this type of system. This strategy is practiced at many of the Cincinnatti Milacron installations [63].

11.4.2 Tool Kitting

A tool kit is a set of tools required to process one part type or job at one station type. The tool kit concept copies the approach conventionally used in job shops, where several different parts are machined in fixed sequences. A tool kit is thus assigned to a machine for a fixed set of tasks on a particular part, part-set or a pallet of batch items. On completion of this task, the tool kit is either returned to its origin, or left on the machine,if it can be accommodated in the PTS. It is more usual to return the kit to the cell STS where it can either be retained, dismantled and the constituent tools used in other kits, if so planned, or simply stored, *figures 11.9 and 11.10*. The limitation of this strategy is that the number of tools constituting a kit is limited to the capacity of the primary tool store. This strategy is particularly applicable to machines where the tool magazine is of a limited size, removable and transportable as is evident for example in the British Aerospace Automax Facility at Preston [166]. This strategy usually finds its application in the area of low volume / high variety production.

11.4.3 Differential or Modified Tool Kitting

Differential or modified tool kits are a modification of the traditional concept of tool kit assignment, such that possible sharing of tools between successive batches, parts or pallets is considered. This concept usually finds its application in mid-volume / mid-variety production. Usually, in this strategy, a '*least number of tools in kit*' kit is loaded first, followed successively by other kits with a high *similarity* or *least difference* of common tools, *figures 11.9 and 11.10*. This minimises machine down time due to tool loading and unloading as is evident in the Okuma machine design concept [224] and the Werner QTC system [232]. Tools can be shared across kits thus further reducing tool inventory. The retention and the movement of tools follow the same principles of operation as that for kitting, except that control and decision criteria tend to be more complex.

11.4.4 Single Tools

The issue of single tools is more progressive in the sharing of identical tools among several batches of parts and is based on group technology principles. A chosen mix of parts, batches or pallets is delivered to the machining station in a fixed period of time, and this part mix is serviced by a rationalised tool complement. This strategy usually finds its application in high volume / mid-variety production, and is particularly suited to machines with a large PTS capacity or to unmanned machining stations. The number of tools loaded and transferred from the STS is dependent upon the capabilities and capacity of the tool handling system and the PTS. The tools are loaded subject to the machining list of the machine and not constrained by part type, part set assignment, *figures 11.9 and 11.10* . Tool changing is minimised at the expense of a large local tool inventory. This situation is common in installations working under the workpiece-oriented tool management strategy as well as for systems with manual tool flow.

The number of tools transferred may greatly influence the management of the cell. The trend towards overhead gantry systems with capacity to transfer only one tool, such as the Cincinnatti Milacron [207a] and the Yamazaki Worcester [189] installations (see chapter two), requires a look ahead strategy to incorporate a number of fixed tools in the primary tool store according to a specified capacity plan. Two sub-operating strategies for this form of tool issue are evident for running this innovative design. *Running full,* implies that tools are added to the fixed tools in the PTS and left there for as long as possible and *running empty* suggests that tools are added to the fixed tools in the PTS when required and then immediately returned to an STS. Look ahead to the next required tool is essential to avoid clashes of demand for tools in this type of system. There is a substantial tooling up period, as for the mainstream single tools concept, before production may commence, unlike in the kitting strategies where machining may commence immediately upon receipt of a kit.

11.4.5 Tool Cluster Sets

Each operation, part or part set has an associated tool set (TS). Cluster Analysis determines the optimum number of TS's in a tool cluster set (TCS). This TCS enables each machine to which it may be assigned to manufacture any operation, part or part set contained in the TCS envelope. The tool issue is two-fold. Firstly, assuming a TCS is present on a machine, then in the event of worn or broken tools or tools required but not present on the machine, the tool strategy will assess the other constituent tools of the TCS for those approaching their tool life limit and transport these back to the cell STS and consequently only pick up enough replacements. Secondly, the issue of tools is based on the issue of TCS's, *figure 11.11* . For maximum efficiency once a tool set is loaded into a PTS it should be utilised for some time. Maximising this time will minimise the number of TCS changes required, thus resulting in higher utilisations. Since the system is based on TCS's it is important that the PTS capacity is sufficient to accommodate the largest of the TCS's, and that the transfer system is geared up for the transportation of TCS's. Another important feature of such systems, not unlike the operating principle of the differential kit, is the commonality between TCS's during a TCS change from one TCS to another. This commonality permits uninterrupted machining with the common tools. This strategy is very much in evidence in all the Makino installations [219].

11.4.6 A Resident Kit

This tool issue strategy functions along the same lines as the tool kit concept but with the flavour of a tool-oriented strategy. The basic principle of operation is that a kit on the machine is continuously replenished with a new but identical kit upto the end of a predetermined production frame or work list. This strategy has been found operating at one of the collaborating companies' sites. The difference between this strategy and the tool cluster strategy is in the definition of tool-part families.

11.4.7 Functional Tool Number (FTN) Issue

The FTN issue is similar in principle to the tool cluster set issue in that a cluster of tools is assigned to a machine. It differs in that the strategy is essentially workpiece-oriented such that the tool groups are not only specified for respective part families but also across all family assignment to a particular machine upto the specified capacity of the PTS. The FTN or tool type concept thus in the first instance, assigns unique tool types (FTNS) to the machine. Some spare PTS capacity must be left on the machine for tool exchange and sister tooling. These sister tools are determined either as for the tool cluster set or as for the single tools concept. A variation of this strategy is the specification of a *tool package* which is effectively the incorporation of sister tools with the unique tool type and the assignment of this package to a specified machine for a specified period. Unlike the resident kit concept, the package may either be updated or the tool configuration reconstituted. This strategy together with the FTN strategy provides for low level control and are essentially found in manual tooling systems of category A definition. In the worst case, the FTN concept may arbitrarily assign all tool types to a given machine, thus requiring machines with large PTS capacity and creating unnecesary duplication of tools on several machines. This strategy was found operating at one of the collaborating companies sites.

11.5 Selection of a Tool Issue Strategy

In conclusion, the selection of an appropriate tool issue strategy is dependent upon a number of parameters, *figure 11.12*. The interaction and specification of these parameters will suggest a suitable tool issue strategy from the options described above. The selection of machine, primary tool store, PTS, and tool store capacity is a primary factor in determining the method of tool issue. The part mix, complexity of machining and the certainty of visits of specified parts to specified machines are secondary factors. The local part buffer, number of operations per part or part set, and operation/suboperation times would also almost certainly dictate the means of tool issue as would the tool flow network, automated or otherwise, and the means of transfer whether mutually exclusive or shared with the part flow network. Last but by no means least as an influencing factor is cost, which bears a direct relationship with all the other factors.

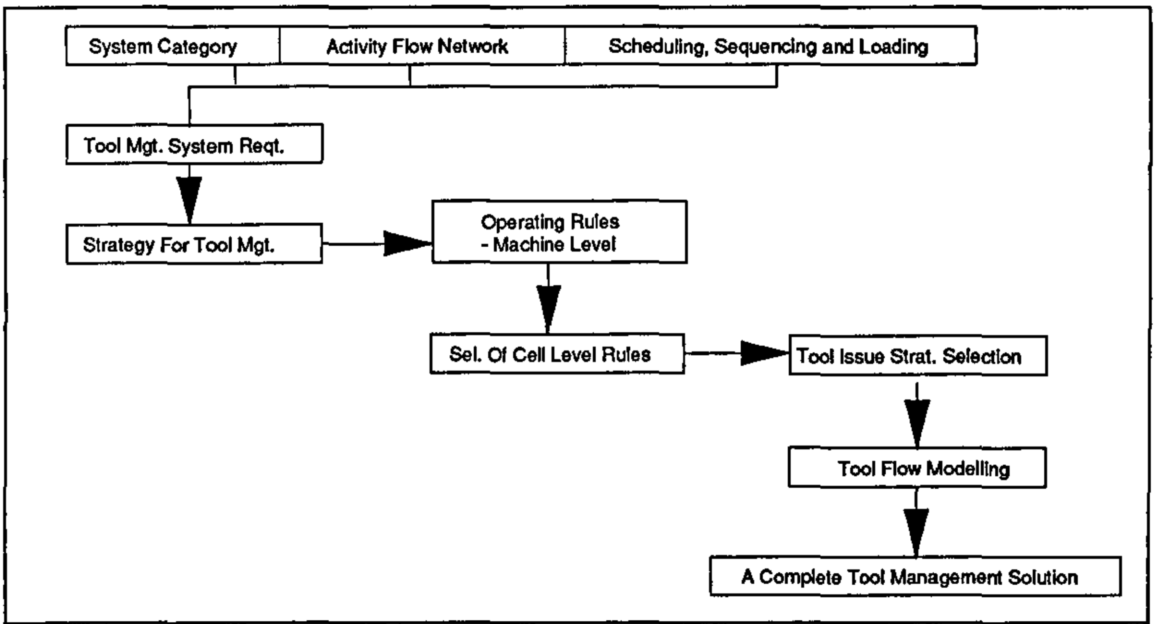

Figure 11.1	FRAMEWORK FOR TOOL MANAGEMENT	LUT - FMS Research Group

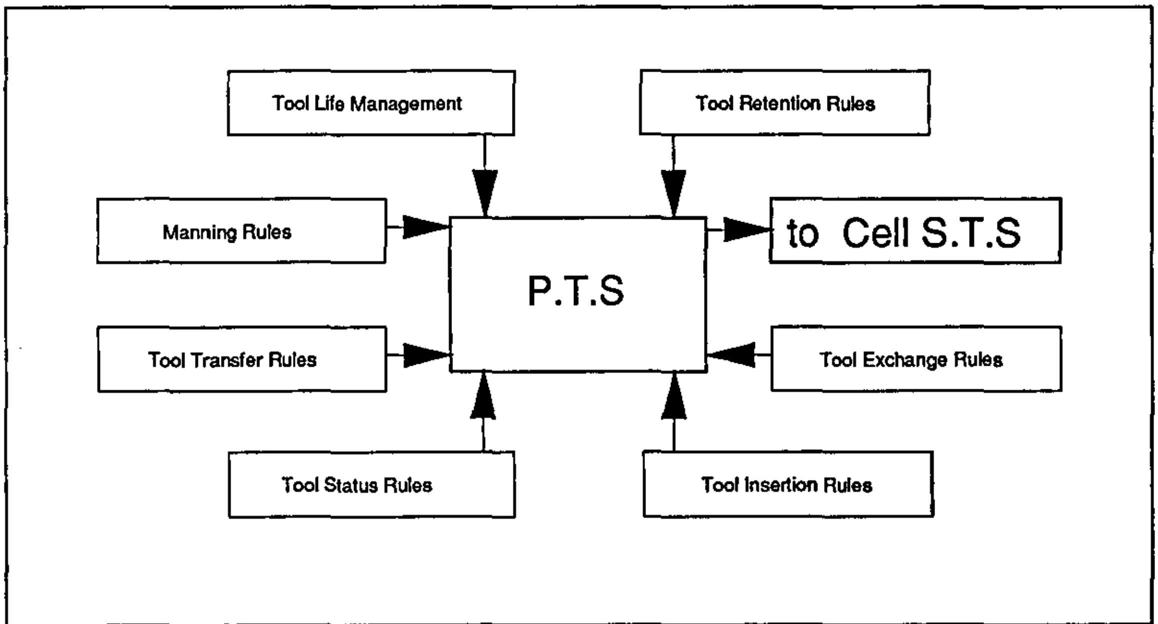

Figure 11.2	INFLUENCE OF RULES AND STRATEGIES ON MACHINE PTS	LUT - FMS Research Group

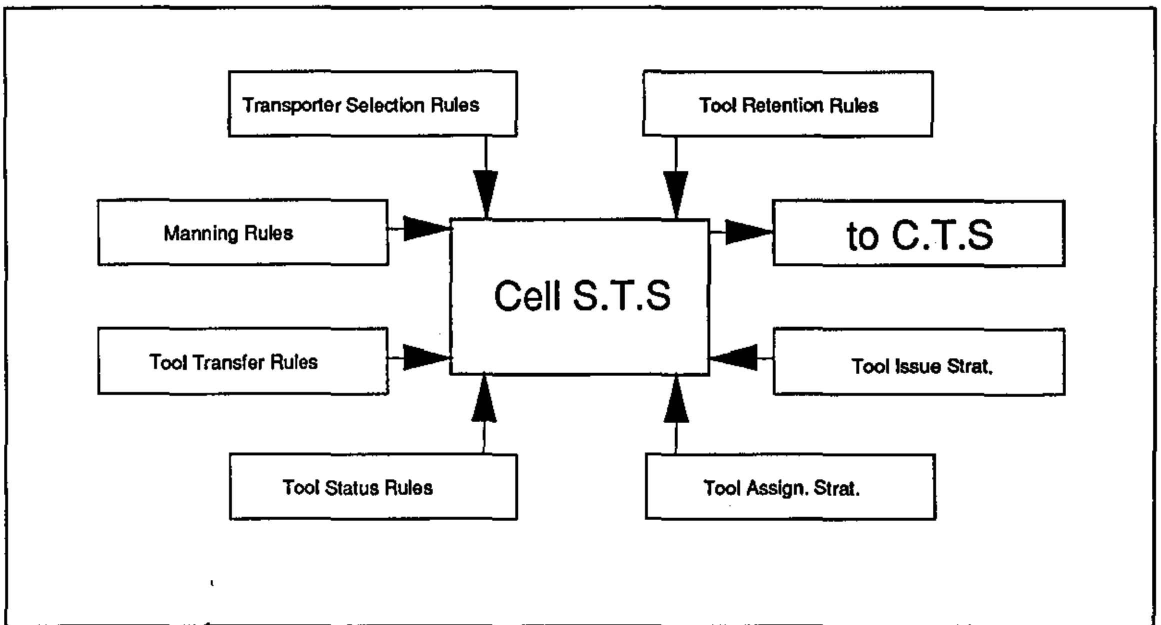

Figure 11.3	INFLUENCE OF RULES AND STRATEGIES ON FMC-FMS STS	LUT - FMS Research Group

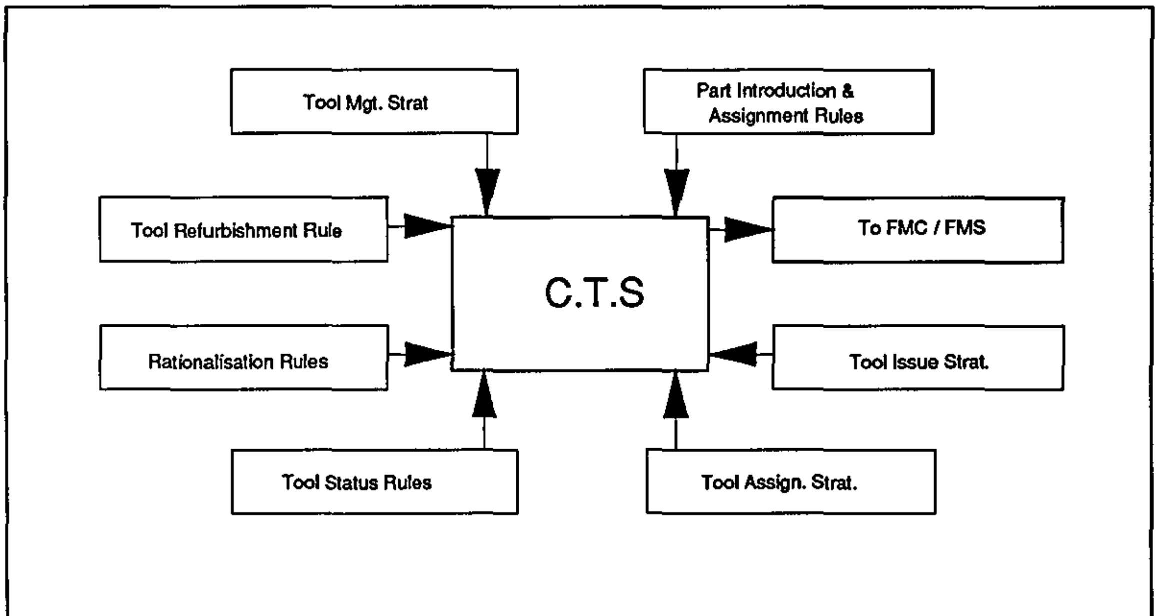

Figure 11.4	INFLUENCE OF RULES AND STRATEGIES ON THE CTS	LUT - FMS Research Group

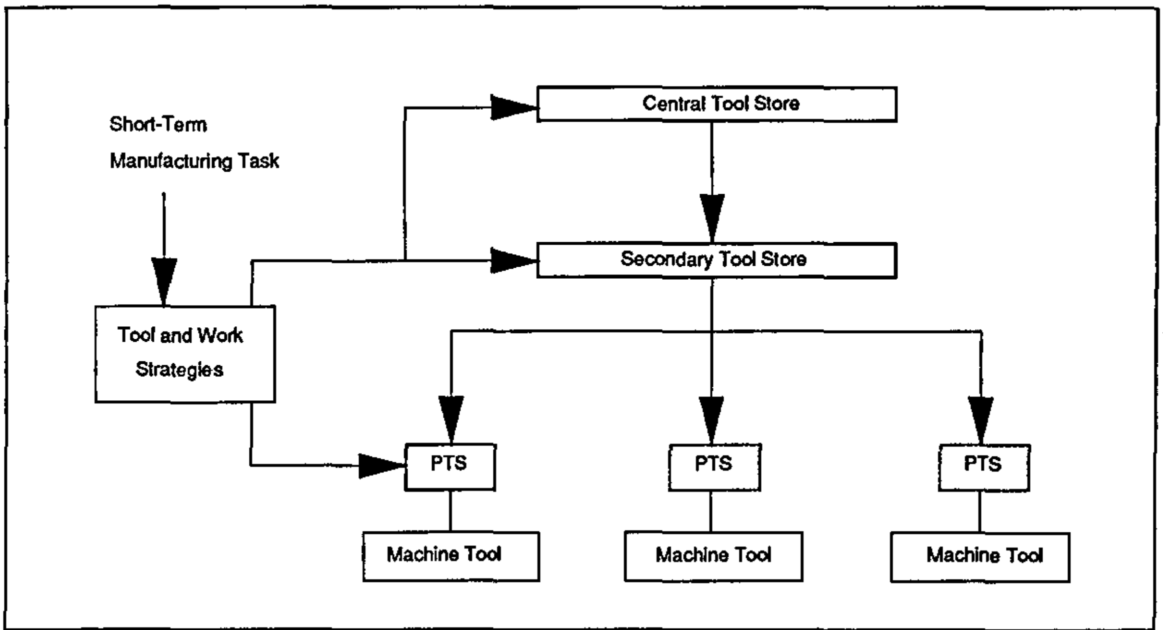

Figure 11.5

SYSTEM STRATEGIES AND RULES
- TOOL STORE HIERARCHY

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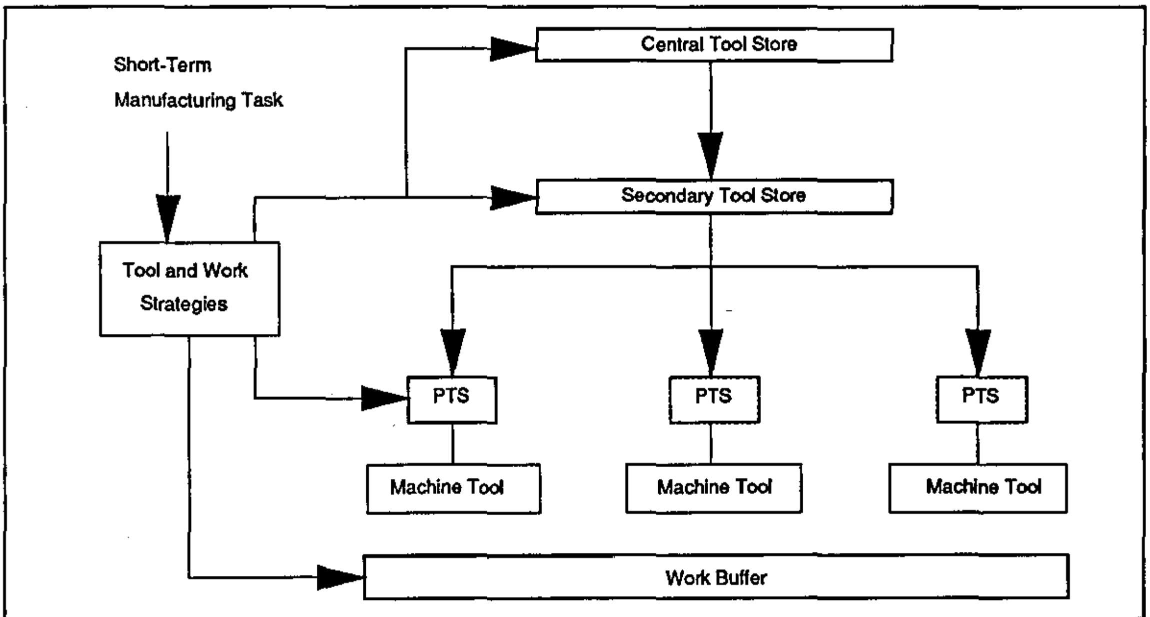

Figure 11.6

SYSTEM STRATEGIES AND RULES
- DUAL FLOW

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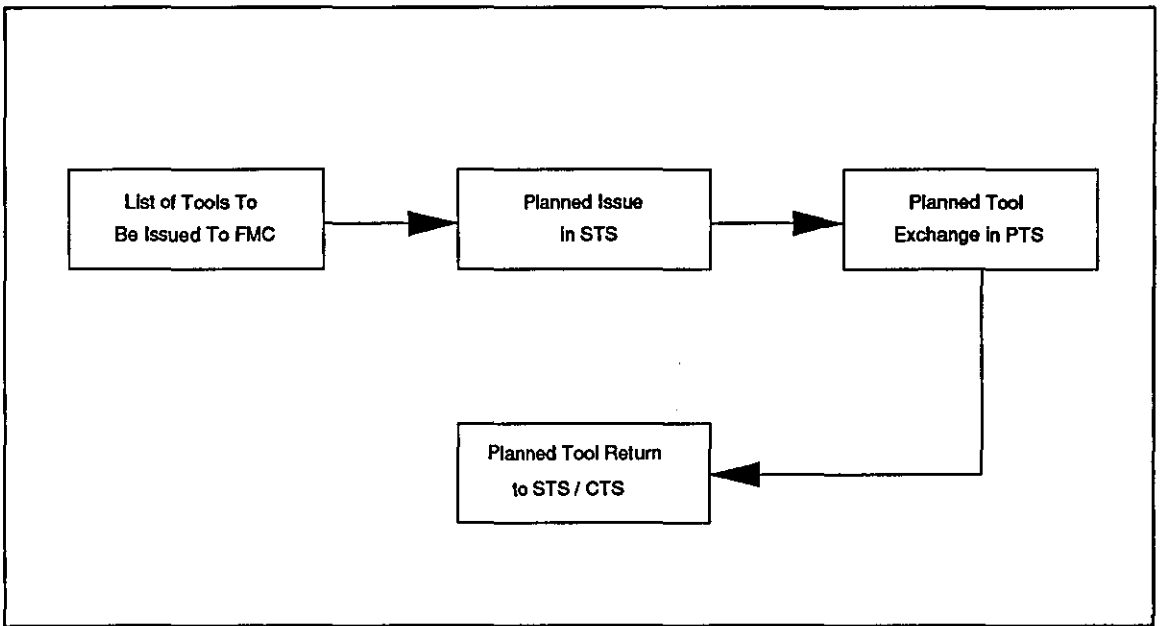


Figure 11.7	OVERVIEW OF TOOL ASSIGNMENT	LUT - FMS Research Group

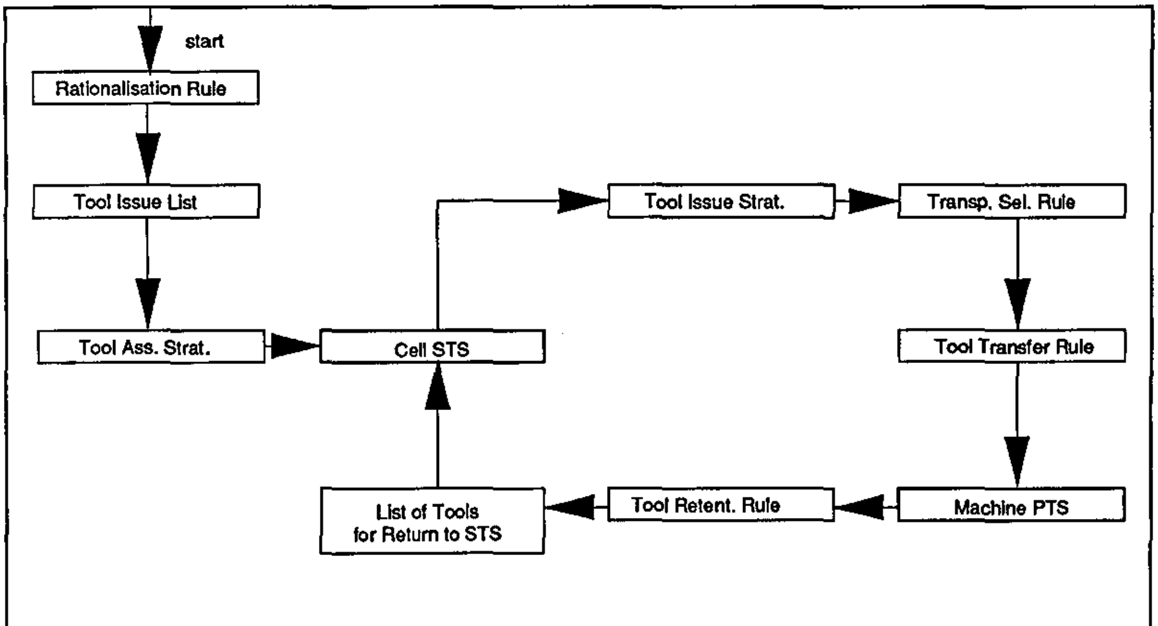


Figure 11.8	ROLE OF TOOL ASSIGNMENT STRATEGY	LUT - FMS Research Group

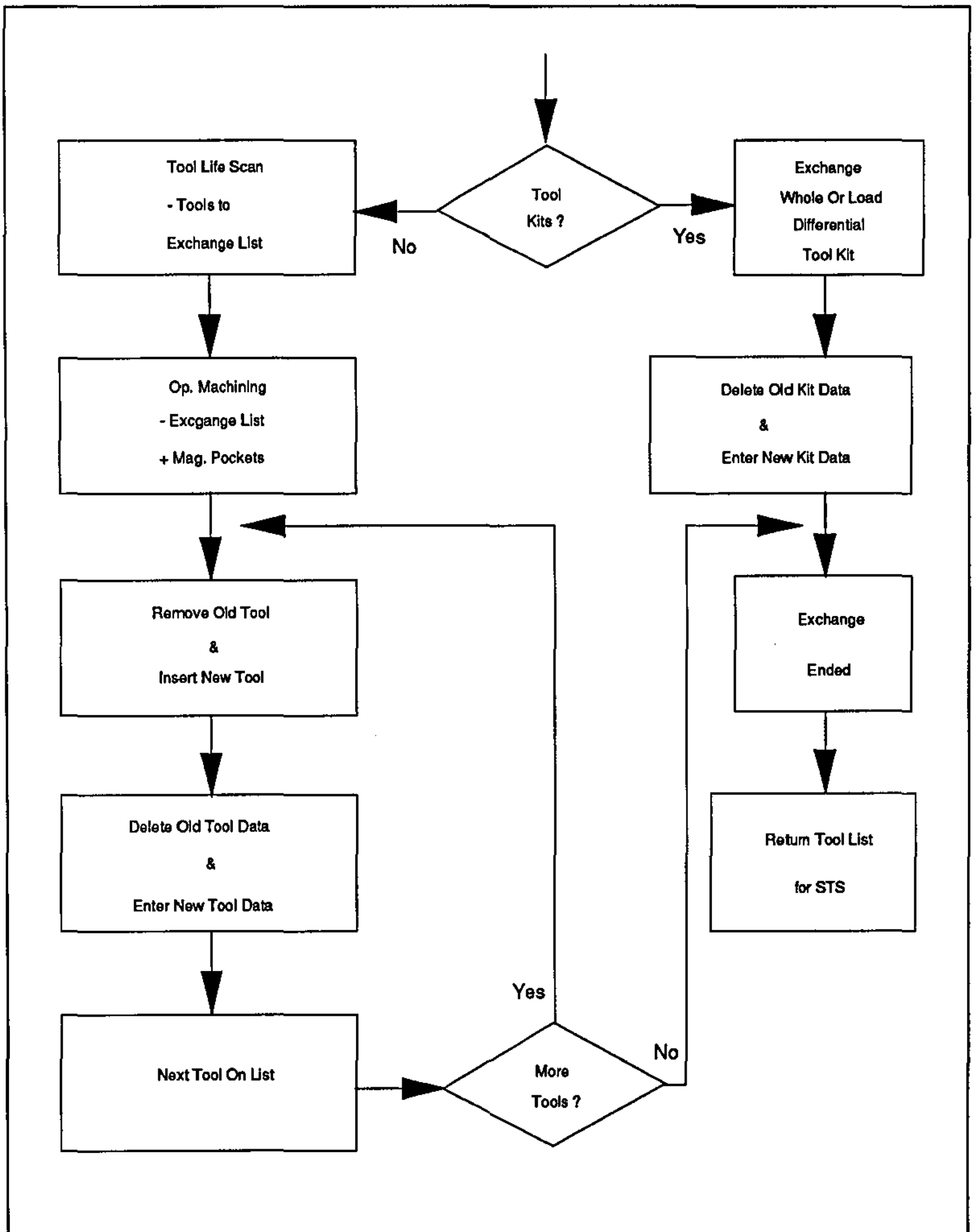


Figure 11.9	TOOL EXCHANGE IN PTS	LUT-FMS RESEARCH GROUP

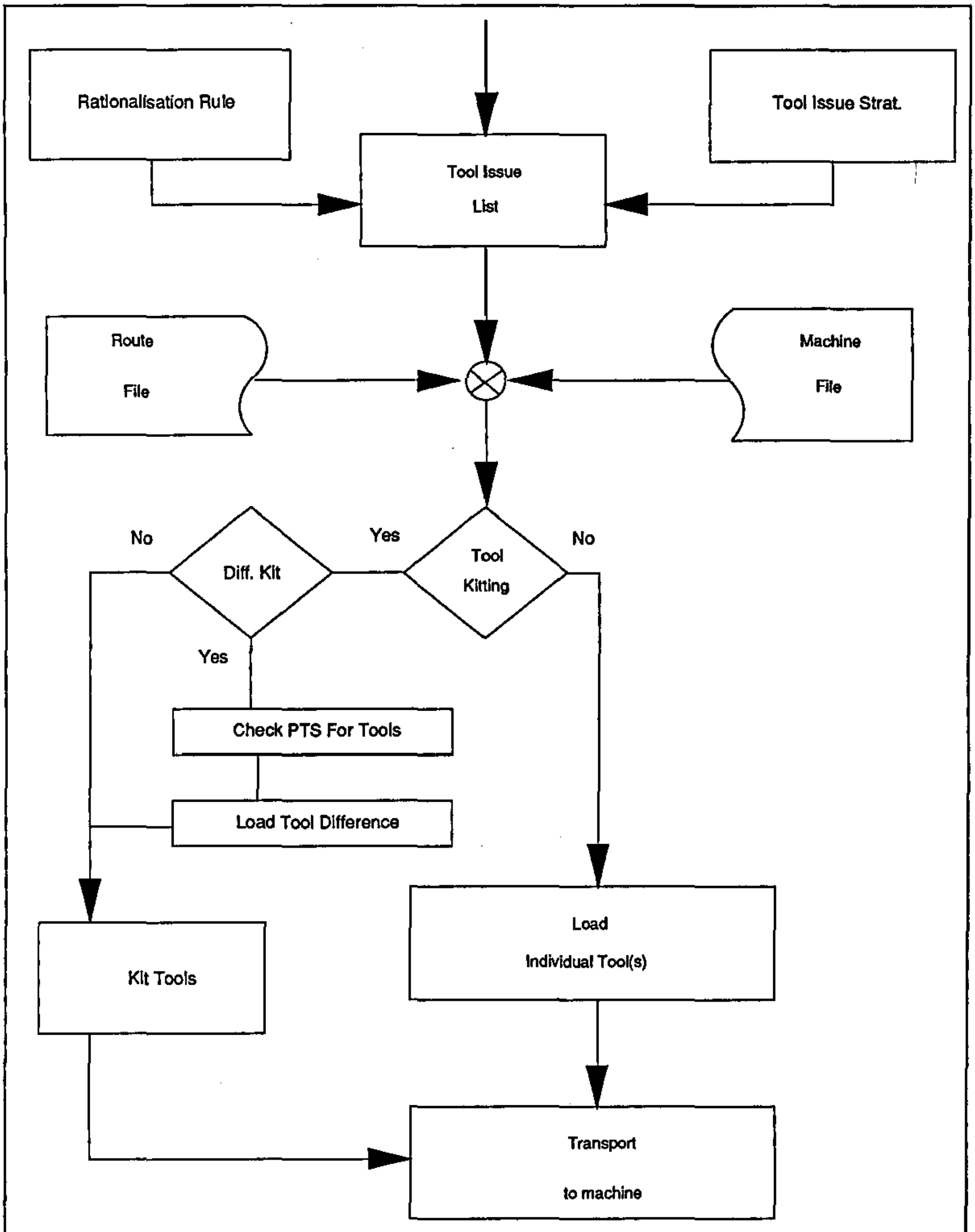


Figure 11.10	PLANNED ISSUE IN STS	LUT-FMS RESEARCH GROUP

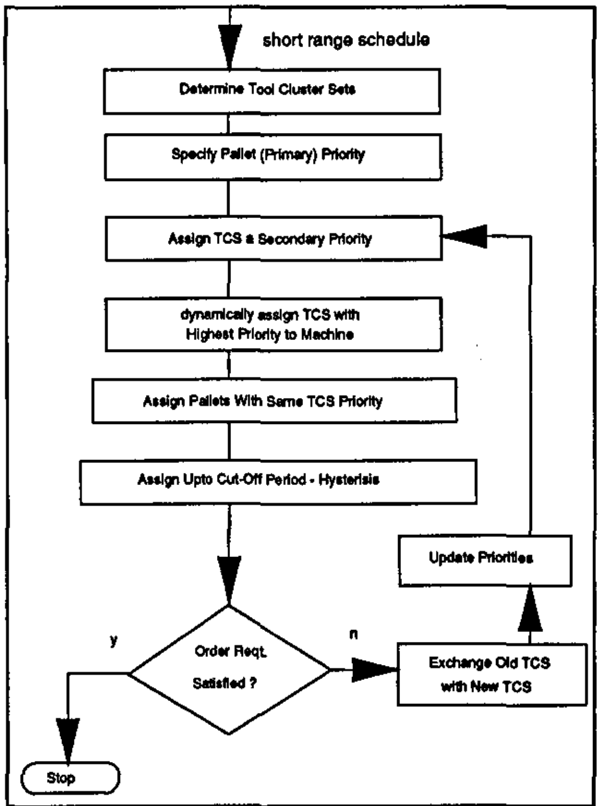


Figure 11.11	ISSUE OF TOOL CLUSTER SETS	LUT-FMS RESEARCH GROUP

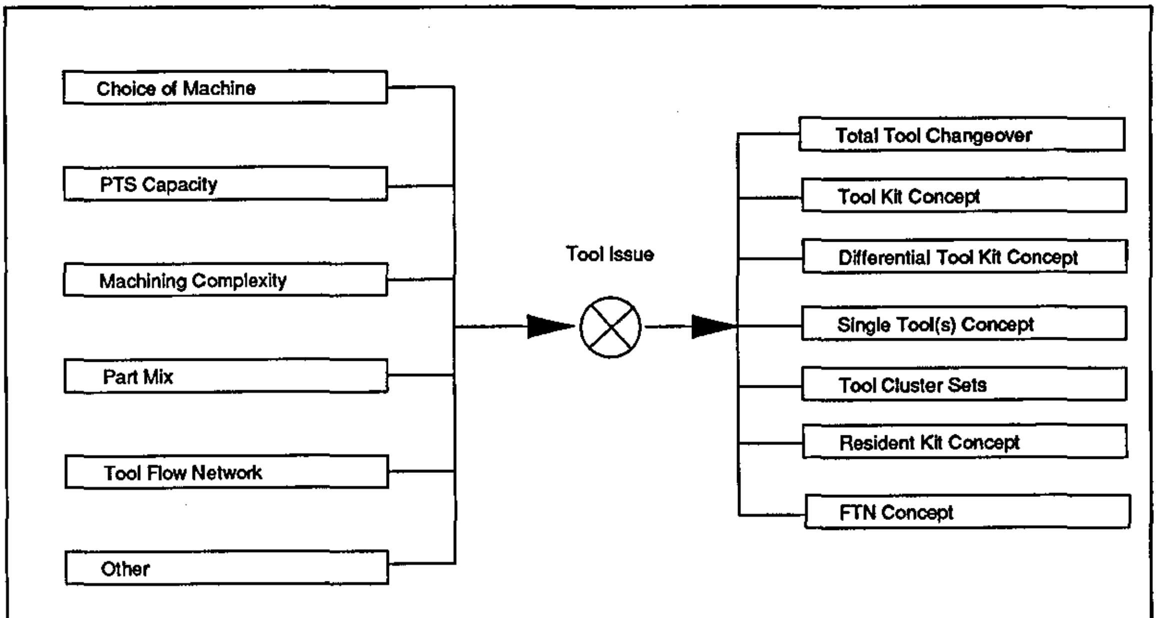


Figure 11.12	INFLUENCES ON TOOL ISSUE	LUT - FMS Research Group

Chapter 12:
CELL LEVEL OPERATING RULES

12.1 Introduction

The reader is introduced in this chapter to the general rules necesary for the provision, supply, transfer, exchange, retention and return of tools within a flexible machining cell. The rules are described with a bias towards the algorithms implemented in the tool flow modelling presented in chapters sixteen and seventeen. The rules adequately represent the functioning and control of a cell tool flow network as described for the network configurations set out in chapter six and seven. The rules provide the experimental base for the evaluation of the selected tool management (see chapter ten) and tool issue strategies described in chapter eleven.

12.2 Central Tool Store Support

Central Tool Store (CTS) support, is not one of those features that interacts directly with the individual machines in the installation, but deals primarily with those activities involved in preparing the tools for the production schedule in a timely fashion. This would imply a tool inventory control system, skilled labour to prepare the tools, and the necessary equipment for gauging and inspection. Some type of automated system for delivery of tool components may be necessary depending on the volume of tools handled. The role of the CTS within a tool management system has been described in chapter six. Attention is focused here on the multi-cell or FMS decision structure in general, and the decision structure within the PTS, in particular.

The decision structure employed in the modelling for the three main building blocks of a highly automated multicell installation, viz. the CTS, the STS and the PTS, is illustrated in *figure 12.1* . Three decision rules are necessary for CTS operation. The CTS organisation rule, *figure 12.2* , is the all embracing decision-making process which directly interacts with the other two rules and is mainly concerned with tool return, tool assessment, tool storage, retrieval and refurbishment. The other two rules termed 'planned issue in CTS' and 'unplanned issue to STS', are primarily concerned with tool assignments to the FMC/FMS. These three rules are primarily intended for cells operating in cascade but with obvious implications for those cells operating in series.

12.2.1 Central Tool Store - Refurbishment Rules

Used tools coming from the FMS/FMC into the CTS have their condition assessed as to whether they are reusable. If the tool is reusable, the whole tool assembly, the ITN, is stored in the CTS together with its tool preset data and information. If the tool condition assessment proves that the tool is in need of refurbishment or has a tool status value of *W* (see chapter thirteen) and that the refurbishment criteria, such as the number of regrinds permissible, is satisfied then the tool is refurbished. Two refurbishment rules are available, subject to the house rules, and are usually company-specific activities. The refurbishment can either be done in-house or sub-contracted outside the installation. In either rule, a certain lead time is involved.

The use of these rules within the modelling are as follows : If the tools are refurbished in-house and provided that the lead time involved in refurbishment is less than or equal to the user specified modelling period, then the tools are refurbished, their data records updated, and after a specified time delay or refurbishment time they may re-enter the system as a *new* tool with a status value *N* (see chapter thirteen). These tools are then treated in the same manner as the reusable tools. The refurbishment time can either be specified globally for all tools or locally for particular tool types or even for individual tools. This also allows the specification of a refurbishment time for a particular tool kit. If tool refurbishment is to be sub-contracted, then with regard to the modelling, these tools are held in the CTS tool parts store and considered as *dead* tools. When a certain level of dead tooling is reached, and if this is within the user specified modelling period then these tools are removed from the CTS. If the lead time for the in-house rule is longer than the modelling period left, then these tools are also treated as dead tools. If tool condition assessment determines that the tool cannot be refurbished, then these tools are also treated as dead tools. In a practical situation, these dead tools would be dismantled and the reusable elements, such as the tool holders, would be stored in the tool parts store.

12.2.2 Central Tool Store - Tool Provisioning Rules

There are three tool lists used for generating tools for the FMC. The first two, that is the 'tool build list' and the 'required tools list' are generated from the schedule of work throughput for the next manufacturing period. These two lists are used to ensure that the required tools are available. The third list, that is the 'tool issue list', is used to load the transporter with tools to be transported to the FMC. Within the model, the tool build list is notional in the sense that it is a reference to what constitutes a particular or individual tool number (ITN) / tool identity and the information associated with this tool number.

The required tools list, *figure 12.3*, is derived from the schedule of parts and quantities for this time period, the tool management strategy and the selected tool rationalisation strategy. The required tools list is in effect the 'minimum tool requirement' for each machining list which is initially stored in the CTS, awaiting transfer to the FMC in accordance with the relevant operating rule (see chapter seventeen). In any modelling it would be necessary to generate data consistent with the activities within a CTS; these overall data requirements for a tool management system have been described in chapter six and are shown in figure 6.3. The lists in the figure form the basis for this discussion.

The 'planned issue in CTS' rule, *figure 12.4*, is the determination of tools to be transferred to a specified FMC and stored in that cell's STS. The result of using this rule is the generation of the tool issue list for the FMC. Within the model and on start-up, the tools are transferred to the respective FMC. After this transfer has been completed the model *clock* is started. This is considered as the initialisation process. The tool transfer is in accordance with the tool issue strategy and also subject to the constraints of the tool handling system. When individual tools are to be transferred to a respective FMC, the tools for the FMC present in the CTS are transported upto the available capacity of the tool transporter. If tool kits are considered, then the tools are moved to a STS according to the part type's processing requirements. In the initialisation process, the tool issue is considered slightly differently. On start-up, all tools required by the FMC are assigned to the STS of that FMC upto a specified percentage of STS capacity. This percentage is user specified and a default value of 95% has been set. A certain percentage of the STS has to remain free to remove any bottlenecks in the tool loading system, and allow for tool exchange albeit planned or unplanned.

The 'unplanned tool issue to STS' rule, *figure 12.5* , comes into effect when there is a conflicting demand for tools by several machines at the same time, or when the situation arises that the tool is on a particular machine when it is required by another, or when a particular tool is required which is already being used in another tool kit. This gives rise to the *New* tools. When a tool conflict arises and a sister tool with status *F* (see chapter thirteen) is not available in the STS, then a call is set up for duplicate or new tools to be sent from the CTS. When this situation arises a tool transporter is scheduled to pick up any worn tools, tools with status *W*, from the cell STS and transfer them back to the CTS, for tool condition assessment. The same transporter or another will then pick up any created new tools for the FMC, including a duplicate for the tool which initially set up the call, add them to the tool issue list, search for any further tools for the FMC, to minimise tool transfer time, and tranport them back to the cell STS. The movement back to the STS is as for the planned issue in CTS strategy. The new tools are then added to the cells tool inventory. On completion of the modelling, the addition of these *new tools*, with status *N*, will result in an 'actual tooling requirement' being established. The difference between this and the forementioned 'minimum tooling requirement' is mainly due to the tool flow constraints. The actual tooling requirement is required to run the tool management system effectively and efficiently with the minimum of delays. This operating rule has been validated against a single cell case study.

12.3 Cell Tool Transfer and Retention Rules

The cell tool transfer and tool retention rules constitute the cell decision-making framework. The tool flow within an FMC has been described in chapter six. Attention is centred, in this section, on the cell level decision structure within the modelling. The two decision (building) blocks at the cell level are the cell STS and the machine PTS. The following discussion is centred around the workpiece-oriented tool management systems. A discussion of transfer and control rules for a tool-oriented system are discussed in chapter fifteen.

Three operating rules are used in the STS and the PTS respectively. The 'planned issue in STS' rule is very similar in principle to the 'planned issue in CTS' rule. The tool issue list specifies the required tools for the FMC in the manufacturing period under consideration. These tools are then transferred to the relevant PTS according to the production schedule and the 'next step' scheduler, chapter nine. The tool issue strategy determines the number of tools transferred and the method of facilitating this transfer. These tools must be accommodated in the machines PTS. Tool kit creation is considered to occur for particular part types in the cell STS. When a tool kit is returned to the STS the tool kit is split up into single tools, which may be used in other tool kits, in accordance with the specified tool rationalisation rule.

The movement of single tools can take place at any point in the work list. A call for tools from the STS is flagged when the required tool is not available in the PTS. In addition to the required tool, any other tools which may be further required to satisfy the machines machining list, are also transferred. The limiting factors are: that the tool magazine is fixed to the machine and that the number of tools transferred does not exceed the capacity of the transporter and the number of available tool slots in the PTS. On completion of the tool delivery to the PTS, the tool transporter may need to pick up, from the PTS, tools which are no longer required or tools which are deemed to be worn. This 'planned tool exchange in PTS' rule is very much machine dependent and strongly influenced by the tool issue strategy. If the PTS is movable, then the exchange of tools in the PTS is as for tool kits, whereas if the PTS is fixed, then the exchange is as for single tools.

If the PTS is movable and tool kits are employed then all the tools in the PTS are exchanged for the new tools in the new tool kit and the old tools are added to the 'return-tools list' for the STS. The old data is deleted from the machine record and the new kit data is entered. Where the PTS is fixed, the old kit simply replaces the kit on the machine which becomes a candidate for removal. The decision making is slightly more complex in the case of single tool transfer as a tool life scan of all tools in the PTS is performed. Those tools which are candidates for removal are added to a 'tools to exchange list'. This exchange list is cross referenced with the machine record which contains the locations of the tools in the list. The old tools are removed, their data deleted and replaced with the new tools and their data. This process is repeated for all possible tools which can be transferred back to the STS, subject to the handling capacity of the tooling system. These tools are then added to the 'STS return tool list'.

Two rules which affect tool transfer in the reverse direction are the 'planned tool return to STS and CTS' and the 'planned tool return to CTS' rules. The former rule specifies tool transfer from the PTS to the STS and the latter specifies tool transfer from the STS to the CTS. Embedded within each of these tool return rules are the tool retention rules. The 'planned tool return to the STS from the PTS' decision framework, *figure 12.6* , uses the tool status rules discussed under tool life management . The condition of all tools in the PTS are assessed; if the tools are required, and single tool transfer / issue rules are used, then so long as the tools are not worn they may remain in the PTS with either of two status values : *R* or *H*, whereas if the tools are worn (*W*) the the tools are added to the exchange list, without regard to the previous status. These tools are registered in a worn tool file and earmarked for transfer to the STS, and subsequent transfer to the CTS, at the earliest oppurtunity. If the tool is no longer required then it adopts either of three possible status values : *F*, *P* or *W* (see chapter thirteen).

When tool kits are considered or if the PTS is movable, then all the tools achieve the status *S*. Tools with status *F*, *S*, *W* or *P* are all candidates, with varying priorities, for the exchange list and subsequently the return tool list. The *W* tools which have been added to the worn tool file for the STS are subject to the tool retention rule.

The tool retention rule for the STS uses a set of specified rules to determine which tools are candidates for removal from the STS and for subsequent transfer to the CTS. The user specifies the maximum number of tools with status *W* that can be tolerated in the STS, this figure is usually the tool transporter capacity, so that the number of journeys between the STS and the CTS is optimised. Alternatively, if the cost of a single tool is high then if its use through refurbishment is possible the STS worn tool limit may be set as low as one to enable the tool to be refurbished as quickly as possible and return in circulation as rapidly as possible. When this limit of worn tools is reached, a list of tools to return to CTS, *figure 12.7*, is constructed. This list is the basis of the 'planned tool return to CTS' rule. The functioning of this rule overlaps with the CTS organisation rules detailed in section 12.7, and completes the loop of the tool flow network.

12.4 Transporter Rules

Two separate handling systems are considered in the modelling, one for parts and one for tools. The handling systems are assumed to be either completely independent of each other, i.e *mutually exclusive*, or able to transport tools and parts on the same transporter at the same time, i.e *single function*. For the purposes of this discussion mutually exclusive flow networks are assumed.

Several transporters may use either network. Each tool transporter can either carry a tool kit or a number of single tools. Each part transporter can carry one pallet of one part type at a time. The transporter flow is unidirectional with no delays or blockages. The emphasis is on the tool transportation network and its performance measures and functions. The tool transporter definition encompasses a wide variety of handling systems ranging from man through gantries for single and multiple tool transfer, agvs, etc. to robot. The important consideration is the tool handling capacity, number of transporters and travel time between stores. The tranportation works on an assignment algorithm. A transporter is either *idle* (and hence empty), *assigned* (and empty) or *loaded*. As a transporter becomes idle, it either receives its next assignment or waits until another movement is needed. Idle transporters notionally remain in the inter- machine/store queue following where they were unloaded, unless they are 'pushed' along by assigned or loaded transporters. Transporters always complete their assignment, there is no on-going reassignment. The tool transporter movement is initiated by a machine requiring a tool and hence flagging a transporter request. The transporter cycle is from origin (where it picks up the tools e.g the STS) to destination (where the request was initiated from e.g the PTS) and back to origin without servicing any other machining station.

Many scheduling rules have been identified relating to the control and selection of independent addressable type materials handling vehicles, such as the automatic guided vehicles (AGVs). Two classes of rules have evolved [105], the 'machining station initiated' rule - where one transporter has to be selected to perform a particular task, when more than one tool transporter is available, and the 'transporter initiated' rules - where the choice of which workstation to service, when more than one is waiting for service as a transporter becomes idle.

The two rules have been implemented as the 'transporter assignment' rule (the machining station initiated rule) and as the 'transporter request priority' rule (the transporter initiated rule). Three control algorithms are available for transporter assignment. These are the 'least used transporter', the 'first available transporter' and the 'highest priority transporter' rules. These control algorithms can be used to define the assignment of many transport devices including man. The transporter request priority is determined by the activity and machine selection phase of the 'next step' scheduler.

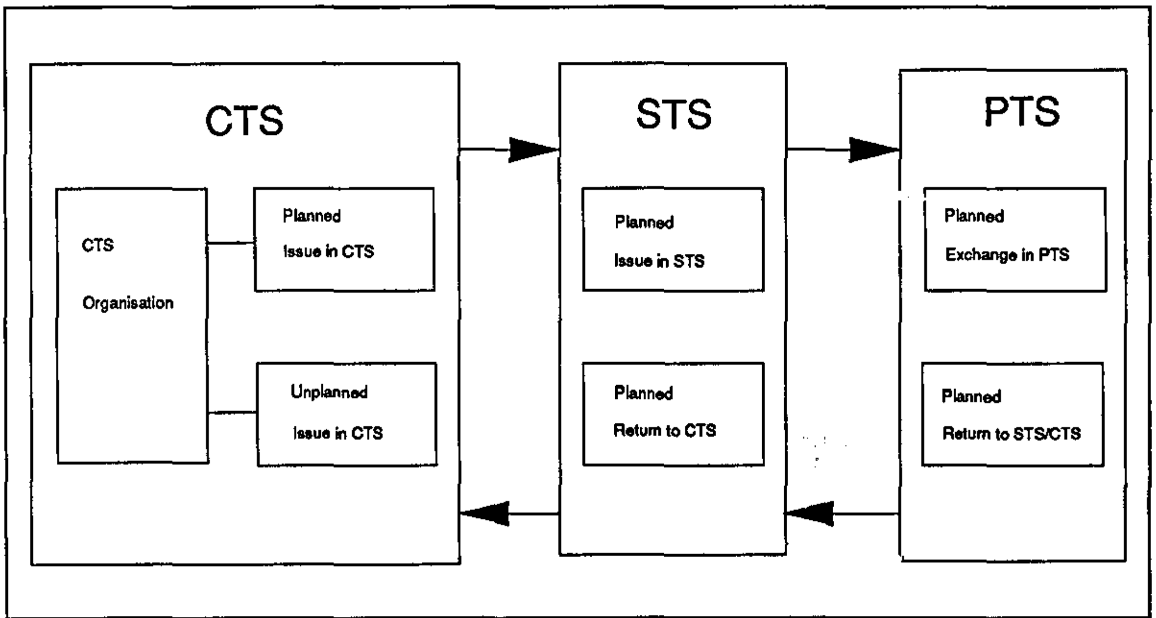


Figure 12.1 | MULTICELL DECISION STRUCTURE | LUT - FMS Research Group

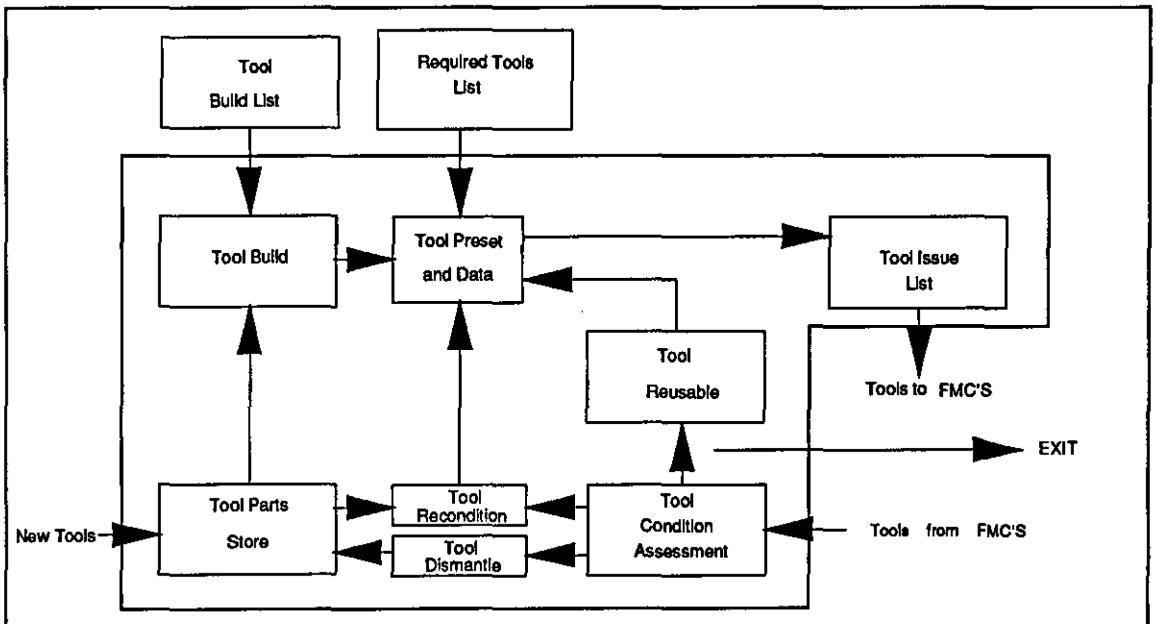


Figure 12.2 | CTS ORGANISATION | LUT - FMS Research Group

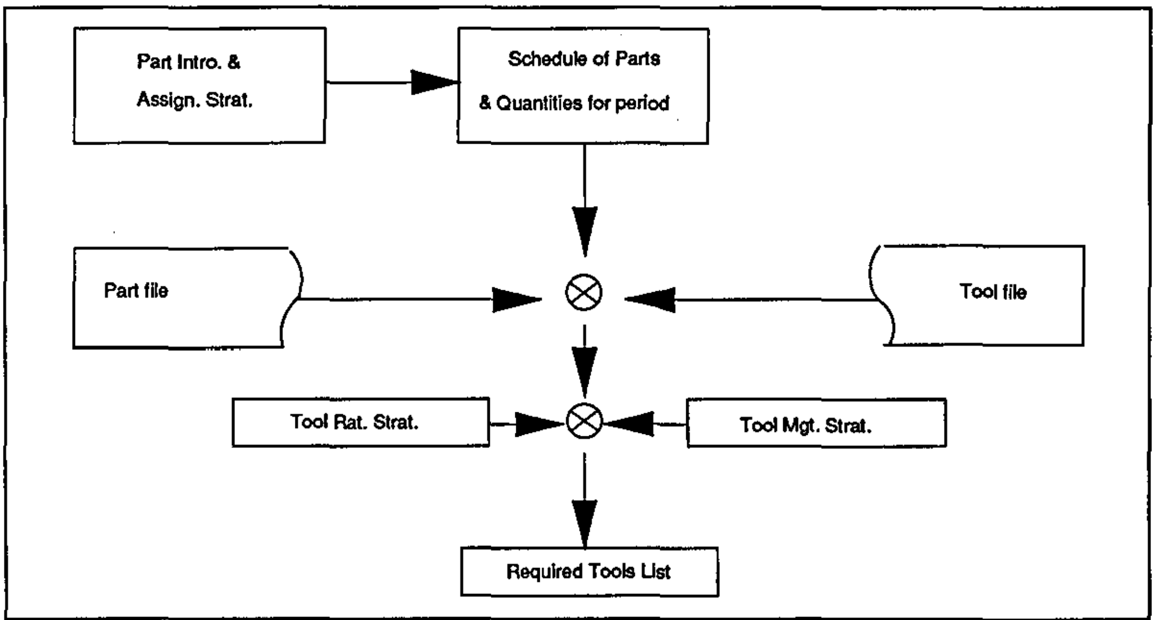


Figure 12.3	GENERATION OF THE REQUIRED TOOLS LIST	LUT - FMS Research Group

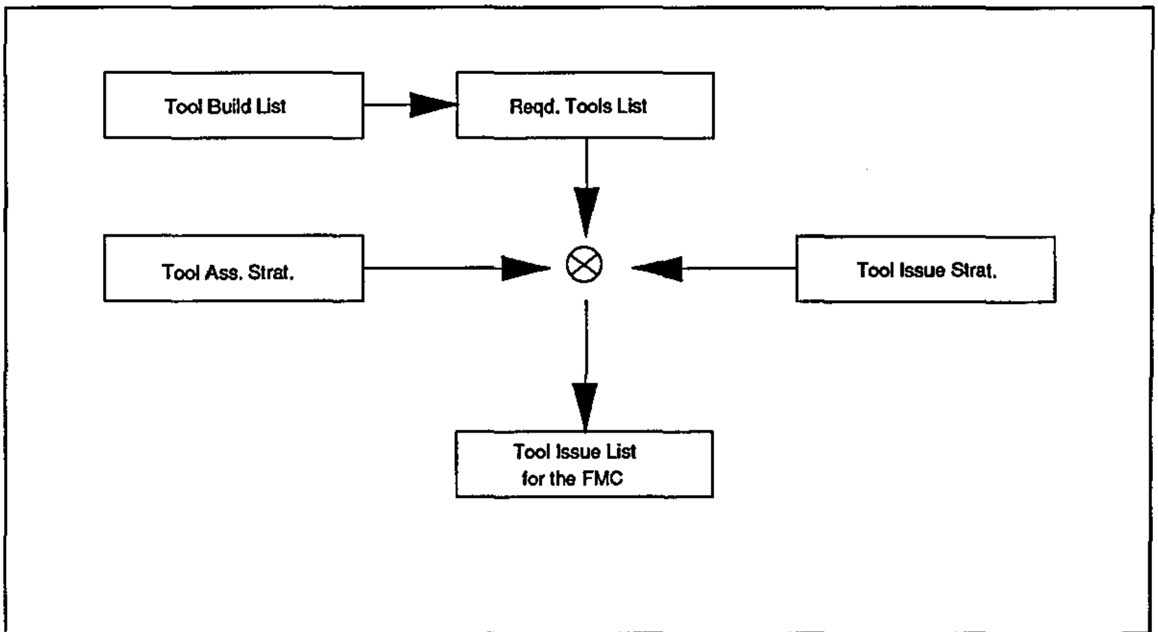


Figure 12.4	PLANNED ISSUE IN CTS	LUT - FMS Research Group

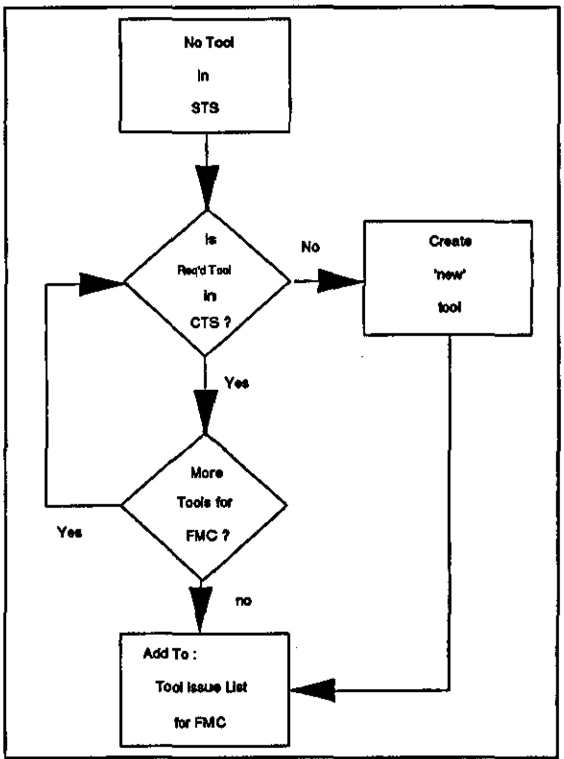


Figure 12.5 | UNPLANNED TOOL ISSUE TO STS | LUT-FMS RESEARCH GROUP

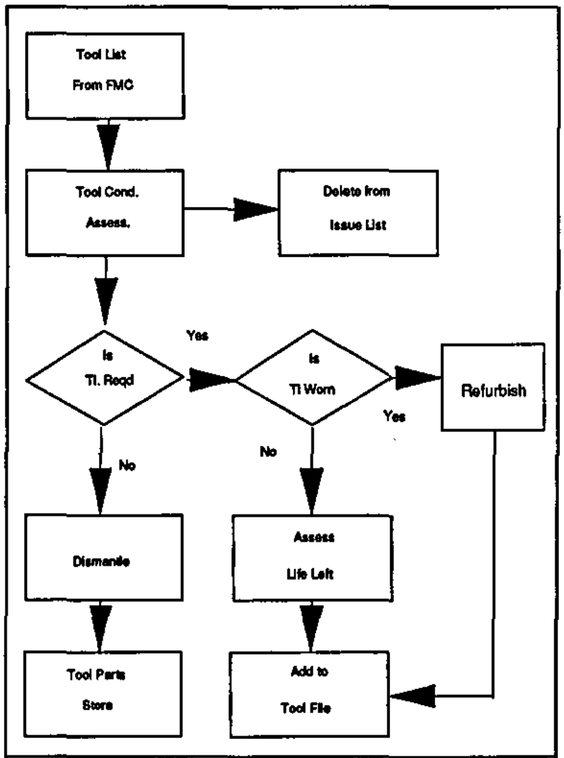


Figure 12.7 | PLANNED TOOL RETURN TO CTS | LUT-FMS RESEARCH GROUP

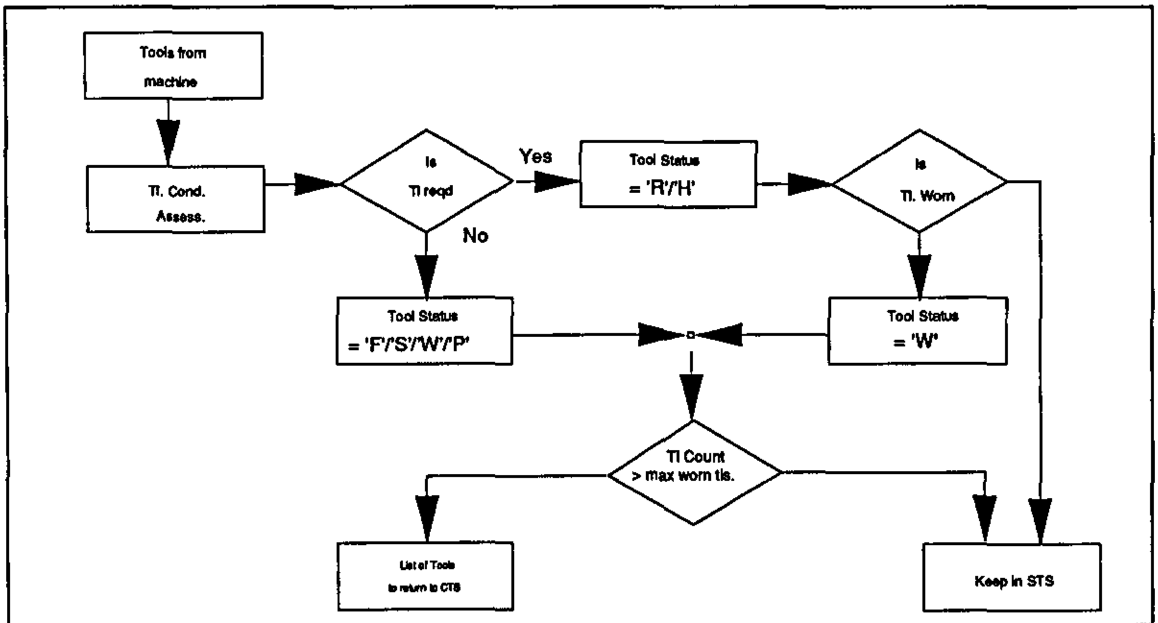


Figure 12.6 | PLANNED TOOL RETURN TO STS AND CTS | LUT - FMS Research Group

Chapter 13:
MACHINE LEVEL OPERATING RULES

13.1 Introduction

For a tool management system to operate effectively, certain decisions are required as to which tools are candidates for removal from the machine-based primary tool store (PTS) or the cell secondary tool store (STS). The tools to be moved, removed, replaced or to act as duplicates need to be identified and exchanged correctly in order that the tool handling system can function smoothly. The reader is introduced in this chapter to sets of rules for determining tool status and change of tool status, tool arrangement and its effects, and tool insertion, all in relation to the tool management and tool issue strategies discussed in chapters ten and eleven and the cell rules discussed in the previous chapter. The introduction of this structure anticipates the design and operation of the modelling package.

13.2 Tool Status Rules

These decisions on tool status are usually made by a cell supervisory computer, which controls transporter requests and priorities. This centralised software needs to interact with the machine tool controller, so that tools may be changed locally at the machine level, and also the secondary tool store computer, so that the locations of the tools in the tool store are known. This type of management system operates on the assumption that there is either an infinite supply of tooling to the STS or that the tooling requirements for the manufacturing period are known. This is often not the case and a study of the problem revealed that there is a lack of rules to control tool flow at this level, although attempts have been made more recently to rectify this situation as in the Werner and Kolb QTC system [232] where the the hardware and software is geared up for worn or undesired tool ejection.

The problem often found within the tool stores itself, is the identification of worn or duplicate tools. Tools may be selected in unplanned situations from the available tooling inventory without regard to the status of that tool in relation to the tooling requirements generated by a work list. The rules seek to set up a framework within which to service the production schedule in an orderly and planned manner by setting tool status values to force the tools to behave in a particular manner. These tool status values are at the heart of the decision process in the models and their use may be emulated in practical tool requirement planning systems.

13.2.1 Decision Status Values

Tools which are selected as part of the *minimum tooling requirement* (see chapter fifteen), to service the machining lists in a specified period and subject to the tool rationalisation rule and tool management strategy, are assigned an initial status value 'R'. This status value implies that the tool is *Reserved* or assigned to a particular operation, or operation grouping or a sub operation or number of sub operations. This type of status value is considered to be a *Decision Status* value. One of three decision status values may follow this initialisation :.

(a) 'W' - *Worn* : If the tool is worn i.e the tool has reached the specified tool life limit (maximum permissible percentage tool life) or if the tool has exhausted its specified tool life units or has exhausted its percentage of available tool life (see chapter fourteen). This decision status value is used by the other operating rules especially the tool retention and refurbishment rules.

(b) 'F' - *Free* : If the tool has completed its assigned task(s) and is not worn. This tool is considered available for use on other machines or may be used as a duplicate tool, if a tool conflict arises and there is a requirement for a new tool. The use of this tool on other machines is, of course, dependent upon tool holder and tool offset compatibility.

(c) 'R' - *Reserved* : If the tool cannot be classed as a 'W' or a 'F', or if the tool is still assigned to the initial set of tasks.

Tools which are introduced into the cell in an unplanned situation are given an initial decision status 'N' - *New*, instead of 'R'. These tools are so identified within the model, because they make up the difference between the minimum and the actual tooling requirements. These tools referenced as 'N' are those that are added to the model to minimise delays due to the tools not being readily available, and are not part of the initial tool complements. As with the other tools of status 'R', these tools may then be assigned decision status values 'W' or 'F'. These new tools are given an initial undecremented (new) tool life (see tool life parameters in chapter fourteen).

13.2.2 Limiting Status Values

The decision status values exist to effect an activity, such as refurbishment, on the tool and are concerned primarily with the selection and assignment to activities. These values are dependent upon the other operating variables, such as the tool rationalisation rule; whether the tool is a standard or a special tool; and the machine assigned to perform the tasks or activity. Furthermore, a *Limiting Status* value may be introduced for a machine which will also affect the status value of the tool. Two limiting status values for the machine PTS, based on the tool management strategy selected (see chapter ten) are :

(a) 'F' - *Fixed* : If the machine is to have a fixed tool complement, replenished as required. This is mainly applicable to systems operating under a tool-oriented tool management strategy.

(b) 'V' - *Variable* : If the machine is to have a variable tool complement, allowing free movement of cutters. This is mainly applicable to systems operating under a workpiece-oriented tool management strategy.

13.2.3 Transit Status Values

The limiting status values for the PTS will determine the tools to be moved or removed. This removal or placement of tools, subject to the tool retention rules, uses three status values. These values are secondary to the decision status values and are used to decide what, if any, tools are to be moved or removed. They do not effect any direct action on the tools in contrast to the decision status values. These secondary values, termed the *Transit Status* values are given below.

(a) 'H' - *Hold* locally : This status is assigned to a tool if the tool has decision status 'R' or 'F' and the machine is of limiting status value, 'F'. This status effectively prevents the removal of tools which are no longer required in the PTS. This permits, for example, a standard tool set to be left on the machine across a number of manufacturing periods. If this is the case, then if the tools are of status 'F' they revert to status 'R', implying they can be used again in a new time period.

(b) 'P' - *Preferentially hold* locally : This status is assigned if the tools' decision status is 'R' or 'F', and the machines PTS limiting status is 'V'. This transit status is used if it is not necessary to hold a tool set on the machine, but it would be preferred if the tools were kept on the machine to save on transfer time. This status differs from 'H', in that tools earmarked with transit status 'P', may be removed from the PTS to make place for other tools or to be used on another machine in the FMC; whereas, tools marked with status 'H' have to be held at the machine and cannot be moved, at least not in this manufacturing period.

(c) 'S' - *Send back* to origin : Tools are assigned this transit status value if the decision status value is 'W' and the machine limiting status is either 'F' or 'V', or in the case where tool kits are used this transit status is used to force removal of the tools from the store and dispatch it back to origin (STS) at the earliest oppurtunity. This enables a whole tool kit to be removed from the PTS. This value is also employed to transfer tools from the STS back to the CTS. This transit value is also influenced by the PTS *Condition Status* values, based on the sub-category of the tooling system (see chapter five):

(i) 'F' : *Fixed* to the machine, or

(ii) 'M' : *Movable* from the machine.

If the condition status is 'M' and single tool transfer is selected then the tools are assigned the status 'S' to enable the whole PTS contents to be moved. This is similar to the tool kit condition. If the condition status value is 'F' and a modified tool kit is selected then certain kits can be forced to stay using the transit status 'H', and others could be removed using transit status 'S'. A discussion of these strategies is presented in chapter eleven.

13.2.4 Supplementary Status Values

The preceeding types of status values, decision and transit, are applied to individual tools. This allows sophisticated control over the flow of tools in the installation. The *Supplementary Status* value, unlike the preceeding values, does not affect the tool flow but is concerned with the tool management information system. The supplementary status values are :

(a) ITN [n] - *Individual Tool Number*, which uniquely identifies each tool.

(b) FTN [n] - *Functional Tool Number*, which uniquely identifies each tool type.

Thus each tool is identified for modelling and classification purposes by an ITN and an FTN.

(c) 'D' - *Duplicate* : Sister or duplicate tools for the ITN / FTN combination are further identified in the tool data files by an index to an array of identical tool numbers. This allows the management system to select a duplicate tool from the tools available in any store with decision status 'F'. The tool selected must be in the array of identical tools for the tool for which the duplicate is sought.

(d) 'Y' / 'N' - *Yes* or *No* : The supplementary status 'Y' is given to those tools which had a decision status value 'W', otherwise the initialisation status 'N' is retained. The status 'Y' implies that the tool has been refurbished and, if possible, the status 'W' is converted to decision status 'F', otherwise if refurbishment is not possible the value 'W' is retained.

The decision tree for all three types of status values is shown in *figure 13.1* .

13.3 Tool Arrangement, Tool Address Systems and the Associated Rules

Tool changing systems on machining centres involve complex tool changing mechanisms with capacities for large numbers of tools. Complexity of action normally rises with capacity in order to separate tool exchanging at the spindle from magazine search and indexing functions. The efficacy of individual types varies considerably with the randomness of demand for the tools. The discussion of these modes of operation and associated rules anticipate their inclusion in the modelling package.

13.3.1 Tool Arrangement Rules

The arrangement of tools may have a considerable effect on the total elapsed time. It is not a difficult task to attempt to optimise the tooling arrangement when there is only one set of machining tasks on one part, and the tool magazine capacity is sufficient to hold all the required tools. Several studies have been carried out to determine this optimum arrangement [93,94,309,324]. In highly automated manufacturing systems, when more than one machine and possibly a STS is involved, the complexity increases due to the presence of more than one part type, each requiring a different, if overlapping, number and set of tools and the possibility of almost random presentation of parts to the machines. Two rules for tool arrangement are evident:

(a) *Typical arrangement without duplication* : Here the tools are given individual tool numbers (ITN's) according to the utilisation sequence and placed in the magazine in that order starting from magazine position one.

(b) *Typical arrangement with maximum duplication* : Starting with the above rule, the tools are duplicated until all the magazine positions are occupied. The rule for duplication is that the tool is used more than once and that the previous tool is as far as possible. This rule is suitable for manual tooling systems.

Tool arrangement rule (a) was modified to insert the tools according to the utilisation sequence in the tool magazine starting from the first available magazine location and progressing along all the other available locations. This rule is dependent particularly upon the tool management, issue and cell tool transfer strategies.

13.3.2 Tool Address Systems and Rules

The variety of tool changers found in practice is fairly wide, but generally two types of address systems and rules are evident :

(a) *Variable address system* : This system is variable in that the tool which is returned from the spindle to the magazine is placed in the pocket in which the tool has just been removed for exchange with this tool. Tool change time will obviuosly vary from one operation to another, and between cycles, i.e from one job to the next identical one.

(b) *Fixed address system* : For this type of PTS, tools are returned to fixed positions in the magazines. Although this system appears to be simpler than the variable address type, the tool magazine has to undergo a more complex indexing cycle in order to satisfy the machining requirement. Tools required out of sequence will require multiple indexing to retain fixed locations. Tool search times are thus the critical factor.

The fixed address system is assumed unless explicitly defined as otherwise. This eliminates any possible variations in performance times and simplifies the analysis of results. Besides the variable address system requires a tool coding system to be implemented.

13.4 Exchange Modes and Rules

Various primary and secondary tool exchange mechanisms are also evident which employ the strategies discussed above [160]. The tool change modes for the primary and secondary tool stores are described below.

13.4.1 Primary Exchange Modes and Rules

(i) *Single action, dual gripper exchange arm* : In this mode, the tool in the spindle is exchanged directly with a tool from the PTS. No auxilliary arm is used and the tools are not placed in their original pockets. In all the other modes the tools are returned to their original pockets. Only one time value is required to define this type of mechanism, *figure 13.2*.

(ii) *Double action, dual gripper exchange arm with auxilliary arm*: In this mode the selected tool is taken from the PTS by the single gripper auxilliary arm to await transfer. When the current machining cycle has finished, the tool in the spindle is exchanged with the tool in the auxilliary arm by the dual gripper exchange arm. The next machining cycle may then begin. The magazine is indexed to return the tool to its original pocket, the tool is replaced and the magazine indexed again to select the next tool. Only one mechanism can function at a time. The system is specified by three time values, *figure 13.3*.

(iii) *Unrestricted Mechanism* : This is the same as mode [ii], except that more than one part of the mechanism can function at once. This would allow the PTS to index to the next tool once the tool has been loaded into the auxilliary arm, *figure 13.4*.

(iv) *Single action, single gripper exchange arm* : This is the simplest exchange in which only one tool at a time may be moved. Each tool is replaced into its original pocket before the next tool is selected, and hence only one time value is required to define the exchange, *figure 13.5*.

Rules for modes [ii], [iii] and [iv] have been implemented with mode [iv] as the default primary tool exchange mode.

13.4.2 Secondary Exchange Modes and Rules

The exchange between the secondary tool store and a tool transporter is referred to as the secondary tool exchange. The mechanism for the exchange may either be manual or purpose built. Three secondary exchange modes and associated rules are evident :

(i) *Single action, single gripper arm* : This is similar in action to primary exchange mode [iv], as only one tool may be exchanged at a time. Each of the receiving units must have an empty pocket at the exchange point. The exchange mechanism can be broken down into three time values : load, exchange and replace. This mode is restricted because the exchange mechanism may only operate when both units, i.e the transporter and the STS empty pocket, are in their correct positions. The algorithm specifying this exchange is given in *figure 13.6*.

(ii) *Unrestricted Mechanism* : This is similar in action to mode [i], but allows the STS to index at the same time as the exchange is taking place or when the tool is being (un)loaded in either unit, i.e the STS or the tool transporter, *figure 13.7*.

(iii) *Single action, double gripper exchange arm* : This is again similar to mode [i], but allows two tools to be exchanged in one action. The tools are not necessarily returned to their original pockets. This exchange can only occur when both units are in their correct positions. The action is defined by one time value, the exchange time. The algorithm is given in *figure 13.8*.

Rules for secondary exchange modes [i], [ii] and [iii] have been implemented with mode [i] as the default selection.

13.5 Tool Insertion Rule

The tool insertion rule implemented is as described for the typical arrangement without duplication tool arrangement rule. Empty pockets in the primary tool store are labelled by a zero in the model. When oversize tools are used, they are considered to occupy three pockets unless two oversize tools are placed adjacent to each other, in which case they will occupy five tool pockets. These unusable tool pockets are labelled with the negative of the individual tool number (ITN) which requires these empty pockets to be reserved. The other major use of negative numbers is in the fixed addressing system to indicate the pocket from which the tool was removed and hence in which to be replaced.

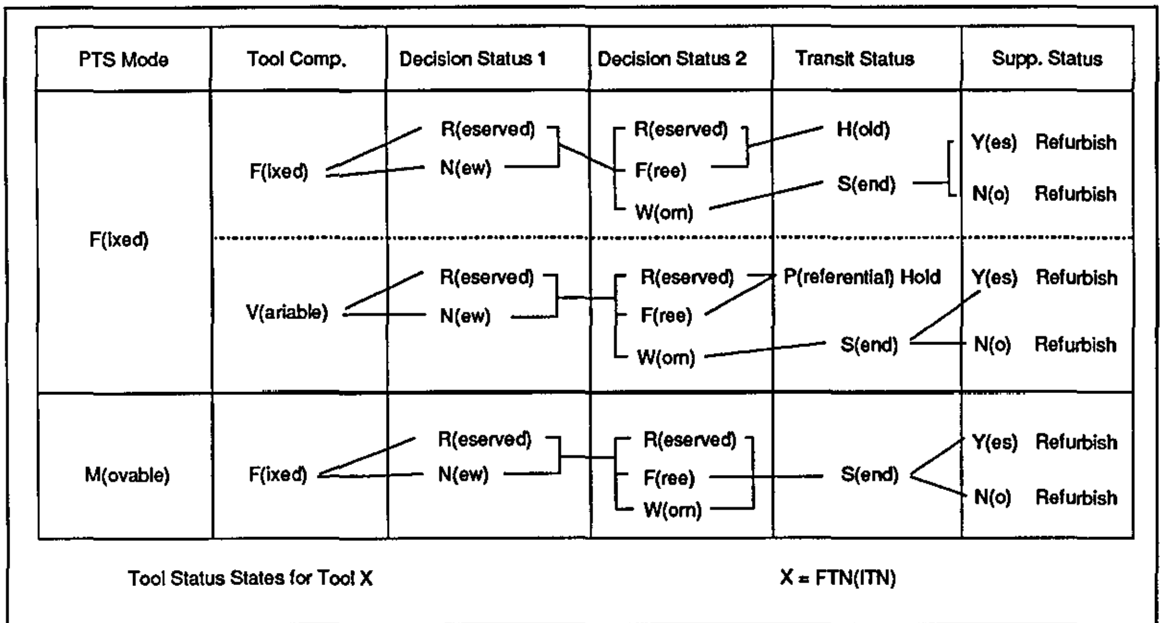


Figure 13.1	TOOL STATUS DECISION TREE	LUT - FMS Research Group

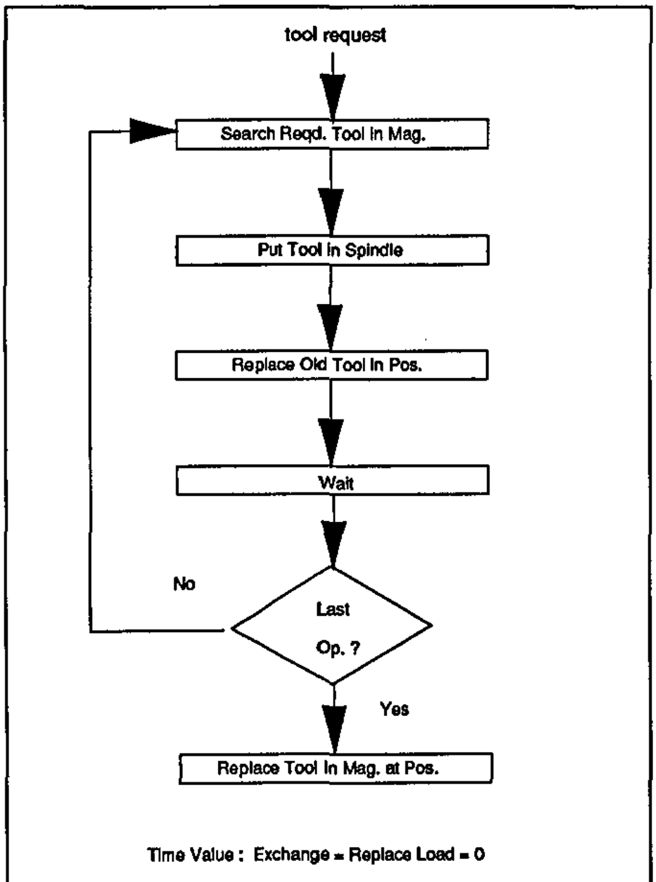


Figure 13.2	PTS EXCHANGE MECHANISM SINGLE ACTION,DUAL GRIPPER	LUT-FMS RESEARCH GROUP

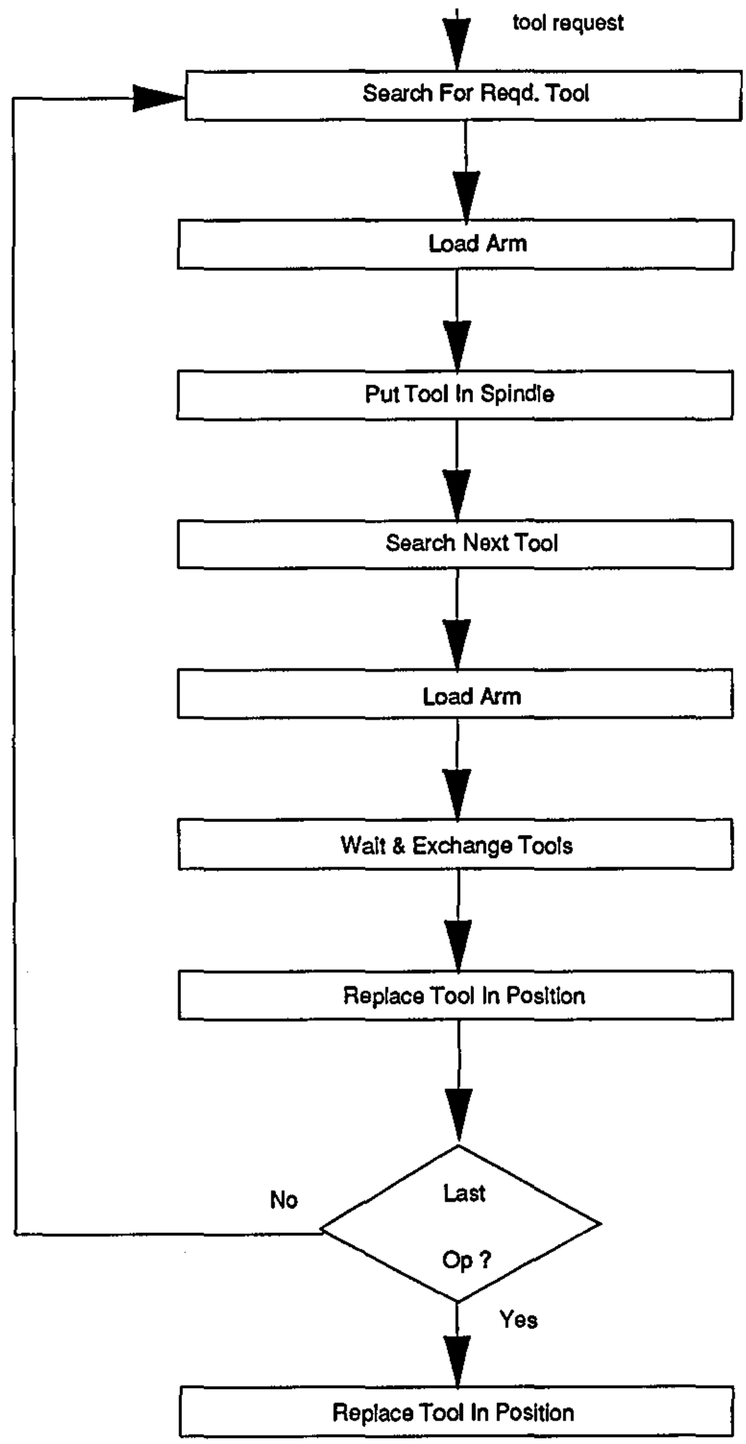


Figure 13.3

PTS EXCHANGE MECHANISM

DOUBLE ACTION, DUAL GRIPPER

Time Values : Replace Time, Load Time, Exchange Time

LUT-FMS RESEARCH GROUP

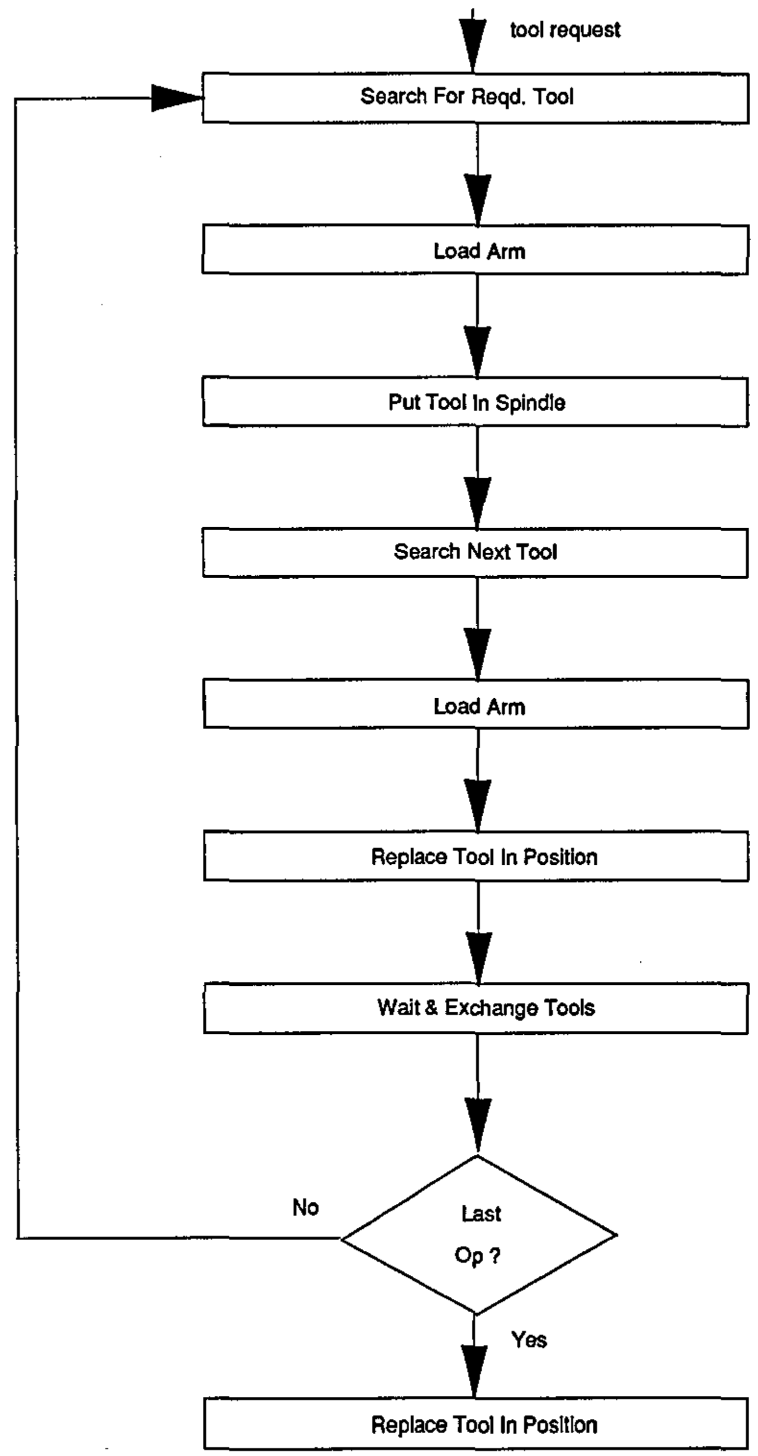


Figure 13.4	PTS EXCHANGE MECHANISM UNRESTRICTED EXCHANGE Time Values : Replace Time, Load Time, Exchange Time	LUT-FMS RESEARCH GROUP

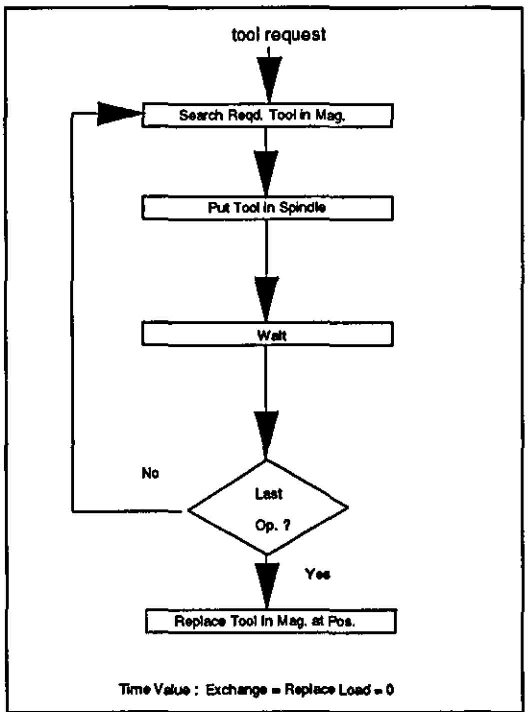


Figure 13.5	PTS EXCHANGE MECHANISM SINGLE ACTION,SINGLE GRIPPER	LUT-FMS RESEARCH GROUP

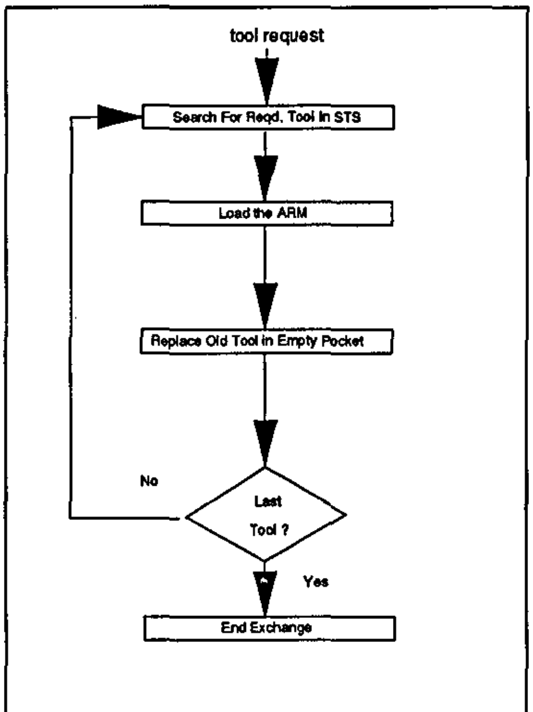


Figure 13.6	STS EXCHANGE MECHANISM SINGLE ACTION,SINGLE GRIPPER	LUT-FMS RESEARCH GROUP

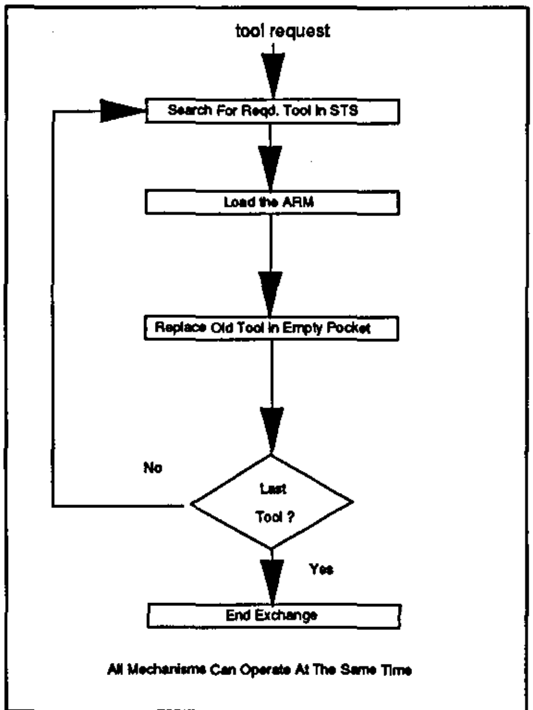


Figure 13.7	STS EXCHANGE MECHANISM UNRESTRICTED MECHANISM	LUT-FMS RESEARCH GROUP

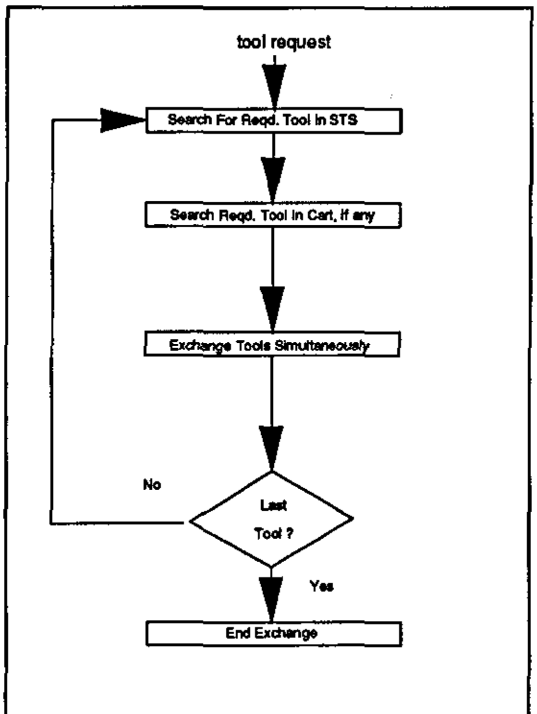


Figure 13.8	STS EXCHANGE MECHANSIM SINGLE ACTION,DOUBLE GRIPPER	LUT-FMS RESEARCH GROUP

Chapter 14:
TOOL LIFE MANAGEMENT

14.1 Introduction

The reader is introduced in this chapter to general tool life rationalisation rules and the tool life parameters required for a tool management system. These rules and parameters directly influence the tool status values described in the preceeding chapter and thus dictate all the activities within the tool flow event chain described in chapter sixteen.

14.2 Rationalisation of Tool Life and Usage

The objective of tool rationalisation is to establish a minimum level of tooling based on tool life and tool usage, before the tools are assigned to an FMC, that can sensibly produce any workpiece or workpiece spectrum, due account being taken of machining economics and handling criteria. A degree of rationalisation can take place without effecting the product design, by selection of appropriate tool management, tool assignment and planning principles [29]. The rules prescribed here assume that the job programmers and planners have already selected the *best* cutters for the job using available process planning technologies [122]. The rationalisation of tools is important in automated tooling systems as huge savings can be achieved in handling costs, and more importantly flexibility may be increased.

Rationalisation can be achieved in four main ways : firstly, by adjusting the cutting parameters to reduce the cutting forces at critical moments and hence less duplicates are required because the chances of tool breakage are minimised; secondly, the system-stored tools can be rationalised in number by restricting the variety of parts to be machined to a fixed system tool set; thirdly, the number of tools may be reduced by modifying designs to include only available tooling; and finally, tool rationalisation may focus on determining the minimum tool life requirement to machine a given parts spectrum within a particular schedule or work list. These rationalisation rules are concerned with tool provisioning and tool life management. Attention is focussed in this section on this latter category of tool rationalisation, which is based on the tool life parameters. This discussion is a prelude to the more detailed description and usage of these rules in the modelling package (see chapter fifteen).

Although provisioning costs may be lower by using a rationalisation rule, the machining time and time spent in waiting for tools to be *freed* will probably be increased. Therefore, depending upon batch size and flexibility demanded, tooling levels can be established in accordance with any of the following rules. The simplest method of tool rationalisation is the '3-duplicates' rationalisation rule. Although, not quite a rationalisation rule, because it actually increases the number of tools, the rule actually involves very reasonable planning principles. The operating philosophy is to hold three duplicates of each tool to allow for one in cut, one as a backup, and one in preparation [61]. Consequently, if several operations are to be performed in which identical tools are to be used, even though the operations might not be identical, the number of tools will be the number of operations multiplied by three. As it is unlikely that all operations will be completed simultaneously, back up tools may serve more than one operation, as long as its accumulated tool life does not exceed its tool life limit.

Rationalisation by grouping of similar operations or tasks assigned to particular machines takes this rule one step further. The duplication of tools in this 'operation grouping' tool rationalisation rule is kept to a minimum. The machine is equipped with a set of tools to machine a given cluster of operations. When this tool cluster set is no longer required (see chapter ten), the whole set is changed. The advantage with this type of rationalisation rule is that the tool inventory is optimised locally for a given period of time or for a given set of machining tasks. Tools which are worn during this period are replaced so that the tool cluster set is always complete. This rule is found operating under the tool-oriented tool management strategy.

Other rationalisation rules commonly encountered in workpiece-oriented tool management systems range from the 'without rationalisation' to the cell rationalisation rules (see chapter fifteen). The 'without rationalisation' rule can almost be classed as a 'one tool per operation' rule. The number of tools is equal to the total number of operations to be machined in the duration of a planning period. The tools will have sufficient tool life to machine the operations to which they have been assigned. This rule involves a large tool inventory and significant under utilisation of the tools, but considerably less delays. This rule is usually employed in situations where the components to be machined are of high intrinsic value or where surface finish of the finished material is of prime importance. Machines with large PTS capacity are required together with an efficient tool handling system.

14.3 Tool Life

Tool life is important in devising the tool replacement and for determining the tool status values (see chapter thirteen), and are at the centre of the tool management decision making process. Perhaps the most important usage of tool life in modelling terms is in the determination of the minimum tooling requirement (see chapter seventeen) which specifies the duplicate or sister tools required for a manufacturing period. A tool is no longer useful when it loses its ability to cut to specifications including geometric tolerance, surface roughness and estabilishing limits on cutting forces. The useful tool life for a particular tool will vary if used on a different machine, say with a greater tool offset, rigidity or load bearing capacity. Such variations between machining centres must be considered when designing and implementing operating control rules, sensing systems, tool monitoring and replacement systems.

If the extent of progressive tool wear is the governing factor in useful tool life, then monitoring the cutting forces, surface finsh, and the size or dimensions of the workpiece will provide feedback of whether the operation was carried out satisfactorily and within predetermined performance limits. This is being studied in the laboratory at Loughborough in a parallel research programme on the analysis of manufacturing data [200]. Workpiece size and surface finish as indicators of tool wear do not provide an early enough warning when tool failure is caused by fracture. Sensor data, used in real time, can compensate for wear by changing of the tool offset. The effects of tool breakage on cutting forces is measurable in real time but the avoidance of damage is machine dependent in that it relies on the ability of the machining centre to quickly reduce feed, stop the spindle or withdraw the offending tool.

In a manufacturing environment, tool life is the economical useful life of a particular tool before refurbishment or replacement. The units in which tool life is measured vary according to the method of tool usage. Tool life can be measured in the number of tasks or assignments completed or the the number of integral workpieces produced under specified machining conditions, such as feed, speed, depth of cut, etc. Tool life is also commonly measured in machining time units, volume of material removed or the surface area machined.

Current sensing technology does not provide a complete, reliable and economical solution to the tool monitoring and failure detection problem, so a rather conservative and deterministic approach is employed in the manufacturing environment to determine useful tool life. The use of such safe and methodical rules for tool replacement, well before any damage to the workpiece is likely to occur, do not provide optimal tool or machine utilisation. Therefore, enhancing the capabilities of the machine to enable it to detect and respond to all modes of tool failure, will increase productivity by utilising a larger portion of the total tool life.

Attempts to develop analytical methods for predicting tool failure and hence for establishing the requisite level of tool duplication, tool state and optimum tool change times, have not been successful. This is mainly because the tool failure phenomenon is probabilistic in nature and failure mechanisms are not yet fully understood. Even so many researchers have studied this phenomenon in Europe [51,167,267] and in the Soviet Union [191,301,307,308]. Intensive efforts are directed towards identification of signals to use as symptoms and for analysis of tool failure.

In the tool flow modelling as well as in the computer assisted cluster analysis module, the emphasis is on the specification and utilisation of tool life. Tool wear and breakage considerations are implemented in a planned and predetermined manner. Tool life is specified in machining time units. Two methods of specification are available to the user. The first method is analytical in that tool life analysis based on the parameters specified by the user is necessary (see chapter eighteen) whereas the second method involves a straightforward user specified tool life. Both methods permit the user to interactively change or specify in the premodelling or post modelling datafiles (see appendix three), a number of tool life parameters for use within subsequent modelling.

Tool life management can be very complex. For example, it is not generally acceptable to replace a tool at the end of its life. The tool must be replaced after, say, 90 per cent of its tool life has elapsed. This concept is explained further in the analysis below. Another consideration is the combination of machine cycle time with tool life. A tool must not be exchanged in the middle of a cutting cycle. To this purpose the rationalisation rules, within the modelling package, work out whether the useful life of the tool will be exceeded if it is allowed to begin a particular cutting cycle. If so the rationalisation rule will signal a tool change and allocate a duplicate or sister tool in this pre-modelling stage. Thus during actual modelling each cutting cycle will be allocated a tool with sufficient life to machine this operation to completion. This situation will only be contradicted in those cases where the monitoring of tool life is not sophisticated enough to carry out this function. The tool life in this case may be exceeded in this case, although the same principle of not changing a tool in mid-cycle still applies.

14.4 Tool Life Parameters

Several parameters are necessary for tool life calculations within the modelling and the computer assisted cluster analysis module. These parameters are either determined from the tool life analysis or user specified for each tool and each operation in the datafiles.

Traditionally to calculate the number of tools used in producing a batch of components, it is necessary to know the relationship between cutting speed and tool life. The work of Taylor (301a) showed that an empirical relationship exists between these variables as shown in the 'tool life curve' in figure 14.1, viz.

$v/v_r = (t_r/t)^n$, where :

v=cutting speed, t=tool life, n=constant and
t_r=measured tool life for a given cutting speed.

The value of t_r may be found for a particular workpiece and tool material and a particular feed either by experiment or from published empirical data. The index 'n' depends mainly upon the tool material. The tool life, 't', for a particular situation is therefore given by :

$t = t_r(v_r/v)^{1/n}$

which has been traditionally applied as :

$vt^n = C$

The number of tools used in machining a batch of components may be given as:

$N_b(t_m/t)$, where :

N_b=batch size, t_m=machining time per component and t=tool life;
assuming that the tool is engaged with the workpiece during the entire machining time. Thus,

$N_t/N_b = t_m/t = (t_m/t_r)(v/v_r)^{1/n}$, where :

N_t=number of tools required.

From this equation for N_t, the machining time for one component may be given as :

$t_m = k/v$

where 'k' is a constant for a given operation and, in general, can be regarded as the distance moved by the tool corner relative to the workpiece during the machining operation (85a).

The use of this analysis to specify operation times and tool life for particular machining operations is given below. The basic tool life equation has a number of variants. One of these variants which takes into consideration a greater number of parameters and used in a flexible machining environment is presented in section 14.5.

In the modelling, an heuristic approach is considered for the determination of the minimum tooling requirement (see chapter seventeen). The approach is more appropriate as it does not assume that all tools of a particular type have the same tool life. This allows the user to specify unique tool lives not only for tool groups but also for individual tools. This allows the user to consider tools in different states of wear. The other main advantage of this approach is that it permits the tools to be used in a number of different machining activities. To this purpose, it is necessary to specify additional parameters such as those given below. These parameters employ the user specified or determined values of tool life and machining time (operation time) based on a given tool life equation to manage the tool over its life, utilisation, assignment and machining history. One possible use of the basic equation for N_t is to ascertain the initial capacity of the cell STS. Research work done at Loughborough University [77a] has extended this equation for use in flexible machining installations. The equation becomes :

$N_t = m\,(T/t_l)$, where :

m=the number of machines, t_l=average tool life and T=the machining period.

(a) *Operation Tool Life* : This is the length of time the cutting tool will last for, dependent upon the calculations given in the tool's tool life equation. This parameter is specifed in the datafiles for each tool or tool type.

(b) *Operation Tool Life Used* : This is the length of time required for the tool to last to complete the operation. This is in effect, in modelling terms, the operation (machining) time in machining units. This parameter may be specified as an operation time (due to the different take up of tool life for each operation, the operation time must be specified in terms of proportion of tool life used or in terms of discrete units) or :

For milling operations, such as face, square, side, pocket and end milling, the operation tool life used may be calculated as :
(length of tool path (mm)) / (feed (mm/rev) x spindle speed (revs/min))

For boring, drilling and reaming the operation tool life used is :
(length of bore (mm)) / (feed (mm/rev) x spindle speed (revs/min))

For thread milling :
(thread length (mm) x 1) / (thread pitch (mm/rev) x spindle speed (revs/min))

For tapping :
(thread length (mm)) / (feed rate (mm/rev) x spindle speed (revs/min))

(c) *Percentage Operation Tool Life Utilisation* : This is the decrementing factor used for determining the tool life used after completion of a particular operation. This parameter is calculated as follows :
(Operation Tool Life Used x 100) / (Operation Tool Life)

(d) *Percentage Tool Life Utilisation* : This parameter, applied to a particular tool ITN (individual tool number) over a number of assigned tool operations, is calculated as the summation of all the operation tool life utilisations using this cutting tool.

(e) *Percentage Available Tool Life (PATL)* : This is effectively the residual tool life or the tool life remaining for a particular cutting tool ITN, of decision status 'R' (see chapter thirteen), after completion of one or more operation assignments. This parameter is calculated as :

PATL = Current Tool Life Allocation - Percentage Tool Life Utilisation

A tool with decision status 'N' (see chapter thirteen), is assumed to have a current tool life allocation of 100% i.e. the equation at the start becomes :

PATL = 100 - Percentage Tool Life Utilisation

and is progressively updated.

(f) *Maximum Permissible Percentage Tool Life* : A tool replacement event is triggered, in the modelling, if progressive tool wear / life exceeds acceptable limits. In the model, tool life usage and the frequency of usage is accumulated until the specified tool life expires.

In *real* situations, sudden tool breakage is a random event. Data on abrupt tool failure is not normally provided by the tool manufacturer, nor is it readily available from users. Only those users who have used a tool monitoring system and maintained an updated tool database can provide reliable abrupt tool breakage data. Unless reliable data is available, tool breakage is not available as an user option in the model, otherwise the results obtained from the modelling would not be meaningful. *Soft coded* in the software is the option for sampling for tool breakage from a random distribuition, but unless the forementioned conditions are met this function lies dormant.

The modelling facility allows the user to explicitly specify a *correction factor* or *tool life limit* (see appendix two) which may be applied to account for variations in cutting conditions and improve the accuracy of failure predictions. Such a factor is normally based on the users past experience or level of confidence. This factor acts very much like the *upper control limits* on a traditional *Shewhart Average Chart*. The *warning limit* on such a chart is analogous to the *maximum permissible percentage tool life* and the *action limit* signals a tool change or worn tool. The factor normally ranges from 50 to 99% of specified tool life. Tools are considered to have converted to decision status 'W' if :

percentage available tool life <= maximum permissible percentage tool life

That is, the value for residual tool life must always be greater than or equal to the *maximum percentage tool life*, except in the case of manual tooling systems where the value may be the full tool life specified. If this value drops to or below this tool life limit, with the exception above, the tool is considered to be fully worn. The other condition which determines a 'W' status (see chapter thirteen) is when the tally or frequency of usage of a particular cutting tool reaches the expected usage specified by a tool rationalisation rule.

14.5 Tool Life Analysis

This sample analysis has been provided by a major manufacturing organisation (64) and the theory is intended for all cutting operations except tapping and reaming. The theory is aimed at cells and FMS in estimating the frequency of tooling changeover. Information for these operations can be obtained from the PERA *MACBANK* (242).

(a) *Tool Life Equation* : $T = ((815\,[H_T / H_B]^{2.66}) / (A\,V^3\,f^{2.5})) * W$

T = tool life in minutes for a 0.762 mm wear land
A = abrasion factor for workpiece material
H_B = Brinell hardnes number of workpiece material
H_T = relative hardness of tool material
f = feed per tooth, or feed per rev. in mm.
W = correction factor for width of wear land

These parameters or components of the tool life equation can be stored in a database accommodating exact user input specifications. The user can specify the precise parameters, such as the tool life required, which are desirable in a given machining situation and the system will provide the cutting speed which would result in the required tool life. Such databases are widely available but are usually company specific in character. For this purpose the tool life equation may be expressed in the inverse relation :

$$V = ((H_T / H_B)^{0.8867}) / ((T\,A / 815\,W)^{0.3333} * f^{0.8333})$$

The factor *A*, is included to account for the odd workpiece material where severe abrasion of the cutting tool is known to occur. For common engineering materials, including cast iron, the abrasion factor may be taken as unity. The ratio $[H_T / H_B]^{2.66}$, is a factor which relates the relative hardness of tool and workpiece materials. The theory is based on the premise that the harder the tool is, with respect to the workpiece, then the longer is the tool life and vice versa. The H_T value is very roughly the Vickers Hardness of the tool material. H_B is the Brinell Hardness number of the workpiece, a value which is most easily obtained by the user.

The *cutting speed factor*, $(1 / V^3)$, relates the rapid fall in tool life with increasing cutting speed. The feedrate factor, $(1 / f^{2.5})$, relates the fall in tool life with increasing feed per revolution, i.e. it concerns the pressure applied to the cutting edge of the tool. Feed per revolution is less critical than cutting speed in its effect on the tool life. The theory will work where it is known that the chips are relatively cold. Using materials such as Sialon and Cubic Boron Nitride, which must be used at high feed per revolution values, the feedrate component of the equation assumes hard chips, overcompensates, and reduces the estimated tool life. In this instance assume a value of feed per revolution of 0.254 mm for the purposes of tool life calculations.

Given a desired, acceptable, width of wear land 'w', then the correction factor for width of wear land, W, can be expressed as :

$W = 1111\,w^2$.

'W' is equivalent to 1 for a 0.762 mm wear land. It is apparent that the greatest time rate of tool wear occurs early in the life of a tool, when the tool is sharp. The rate of wear subsequently decreases. The acceptable width of wear land for finishing tools, such as face mills and boring bars, varies according to the tolerance band of the machined feature, and can be calculated from the specified tolerance and the geometry of the back relief of the tool, e.g. if :

t = tolerance band of machined workpiece
w = width of wear land
a = back-relief angle

then $w = t \, COT \, a$

The nominal tool life equation enables tool life to be calculated for a nominal 0.762 mm wear land, and is thus aimed at rough machining operations. When applied to twist drills in this basic form it is assumed that a 0.030" wear land is acceptable, but for small drills a 0.762 mm wear land may be a considerable proportion of the tool diameter. It is proposed therefore that for drills greater than 16 mm diameter, a 0.762 mm land width is acceptable, and for drills less than 16 mm diameter, the acceptable land width be reduced in a linear fashion with the drill diameter. This is calculated as follows :

$$w = (0.762 \, D) \; / \; 16 = 0.048 \, D$$

where D is in mm.

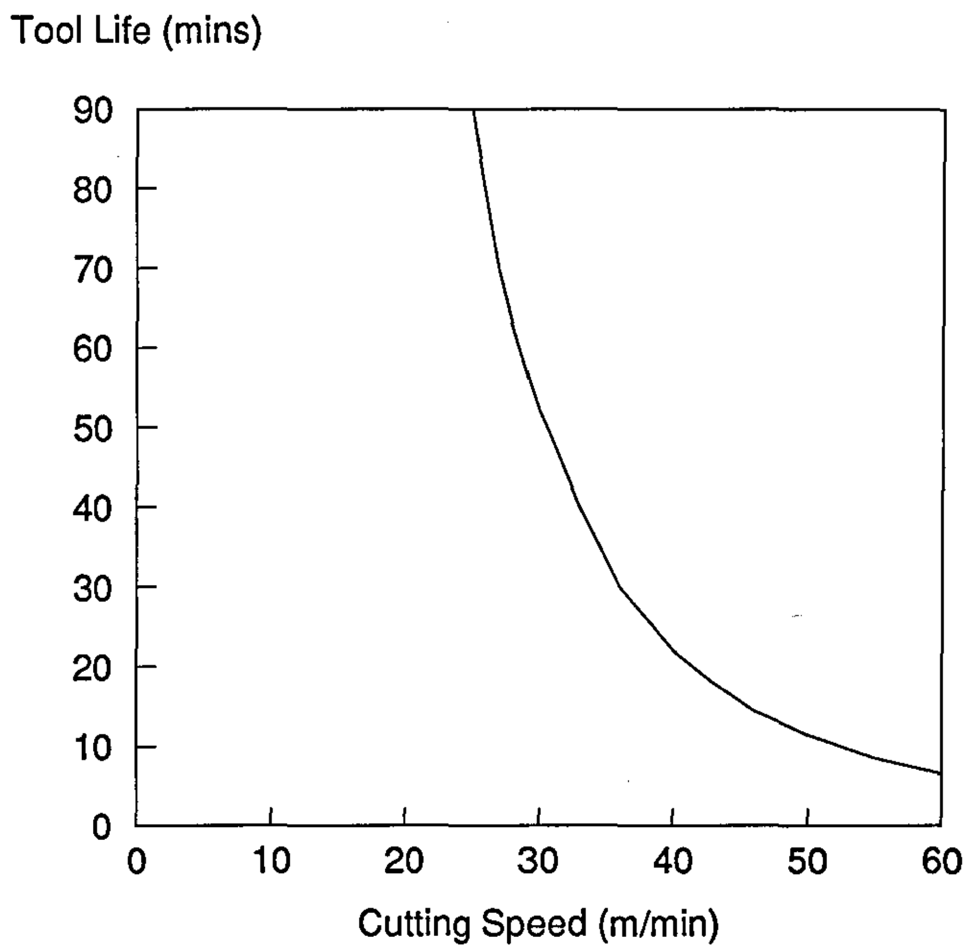
When D = 16 mm, W assumes the value 1.

The *correction factor,* 'W', may then be expressed in terms of the drill diameter. i.e.

$$W_d = 1111 \, w^2 = 1111 \, (0.048 \, D)^2 = 2.56 \, D^2$$

The above theory appears to work reasonably well, for the manufacturing organisation that undertook this analysis [63], when tested against laboratory tool life data as published by METCUT [64]. The theory has been shown not to work in testing commercial tool suppliers' claims concerning tool life. Tool life values generated for very small chip values are unreliable. Nevertheless it should be emphasised that the theory is approximate and may not work in all cases. The choice of workpiece hardness is critical to realistic calculation.

No known mathematical models exist for reaming and tapping operations, mainly because in these operations, the tool changes are dictated by workpiece quality, e.g. size accuracy, surface finish, thread form etc., rather than tool wear. Databases are in existence for these operations which contain actual listings of cutting speeds, feed rates, tool life, etc., based on the best data available.



tool life curve 12.7 mm guhring s-drill

f = feed/rev = 0.18 mm

workpiece : grey iron

Figure 14.1	SAMPLE TOOL LIFE CURVE	LUT-FMS RESEARCH GROUP

Chapter 15:
MODELLING OF THE
OPERATING RULES AND STRATEGIES

15.1 Introduction

This chapter describes how the major rules and strategies, described in the preceeding chapters, have been selected for implementation in the tool flow modelling based on the modelling representations and activity flow networks described in chapters six and seven. The structuring of these rules and strategies provides a firm grounding for the event chain described in chapter sixteen.

15.2 The Modelling

The tool flow rules and strategies discussed in the preceeding chapters are intended to manage the total combination of stations, stores and transfer devices in a manufacturing system and contribute to the effective and economic management of flexible machining cells. These strategies and rules co-ordinate and supply all the control, management and tracking functions that firstly, enables the tool flow system to achieve a high utilisation, and secondly permits the modelling of such systems to explore alternative designs and operating rules and strategies. The adaptation of each strategy for modelling purposes is presented below with the modelling structure, inputs, outputs and assumptions reported in chapter eighteen. The specification of these rules and strategies in the modelling is undertaken in the user interface described in appendix two. Conclusions drawn from the case study work have also been introduced as supplementary rules.

15.3 Modelling Of Tool Management

The tool management strategy implemented is essentially workpiece-oriented in that the number and type of tools is determined from the machining requirements of the part spectrum introduced over a given period (see chapter ten). The tool inventory is rationalised to the machine level, i.e with regard to the machining lists for a planning period for a particular machine (see chapter seventeen). This tool rationalisation permits all the tools required to satisfy the machining list to be held at the machine until the end of the planning period or a change in the part mix. This is one of the salient points of the tool-oriented strategy. Tools which cannot be accommodated in the primary magazines are stored either in the auxilliary or secondary tool stores, if present. Variations of a combined tool and workpiece-oriented management strategy are possible with different tool issue and tool assignment strategies.

The Computer Assisted Cluster Analysis (CACA) module, developed in parallel to the mainstream modelling and described in chapter eighteen, incorporates some novel techniques for determining preferred tool clusters based on a given tool-part matrix (work list) for a specific manufacturing period. The CACA module specifies *tool packages* for each machine with or without sister tools. CACA gives the user the option of quickly adjusting and specifying tool sets for each machine without going through the rigours of full scale modelling, as is necessary for the workpiece-oriented tool management systems, to determine transfer schedules, etc. CACA permits optimum tool set configurations for changes in batch sizes, maximum permissible tool life and different tool life specifications. CACA also has potential for assessing manual tool flow systems, i.e PTS tooling configurations, and for determining fixed or resident tools to be held in the PTS in the newer single tool transfer systems. The output from the CACA module may either be subjected to the rigours of the workpiece-oriented tool management strategy through modelling or be managed in its own right as a tool-oriented system. The former approach allows the system to be managed along workpiece-oriented lines with a high degree of certainty of visits of specified parts to specified machines.

15.4 Modelling Of Tool Assignment

In the modelling, all the required tools are initially assigned to a specific tool store, see chapter eleven. In the case of the single cell model, this store is the cell's STS, whereas in the multicell model, the tools required to satisfy each cell's machining lists are stored in the respective cells STS. Since the single machine does not have a STS, a store of unlimited capacity is created to hold the tools to satisfy the machines machining list over the scheduled period. This operating strategy eliminates the need for the user to specify the locations or proportions of tools to be held at each major store. This form of tool assignment creates an effective methodology for linking and interpreting several runs of the computer model, as the starting point is always the same. During the modelling, the tools may migrate freely in and out of the STS and between machines, thus ensuring a wide distribuition and availability of tools subject, of course to the other selected operating strategies, particularly the tool rationalisation rules and tool issue strategies, *figures 11.2 and 11.3* . This rule for tool assignment is essentially a compromise between two extremes and overcomes the disadvantages of both, but incorporates many of their advantages.

15.5 Modelling of Tool Issue

The model gives the user the choice of assigning tool kits for a particular part type, differential or modified tool kits, total tool changeover, a single tool, tool cluster sets or alternatively the transport of single tools as described in chapter eleven. The issue of unique FTN's (tool types) or resident kits is considered too basic for inclusion in the tool flow modelling and is adequately represented within the emulation environment. Furthermore, in the multicell version the user is allowed to specify the tool issue strategy globally for the whole installation or choose either of the tool issues strategies for each of the constituent cells (FMC'S), i.e each FMC may have its own tool issue strategy.

The assignment of single tools is far more complex than the assignment of tool kits. This is because in the latter case the restriction in the transfer of tools is that the tool set to produce a given part type is a known quantity and assumed to be within the capacity of the PTS of the machining centre to which the tool kit has been assigned, whereas in the former the only restrictions are the capacity of the transport system and the tool spaces available in the PTS. Thus the movemement of single tools needs to interact actively with the tool retention rule, operation assignment rule and the part sequencing rule (presented in chapter nine).

The transfer of one tool at a time as is now evident in the newer installations like Cincinnatti [207a] and Yamazaki Tool Hive [190], calls for different handling from the single tools strategy. Here a fixed set of tools needs to be pre-assigned to each machine to ease the initial tool flow congestion in this *warm-up* period. Subsequent tool transfer to the machine will be in the same vein as the issue of single tools except that the transporter capacity after the initial transfer of the fixed tool complement will be modified to one unit. The determination of this fixed complement will be determined as a result of running the computer assisted cluster analysis module (CACA) and assigning the basic clusters to the machines. Transfer of the unitary sister tool is then, as for the single tool issue strategy.

The movement of tool kits is simpler as the tool kit can be considered as an entity in itself without reference to the tools within the kit. The tool kit is then effectively treated as a single tool and only changed when the parts' machining list has been satisfied. Several tool kits may be accommodated within a particular PTS, although this is often not the case in practical situations.

In the differential tool kit strategy the assignment and rationalisation of tools is not treated by part type, as for the tool kitting strategy, but is similar to the the treatment of single tools. The movement of tools, though, is the same as for the movement of tool kits, except it is common for the tool kit to remain on the machine in the PTS, and to interact with other assigned tool kits to service a predetermined number of part types. Thus only tools not already present in the PTS are transferred in this modified kit. An alternative to holding both kits on the machine is to remove all tools not common to two successive kits from the PTS and transfer these back to the STS. The same restrictions in tool issue apply as for the kits regarding PTS capacity. This strategy has been examined and compared with the two other issue strategies in an industrial case study presented in appendix three.

The issue of FTN's may be considered as for the assignment of single tools except that the issue will be restricted to unique tool types and only supplemented by sister tools or other FTN's. Similarly, the assignment of a resident kit could be as for the assignment of tool kits except that the kit on the machine would be replenished with an identical tool kit.

Tool issue strategies for the tool-oriented tool management systems have been implemented within the modelling framework at a basic level. A more detailed implementation strategy has been researched, developed and offered for consideration within the dynamic environment of the emulator [239] and the knowledge based models [316], which is necessary for the operating of this strategy. Both implementations are discussed below.

In the tool flow modelling implementation, *figure 15.1*, the clusters are determined from the CACA module. These clusters are not directly input into the tool flow modelling but are used to determine part sets based on the clusters. The clusters are then earmarked for particular machine assignments. Each of the resulting part sets is then sub-divided into smaller part sets. Each of these smaller parts sets, containing one or more part types, is termed an *exceptional* part. The reasons for this subdivision is two-fold : firstly, to compensate for scheduling within a static rather than a dynamic environment, and secondly, to account for priority hysteresis and unnecessary tool set changeovers. Each of these exceptional parts is then assigned a rationalised tool kit according to an order requirement, specifed for the part(s) within the exceptional part, for the period. The summation of these tool *kits* for all the exceptional parts within the original global part set would then equal the original tool cluster set specified by the CACA module. The sequencing of these exceptional parts within a machining list would then mimic the *dynamic* changing of tool cluster sets. This implementation would allow the assignment of multiple cluster sets or kits to a machine. The tool kit assigned for the machining of an exceptional part would then be as for the tool kit concept and transferred along workpiece-oriented principles. Although this relatively simpler facility is available in the tool flow modelling it is considered more appropriate to run the CACA module as a front-end to the Emulator and Knowledge Based models [316].

The more detailed algorithms, suggested for use in the Emulator, *figure 15.2*, are based on priorites not unlike those described in the tool cluster set concept. Having estabilished preferred tool cluster sets with the aid of the Computer Assisted Cluster Analysis (CACA) module, a secondary priority is assigned to each cluster set based on the highest pallet or part priority contained within the part group. The latter priority is termed the primary priority and is used by the simulation to dynamically assign pallets to a machining centre. The use of these priorities would be as follows : Cluster set(s) would be assigned to a machine based on the secondary or cluster set priority.

A cut-off point for use of this cluster set would be specified which would be the *priority hysteresis* described in chapter eleven. This cut-off could be the achievement of a production run or a specifed time. The cut-off is essential because all parts (pallets) compromising one cluster set may not possess sequential primary priorities and consequently as parts in one cluster set complete their operation, parts in other clusters may have a higher priority than the current cluster on the current machine. This cut-off period thus effectively minimises or eliminates the possibility of unnecessary tool cluster set changeover and smoothens the flow of pallets through the manufacturing system.

Parts with the same cluster set priority would then be sequenced to the machine based on the primary priority. On expiry of a cluster utilisation period, another cluster may be loaded dependent upon the secondary priority. The former clusters' priority would be derated to avoid reloading. This algorithm would result in the determination of a short range schedule.

15.6 Modelling of Tool Rationalisation Rules

Four tool rationalisation rules have been selected for inclusion in the modelling, based on the discussion of tool life management in chapter fourteen, these are : the 'one tool per operation' tool rationalisation, 'cell' tool rationalisation, 'batch' tool rationalisation and 'machine' tool rationalisation, figure 15.3. A cluster set tool rationalisation rule is included within the CACA module. The algorithms for these rules are presented in chapter seventeen.

15.6.1 Cell Tool-Rationalisation Rule

The cell tool rationalisation rule is at the other extreme of the spectrum from the 'without -' or 'one tool per operation' tool rationalisation rule, previously discussed in chapter fifteen. In the cell tool rationalisation rule, the tool inventory is drastically reduced as all the operations, irrespective of the machine to which they are assigned, come under scrutiny for possible rationalisation. This rule involves a central tool pool, usually the cell STS, servicing many machining centres. A very efficient tool handling system is required as a lot of secondary tool exchanges are necessary. Considerable delays might arise in the system if there is a conflicting demand for the same tool by two or more machines. Standardisation of tool holders and presetting information is of prime importance in systems using this rule as the tools should be able to be used on any machine if and when required.

In many installations a capacity plan is decided at least one shift in advance and hence a tooling requirement based on suitable tool life management rules is generated for the cell STS. Cell tool rationalisation is employed if respective parts are permitted to visit alternative machines for any of several reasons. Cell tool rationalisation is thus practiced in those installations which have a dynamic scheduling environment. This rule is more carefully assessed through a simulation exercise rather than in the modelling although it is available as an option.

15.6.2 Batch Tool-Rationalisation Rule

The batch tool rationalisation rule is an intermediate rule, commonly used in tool kitting situations, where a rationalised tool set is organised around a particular part type or part set, due consideration being given to the production control data. The necessary tools for a batch are determined in two categories : basic tools and tool life tools. The basic tools are the tool types necessary to machine the part or part set i.e the tool variety. By combining this information with the production control data and tool life details, such as operation tool life, tool life limit etc., for each tool type, the minimum number of necessary tools or tool life tools to machine a part, batch or a part set can be determined. This rationalised tool complement is compared with the tools already available in the system so that not only rationalised tool kits are created but also the overall tool inventory of the cell is reduced.

15.6.3 Machine Tool-Rationalisation Rule

The machine tool rationalisation rule is more progressive as this tool inventory can be further reduced by eliminating the batch boundary and considering the part assignments to a particular machine, that is the machining list. This situation arises mainly when the single tool or modified tool kit concept is used. This machine tool rationalisation rule does not consider alternative machine assignments for the parts. The rule is thus organised around a fixed schedule for a given work list. For each machine's machining list or part loading, the production control information is used to determine the basic tools (tool types) and thus, the tool life tools (sister tools) to machine the whole of the machining list over a given planning period. This rationalised complement is then compared with the tools available in the system to determine the type and number of system tools. This machine rationalised complement is then assigned to the machine according to the differential or modified kit concept adopting the 'least number of tools per kit first' or the single tools concept where all the tools may be assigned subject to the tool handling capability and capacity.

15.6.4 Cluster Set Tool-Rationalisation Rule

A tool rationalisation rule has been implemented within the computer assisted cluster analysis module. This tool rationalisation rule is in a similar vein to the application of the batch tool rationalisation rule to a cluster of parts included within a respective tool family. The rule implementation in the CACA module is highly interactive in that the user can find a suitable rationalised tool complement for a cluster set almost instantly by adjusting tool life parameters on-screen. In contrast, the preceeding tool rationalisation rules, integrated within the tool requirement module are transparent to the user and do not offer this fast response facility. This rule is more progressive if several cluster sets are assigned to one machine or repeatedly assigned to several machines to allow increased flexibility in routing, in which case rules not unlike the machine or cell tool rationalisation rules, but based on clusters are implemented. This situation is illustrated in a single cell case study in appendix four.

15.7 Modelling of Part Introduction and Assignment Rules

The production schedule and the tool management strategy governs the parts availability, mix and arrival pattern. Parts may be introduced in batches or as a *batch of one*, either of the two being considered as a job. The choice of which job to select is based on a user-specified sequence of jobs to introduced. There has been a great deal of work done on the part assignment problem, covered in the literature survey in chapter two. A discussion of the part assignment problem and its handling within the overall modelling is presented in chapter nine. Deterministic or 'as available' arrival patterns are easily modelled. If the tool flow modelling is used as a 'module' of the LUT Emulator then these arrival patterns specified as inputs, may be derived as outputs from the LUT Emulator, and are handled as inter-arrival times, or earliest possible machining start times in the *static* model, *figure 15.4*. Other dependent activities cannot be started till the *machine clock* reaches the appropriate time. The part, then introduced to the system, triggers a chain of events aimed at satisfying its processing requirements in accordance with the specified tool management and system operating rules.

When operating in 'stand alone' mode the model treats all part arrivals as being available at the start at the modelling period. Hence, the movement of pre-sequenced parts is dependent upon the ability of the tooling system and the *next step* scheduler decision rules, to ensure that the tools are at the right place, in the appropriate quantities at the right time, see chapter nine. Parts are thus considered to arrive at the machine at the appropriate point in the event cycle, without detailed consideration for part flow or the material handling system as in the Emulator. The use of inter-arrival times is less appropriate than the 'as available' rule as it restricts the flow of tools to a constrained schedule of parts which does not take tool flow into consideration in the first place, but assumes that the tools will always be available at the machine. This situation is very common in many simulators, the LUT Emulator not being an exception. To fully examine the operation of a tooling system, the selection of the 'as available' rule is more appropriate as the system can be thoroughly investigated with the minimum restrictions or constraints.

As no simple, suitable or appropriate scheduling rule is available, at the time of writing, which considers both tool and part flow adequately, the modelling thus uses the two-stage process, described in chapter nine, to minimise any shortcomings. The model may additionally consider those cases where there are different part types on the same pallet, different fixturing on the pallet, or different stages of completion of operations. In each of these cases, the modelling would treat each individual part as unique with its own work list sequenced within an overall machining list. The use of interarrival times or user-specified arrival times is only appropriate when the user wishes to examine the suitability of the tooling system for the recently emulated part flow system. Thus, the use of the inter-arrival times, in this instance, allows for any limitations in the material handling system. An adequate picture can then be constructed for analysis of a complete manufacturing system.

The computer assisted cluster analysis module offers preferred tool cluster sets required for processing of part sets or revised short-range work schedules. Rules for introduction and assignment of parts, under this strategy, to machines are discussed in relation to tool issue.

15.8 Modelling of Operation Assignment Rules

Two operation assignment rules have been highlighted through case study work (see appendix three) for batch manufacturing systems. An operation in the tool flow modelling is considered as a tool activity within a work list. This is in concept the same as a sub-operation when an operation is considered in the wider sense as being a visit to a machine. Both these rules have been implemented in the model, *figure 15.5* . The first assignment rule, termed *Operation Group*, is where all operations of particular operation number on each batch item on a particular pallet are completed before proceeding onto the next operation number. This rule can be extended to mimic the *random tool flow* philosophy exercised in the Tos Oloumouc installation in Czechoslovakia [330], in that similar operations might be grouped together to minimise tool requirements. This rule is particularly effective in situations where the batch size (pallet capacity) is high. The second operation assignment rule, termed *All Item Operations*, implies the completion of all operations on each batch item on a particular pallet before proceeding onto the next batch item. This rule is effective for smaller batch sizes and particularly in the case of *batch of one*.

The two rules have been examined in detail and are presented through the results of a single machine case study in appendix three. The 'operation group' rule employs less tool magazine indexing and reduced tool change times, but greater pallet indexing times. A reverse situation applies to the 'all item operations' rule. This is because when the former rule is used, the same tool may be used for several operations, tool life and tool life limit permitting, before it has to be returned to the tool magazine; whereas, in the latter rule, a whole cycle of tool changing has to be performed for each item in the batch, or on the pallet. The choice of which operation assignment rule to employ can only be examined by modelling although in a *batch of one* situation, either may be employed.

15.9 Modelling of Manual or Semi-Manual Activities

Men are required to input new parts and tools into the system and to remove completed parts and worn tools. The number of men available at any one time and the number of shifts to which they are assigned to work may be controlled within the modelling.

Three modes of operation of a manufacturing system are examined, the first is fully manned operation where the men are available for tool and part loading and unloading at the machines as well as at the respective tool and part stores. The second mode of operation is fully automated where men are available only at the part and tool stores. The third mode of operation is where men are integrated in an automated manufacturing system to perform auxilliary functions at the machine tool.

In modelling terms, the proportion of manual activity within an event can be accounted for in either of two ways : either by sampling from a stochastic distribution or by the incorporation of deterministic values. The former is more appropriate for simulation rather than for the tool flow modelling. The latter has been implemented within the modelling as user specified values which are tagged onto load, transfer and unload times respectively for the parts and the tools. These determined values have been expanded and explicitly defined for use in the Emulator (248) to include several other functions and additional categories such as inspection etc. These values, in mode one, would be exclusive for men whereas in modes two and three they would be in a fixed proportion to actual transfer, load and unload times for the automated elements, albeit agv, robot, or other device. To measure different levels of manning and efficiency, these values can be derated to reflect more manpower or uprated to account for more efficient use of manpower. This has been examined through the single machine case study to decide on appropriate levels of manning. The number of men available and their usage in transfer terms is treated as for the cell transporters, see chapter twelve.

15.10 Modelling of the Flow of Fixtures

Fixtures can take many forms in a highly automated manufacturing system. They may range from simple, one-part clamps, similar to those used in stand-alone machining, to complex picture-frame and pedestal fixtures that allow machining access from several sides to even larger fixtures accommodating two or more parts which aid in reducing the non-productive time used by tool changing and part transportation.

Although fixtures are not entirely essential from the point of view of tooling sytem design, they are important in the operational sense. The tracking of fixtures is necessary in a manufacturing system to ensure there are no unnecessary restrictions on the part flow.

Fixturing, although not currently implemented in the tool flow modelling is to be included according to the following suggested rules (see chapter twenty-one). Firstly, simple single fixtures on pallets could be treated as single tools, rationalised and assigned to machines, returned to fixtures stores and reused, or secondly, several fixtures on a pallet may be treated as a *kit* of fixtures analogous to a kit of tools, or as a set of single tools if fixtures are to be shared among part types. The consideration of fixtures could be implicit and handled with the tool flow or explicitly with little emphasis on the actual tools but on the flow of tools.

For the fixturing rule to be effective, it would require limited modelling of part flow networks on a mutually exclusive basis from the tool flow network and the restriction that a fixture is limited to a part type. The tracking of fixtures and the determination of the type and number of these fixtures could then be monitored. The in-depth consideration of fixtures, free fixturing, pallet restricted fixtures, pallet requirement, buffer capacity and bottleneck predictions are implemented within the Emulator.

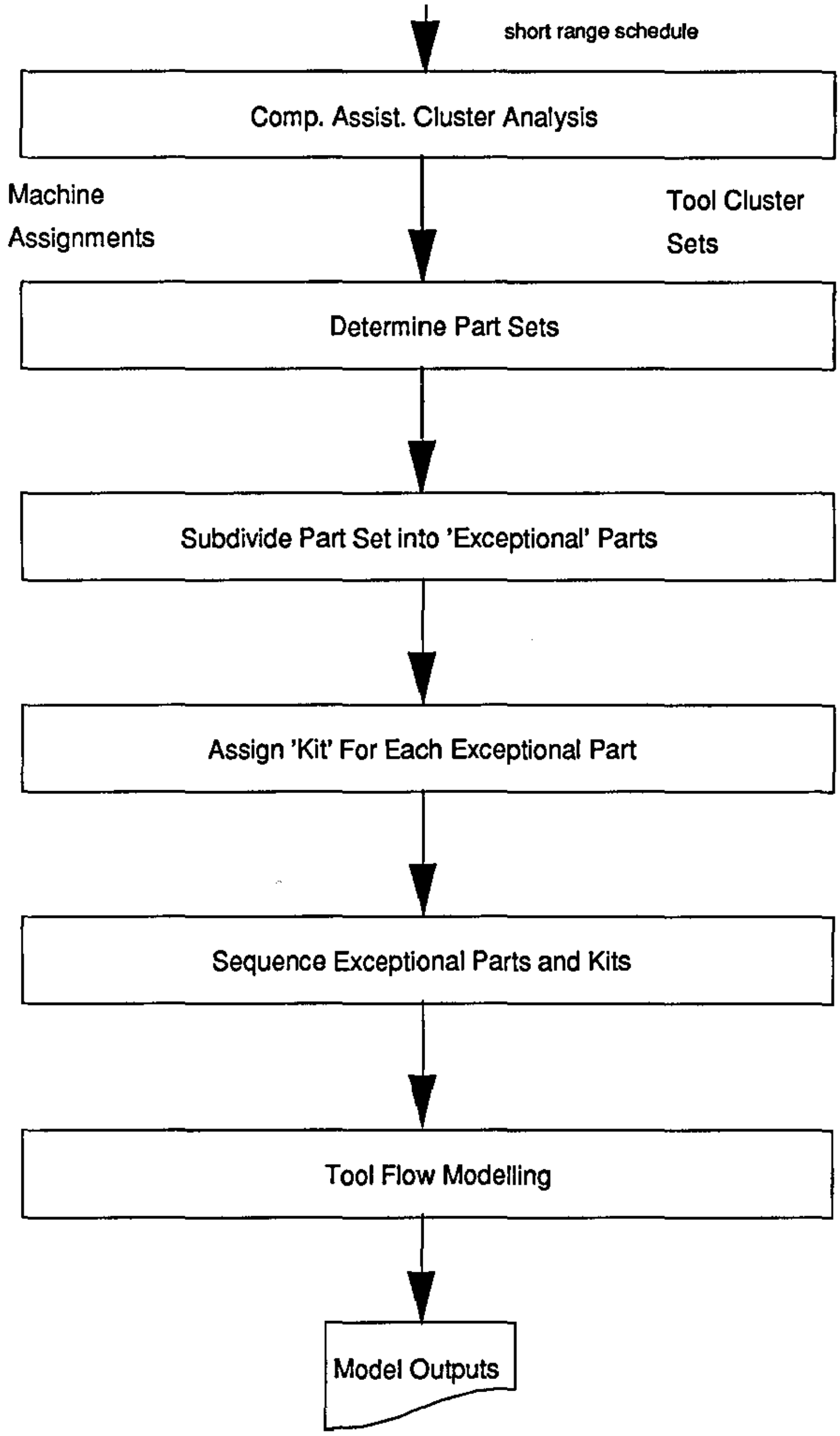


Figure 15.1	TCS Implementation In Tool Flow Modelling	LUT-FMS RESEARCH GROUP

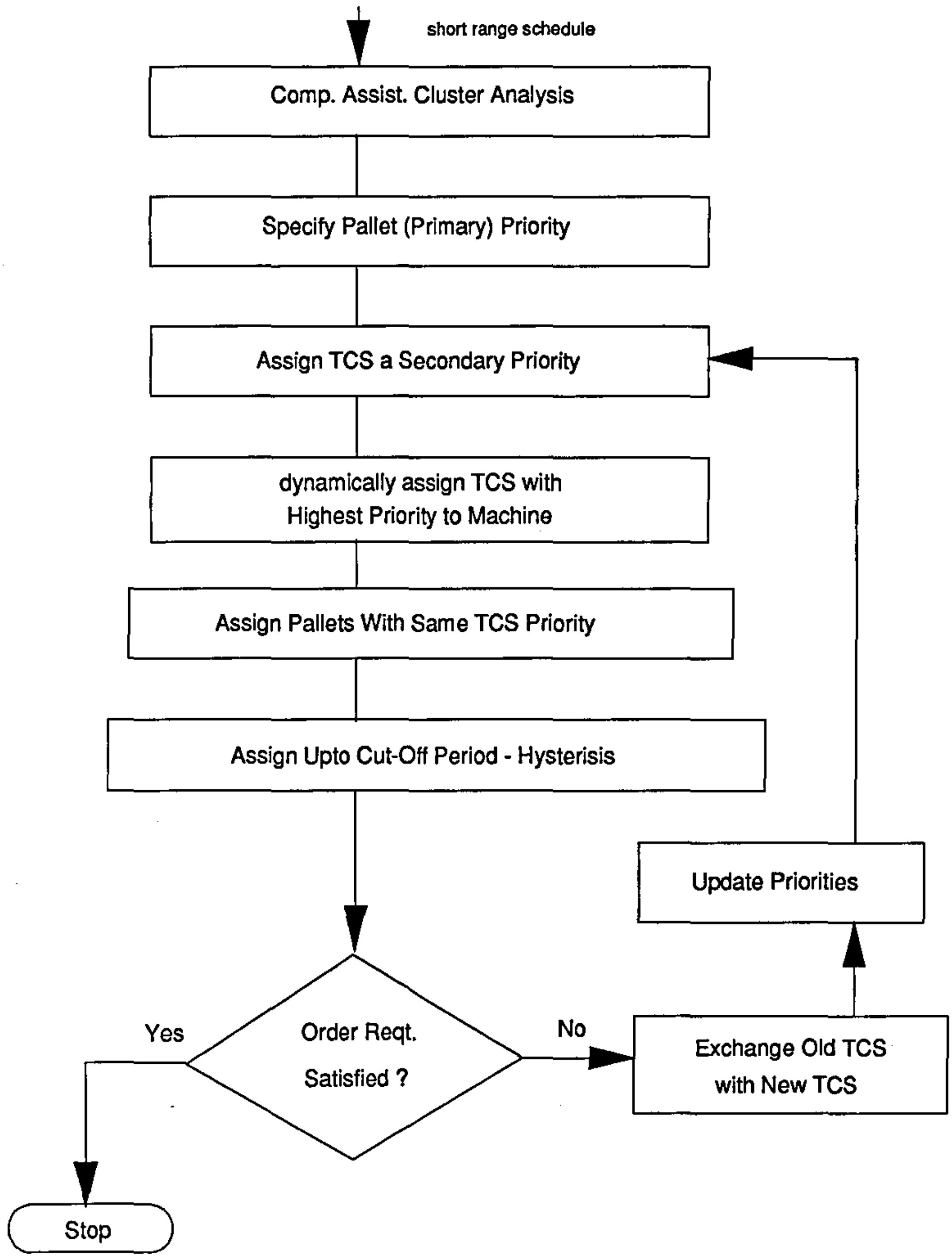


Figure 15.2	TCS Implementation In Emulator	LUT-FMS RESEARCH GROUP

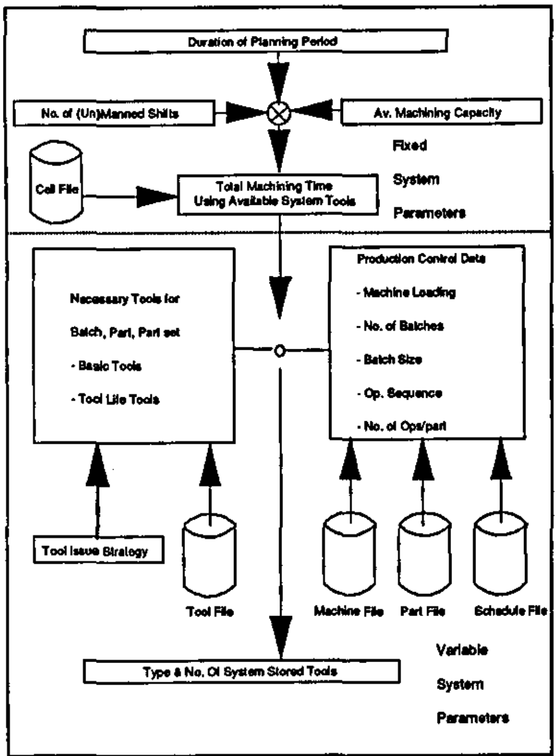


Figure 15.3	RATIONALISED TOOL REQUIREMENTS PLANNING	LUT-FMS RESEARCH GROUP

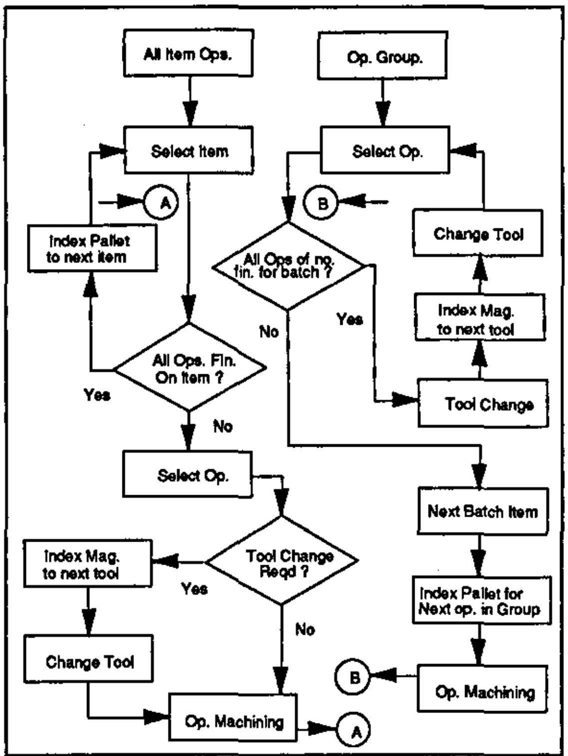


Figure 15.5	OPERATION ASSIGNMENT STRATEGIES	LUT-FMS RESEARCH GROUP

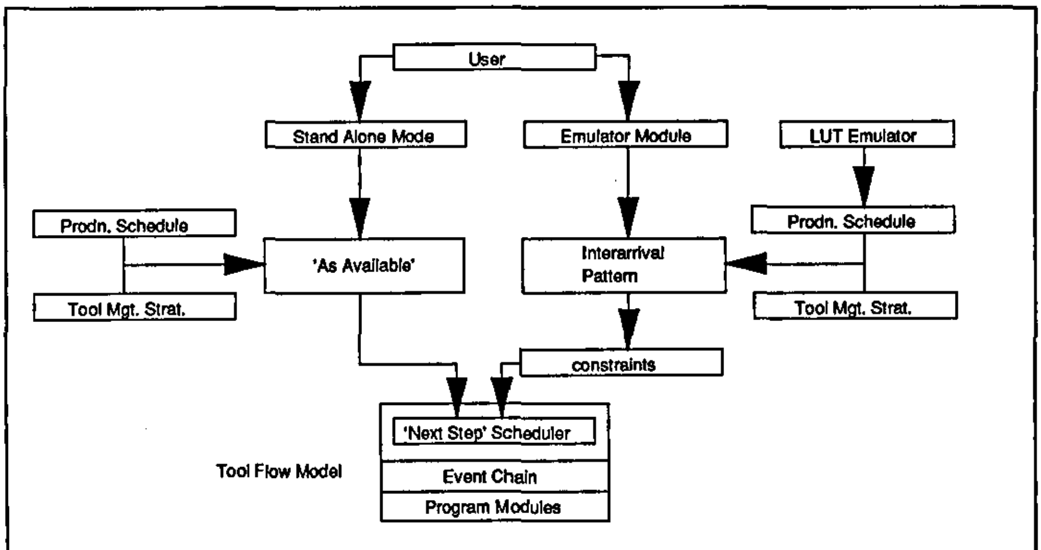


Figure 15.4	PART INTRODUCTION AND ASSIGNMENT STRATEGIES	LUT - FMS Research Group

Chapter 16:
GENERAL TOOL FLOW ALGORITHMS

16.1 Introduction

This chapter deals with the scheduling of events within flexible machining installations. Heuristic algorithms are presented for this scheduling of the event chain of machining, transporting parts, and of transporting cutting tools efficiently and economically so as to minimise the throughput times for parts. The algorithms form the basis for the modelling of tool flow systems, described in chapter eighteen, under the rules and strategies decribed in the preceeding chapters. The algorithms also add a time base to the activity flow networks discussed in chapter seven.

16.2 Status Report

The heuristic algorithms presented in this chapter are essentially workpiece-oriented, in that the manufacturing system they most appropriately represent is considered to be demand-driven. Until fairly recently, this workpiece-oriented approach was solely in evidence and still is to a large extent. It was decided at the onset of the research work to focus attention on the developments, rules and strategies for these types of flexible machining installations. The modelling approach and the writing reflects this decision and provides a tool for appraisal and testing of an existing or proposed tooling system. With the advent of the newer single-tool transfer installations it became necessary to devote some attention to the tool-oriented tool management approach. Effort in this area primarily culminated in the development of the Computer Assisted Cluster Analysis (CACA) module for quick determination of tool cluster sets, magazine capacity and a short range schedule. This development has found favour and many possible applications with many of the collaborating companies involved with this research. Further investigations and developments are necessary to model the flow of cluster sets around the installation. But, at this late stage it is felt necesary and more fruitful to dedicate the remainder of the time to ensuring the robustness of the current model and to enhancing the user 'front-end' than on embarking on a relatively new course.

Attention has been given to the incorporation of the tool-oriented rules at a lesser level in the current model. Suggestions for the inclusion of the more developed tool-oriented rules in the parallel Emulator research work [239] have been offered for further consideration. These two implementations have been discussed in chapter fifteen.

16.3 Objective Function

The primary objective function of the algorithmic structure is to minimise the part throughput times by scheduling and sequencing the activities of machining and transportation of parts and tools ,*figure 16.1*, efficiently and economically according to specified decision rules and strategies in order to evaluate the relative merits of these particular operating strategies or to evaluate alternative tool flow network designs.

16.4 Hierarchical Algorithmic Structure

The hierarchical structure of decision making within the modelling algorithms comprises essentially of three levels, *figure 16.2* : Firstly, selection of a machine tool for the processing of each stage of all the parts work lists according to a pre-defined machining list for each machine. Secondly, the selection of cutting tools and their assignment to the machines. This corresponds to the determination of a schedule for the transfer of cutting tools. Thirdly, selection of a transport device, among candidate devices, to carry the selection of cutting tools scheduled for delivery to the machines. This corresponds to the scheduling of the movement of parts.

For a formulation of the algorithm, several different kinds of activity for each part need to be defined. The set-up, part loading, machining and unloading correspond to the decision making at the first level. The activities of tool loading and tool unloading to decisions at the second level whereas part and tool transporting correspond to decisions at the third level.

The decision making at each level is equivalent to determining the start and finish times for each activity for all the parts to be manufactured in the given planning horizon. The equations and constraints on the time relations of all the activities are formulated in a generally accepted sequential manner [150,151,152], and focus on the activities within a flexible machining cell.

16.5 Algorithm Notation

Parts :

P_i	part or job number
	i=1..I {I=total number of jobs/parts scheduled}
P_{ij}	the jth item of job i
	j=1..J {J=total items in job i}
$P_{ij,k}$	The kth operation on the jth item of job i
	k=1..K {K=total number of operations for each item in job i}
$P_{ij,k,r}$	the rth tool for operation k of item j on job i
	r=1..R {R=total number of tools in cell}

Machines :

$MT_{m,c}$	machine tool number m with magazine capacity
	m=1..M {M=total number of machines in manufacturing system}

Tools :

r	tool number
$r_{(s,l)}$	tool number r at store s in location l
$r_{tlife,state}$	where tlife=tool life and state=decision status of tool r,
	state={F,R,W,N}
r*	tool or tool set

Stores :

$STS_{d,c}$	secondary tool store of cell d with capacity c
	d=1..D {D=total number of cells}
CTS_c	central tool store of capacity c

Transporters :

$TT_{q,c}$	tool tranfer device q of capacity c
	q=1..Q {Q=total number of tool transfer devices}
$PT_{v,c}$	part transfer device v of capacity c
	v=1..V {V=total number of part transfer devices}

Times :

T	maximum throughput time of all machining lists
$\bullet T_s[\ ]$	start time of event e
$\bullet T_f[\ ]$	finish time of event e
	e=1..E {E=total events in event chain}
$t_p[-]$	time to perform [-]
AVT	Available Time

Sets :

$N_{A,a}$	activity
	A=1..Z {Z=total number of activities for manufacturing system}
	a=activity state {a=0,1,2,3}
Q_{cut}	a cut set of $Q_{a=2}$, of activities which are candidates for selection from the first unprocessed stage of each machines machining list
q_s	selected activity from cut set

Events :

[entity,store] [q_s]
unloading of entity from store when activity q_s is selected

[entity,store,transporter] [q_s]
loading of entity from store into transporter when activity q_s is selected

[entity,store1,store2] [q_s]
transfer of entity from store1 to store2 when activity q_s is selected

[entity,transporter,store] [q_s]
unloading of entity from transporter to store when activity q_s is selected

t_p[entity,transporter,store1,store2] [q_s]
transfer of entity from store1 to store2 using a transfer device
when activity q_s is selected

16.6 The Workpiece-Oriented Flow Algorithm

The time relations of the activities considered are formulated for the kth processing stage of the jth item of the ith part or job on the mth machine tool which carries out the machining operation according to a predetermined machining list for each machine.

The maximum throughput time of production is defined as the length of time required to complete all the parts to be manufactured. Therefore, the throughput time, T, is given by :

$$T = \max\{ T_f[P_i] \} - \min\{ T_s[P_i] \} \quad \text{for } 1<i<I$$

where $T_f[P_i]$ is the completion time for the machining of the last operation in the processing of a part, P_i, and $T_s[P_i]$ is the start time of the first operation on a part, P_i.

The examination of the throughput times, tool life analysis and the elements that influence the troughput wiil provide comparisons and evaluations of the usage of different operating strategies and decision rules.

16.6.1 Internal Scheduling Algorithm

The role of internal scheduling has been previously discussed in chapter nine, but is described here algorithmically as a starting point for the mainstream structure.

The algorithmic procedure for this phase corresponds to the decision making at the first level. First, all the activities are grouped into four states corresponding to their progress in the simulated production cycle. They are indexed as *a*, and are subscripted to the activity $N_{A,a}$ as follows :

a=0 for an activity which is rejected or any other activity not in the other states.
a=1 for a completed activity
a=2 for an activity which belongs to the earliest technologically feasible process among those which are candidates to be determinedif they are selected or rejected.
a=3 for a selected activity.

The set of activities indexed as a=b where (b=0,1,2,3) is denoted as $Q_{a=b}$. Starting from the initial state, a=0, an event schedule is determined by sequentially tranforming the states of the activities until all of them are indexed with a=1.

A set, Q_{cut}, is defined as a set $Q_{a=2}$ which forms a basis for transforming the state, i.e., $Q_{cut}=Q_{a=2}$. From within this set an activity, q_a where $q_a = P_{i,j,k}$, has to be selected according to a dispatching rule. The purpose of this selection of an activity from within the cut set is firstly, to resolve any conflicts for demands on particular cutting tools, demands on the secondary tool store, and to ensure that the selected activity is technologically feasible, i.e. it has no uncompleted predecessors, i.e. if k>1 then $P_{i,j,k-1} = N_{A,1}$. The activity, q_a, is selected using an earliest start time rule (EST), and when multiple activities have the same EST then the conflict is resolved by selection of the lowest activity number, A. Although, the EST rule has been selected here, any of a multitude of appropriate dispatching rules may be selected and/or examined (see chapter nine).

The selection of this activity thus corresponds to the satisfaction of a request from a machining centre for tool(s) from a secondary tool store (STS). The algorithms that now follow are the sequential scheduling of activities through to the stage where q_e may then be indexed as $N_{qe,1}$. This process at the start of the event chain is repeated for each successive activity in each machines machining lists.

16.6.2 Event 1 : Tool Location and Search

The location of cutting tool, r, required for processing of $P_{i,j,k}$ needs to be specified in order to determine whether tool transfer is necessary. To this purpose, the search commences at the primary tool store (PTS) of machine, $MT_{m,o}$, where *m* denotes the machine number and machining list which contains the selected activity, q_e. The search is enhanced, as each tool possesses two dynamic variables, *s* and *l*, where *s* denotes the current store location and *l* the current location within that store. A succesful search is given the value of *1* and an unsuccesful search the value of *0*. This corresponds to the rules applied at the machine level described in chapter thirteen.

(a) PTS Search : A successful search of the PTS is given as $MT_{m,o,r(s,l)}=1$. Further examination is necessary to determine whether the tool, r, possesses sufficient tool life to machine the tool activity, $P_{i,j,k}$, i.e. whether $r_{tlife,R}>=t_p[q_e]$ or if $r_{tlife,R}<t_p[q_e]$ then a request is necessary for a cutting tool from the STS, provided that a further condition, $r_{tlife,F}<=t_p[q_e]$ is also not satisfied.

(b) STS Search : If $STS_{d,c,r(s,l)}=1$, then if $r_{tlife,R}>=t_p[q_e]$ tool transfer is necessary as the tool has been located in the STS, else if $r_{tlife,R}<t_p[q_e]$ or $r_{tlife,F}<t_p[q_e]$, then a search of the CTS is initiated.

(c) CTS Search : If $CTS_{c,r,(s,l)}=1$ then if $r_{tlife,R}>=t_p[q_e]$ tool transfer is necessary from CTS to STS, then if $r_{tlife,F}$ and $r_{tlife,R}$ are $<t_p[q_e]$, then creation of a new tool is necessary in the CTS, indexed as $r_{tlife,N}$ with $tlife>t_p[q_e]$.

If the PTS search is successful then machining (event 11) may commence, else machining may only commence on completion of transfer from STS to PTS and CTS to STS.

16.6.3 Event 2 : Unload Tools from PTS

The unloading of worn tools or tools no longer necessary from the PTS is in accordance with the tool retention and tool status rules and is given as follows for each tool :

$$^{2}T_s[r^*,MT_{m,c}]\,[q_e] >= \max\{\,^{10}T_f[r^*,MT_{m,c}]\,[q_.],\ MT_{m,c}AVT\}$$

suggesting that tools can only be unloaded at the end of machining or when the PTS is considered to be inactive.

$$^{2}T_f[r^*,MT_{m,c}]\,[q_e] = {}^{2}T_s[r^*,MT_{m,c}]\,[q_e] + t_p[r^*,MT_{m,c}]$$

where $t_p[r^*,MT_{m,c}]$ is the time to unload r^*.

16.6.4 Event 3 : Load Tools at STS

Tool loading of requested tool onto tool transporter, $TT_{q,c}$, is subject to the selected tool issue strategy described in chapter eleven. In the case of tool kit issue then all tools for a particular part type will be loaded upto the capacity of the transporter, c. In the case of single tools then the machining list is examined for further tools that may be transferred in this loading. Other tool issue strategies will similarly determine the tools to be loaded and the time taken to perform this activity. Generally the time relations are as follows :

$${}^{3}T_s[r^*,STS_{d,c},TT_{q,c}]\ [q_e] >= \max \{ STS_{d,c}AVT, TT_{q,c}AVT \}$$

This rule involves decision making at the second and third levels which correspond to the selection of a transport device among candidate devices and the determination of a tool transfer schedule.

$${}^{3}T_f[r^*,STS_{d,c},TT_{q,c}]\ [q_e] = {}^{3}T_s[r^*,STS_{d,c},TT_{q,c}]\ [q_e] + t_p[r^*,STS_{d,c},TT_{q,c}]$$

where $t_p[r^*,STS_{d,c},TT_{q,c}]$ is the combination of search, load and exchange times for each tool from the STS into the tool transporter and r^* denotes the tool or tools transferred.

16.6.5 Event 4 : STS to PTS Tool Transfer

The movement of the tool transporter from the secondary tool store, after event 3, to the machine which originated the request for a cutting tool is in accordance with the tool transporter rules, presented in chapter twelve, and is given as :

$${}^{4}T_s[r^*,STS_{d,c},MT_{m,c}]\ [q_e] >= {}^{3}T_f[r^*,STS_{d,c},TT_{q,c}]\ [q_e]$$

$${}^{4}T_f[r^*,STS_{d,c},MT_{m,c}]\ [q_e] = {}^{4}T_s[r^*,STS_{d,c},MT_{m,c}]\ [q_e] + t_p[r^*,TT_{q,c},STS_{d,c},MT_{m,c}]$$

where $t_p[r^*,TT_{q,c},STS_{d,c},MT_{m,c}]$ is the transfer time from STS to the machine tool using the transport device $TT_{q,c}$.

16.6.6 Event 5 : Unload Tools Into PTS

The unloading of each tool transferred into the PTS from the transporter, after the transporter has reached its destination or on completion of event 4, is given as :

$${}^{5}T_s[r^*,TT_{q,c},MT_{m,c}]\ [q_e] >= {}^{4}T_f[r^*,STS_{d,c},MT_{m,c}]\ [q_e]$$

$${}^{5}T_f[r^*,TT_{q,c},MT_{m,c}]\ [q_e] = {}^{5}T_s[r^*,TT_{q,c},MT_{m,c}]\ [q_e] + t_p[r^*,TT_{q,c},MT_{m,c}]$$

where $t_p[r^*,TT_{q,c},MT_{m,c}]$ is the addition of the time to locate an empty pocket and the time to insert the tool in this pocket. This is subject to the insertion rules.

16.6.7 Event 6 : Loading of Tools at PTS

The collection of tools at the PTS for return to the STS subject to the tool issue (see chapter eleven) and tool management strategies (see chapter ten). This event is scheduled after the tools have been made ready for unloading from the PTS, and a suitable transporter request has been flagged, is given as

$$^{6}T_s[r^*,MT_{m,c},TT_{q,c}]\ [q] > \max\{\ ^{2}T_f[r^*MT_{m,c}]\ [q];\ TT_{q,c}AVT\ \}$$

$$^{6}T_f[r^*,MT_{m,c},TT_{q,c}]\ [q] = {}^{6}T_s[r^*,MT_{m,c},TT_{q,c}]\ [q] + t_p[r^*,MT_{m,c},TT_{q,c}]$$

where $t_p[r^*,MT_{m,c},TT_{q,c}]$ is the addition of the time to locate the tool to be removed and the time to put it into the transporter.

Events 5 and 6 may either take place simultaneously in that a tool is removed and another is inserted or event 6 may take place on the assumption that there is an auxilliary worn tool store into which tools have previously been unloaded. The consideration of the machine at this stage is also necessary as a removable PTS would effect the time, $t_p[-]$.

16.6.8 Event 7 : Tool Transfer PTS to STS

The transfer of tools, or an empty transporter back to its origin after completion of event 6, the STS, is given as :

$$^{7}T_s[r^*,MT_{m,c},STS_{d,c}]\ [q] >= {}^{6}T_f[r^*,MT_{m,c},TT_{q,c}]\ [q]$$

$$^{7}T_f[r^*,MT_{m,c},STS_{d,c}]\ [q] = {}^{7}T_s[r^*,MT_{m,c},STS_{d,c}]\ [q] + t_p[r^*,TT_{q,c},MT_{m,c},STS_{d,c}]$$

where $t_p[r^*,TT_{q,c},MTm_{,c},STS_{d,c}]$ is the transfer time to the STS from the machine tool using the transport device $TT_{q,c}$.

16.6.9 Event 8 : Unload Tools in STS

The unloading of the returned tools into the STS, on completion of event 7 and at the time that the STS server is ready, is given by :

$$^{8}T_s[r^*,TT_{q,c},STS_{d,c}]\ [q] > \max\{\ ^{7}T_f[r^*MT_{m,c},STS_{d,c}]\ [q],\ STS_{d,c}AVT\ \}$$

$$^{8}T_f[r^*,TT_{q,c},STS_{d,c}]\ [q] = {}^{6}T_s[r^*,TT_{q,c},MT_{m,c}]\ [q] + t_p[r^*,TT_{q,c},STS_{d,c}]$$

where $t_p[r^*,TT_{q,c},STS_{d,c}]$ is the time to search for a vacant location in the STS and to unload the tool into that location.

16.6.10 Event 9 : Set-Up

The set-up of the machine to perform the activity q_e on the machine $MT_{m,c}$ is given by either of the following :

(a) Tool from STS :

$^{9.1}T_s[r,MT_{m,c}]\,[q_e] >= \max\{^{11}T_f[r^*,MT_{m,c}]\,[q]\,,\ ^{5}T_f[r^*,TT_{q,c},MT_{m,c}]\,[q_e]\,,\ ^{10}T_f[P_{i,j,k},MT_{m,c}]\,[q_e]\,\}$

(b) Tool from PTS :

$^{9.2}T_s[r,MT_{m,c}]\,[q_e] >= {}^{11}T_f[r^*,MT_{m,c}]\,[q]$

The finish time for either of the cases above is given by :
$^{9.1/9.2}T_f[r,MT_{m,c}]\,[q_e] >= {}^{9.1/9.2}T_s[r,MT_{m,c}]\,[q_e] + t_p[r,MT_{m,c}]$

where $t_p[r,MT_{m,c}]$ is the tool exchange and magazine indexing times specified for the machine. The setting up of the machine tool to machine the activity is also dependent upon the operation assignment rules selected (see chapter fifteen).

16.6.11 Event 10 : Part Loading onto Machine

The loading of a pallet onto a machine is considered within the algorithm but not the movement of a part from a part stores. The loading and transfer of a pallet to the machine is assumed to be instantaneous and the transporter and part as available, i.e part transfer time is negligible and parts are always available. The time relations are as follows :

Part Loading onto a machine is given as :

$^{10}T_s[P_i,PT_{v,c},MT_{m,c}]\,[q_e] >= {}^{12}T_f[P^*,MT_{m,c},PT_{v,c}]\,[q]$

$^{10}T_f[P_i,PT_{v,c},MT_{m,c}]\,[q_e] = {}^{10}T_s[P_i,PT_{v,c},MT_{m,c}]\,[q_e] + t_p[PT_{v,c},MT_{m,c}]$

where $t_p[PT_{v,c},MT_{m,c}]$ is either of two times : Firstly, the time to load a part from part stores onto a part transfer device, $PT_{v,c}$, transfer it to machine and unload into machine buffer or secondly to index the pallet to present the next part on the pallet for machining.

16.6.12 Event 11 : Machining

Machining may commence immediately upon loading of the part onto the machine table or on completion of indexing of the pallet to gain access to the next part, if several parts are on a pallet.

$^{11}T_s[r^*,MT_{m,c}]\,[q_e] >= {}^{10}T_f[P_i,PT_{v,c},MT_{m,c}]\,[q_e]$

$^{11}T_f[r^*,MT_{m,c}]\,[q_e] = {}^{11}T_s[r^*,MT_{m,c}]\,[q] + t_p[r_{s,i},q_e,MT_{m,c}] + t_p[q_e]$

where $t_p[r_{s,i},q_e,MT_{m,c}]$ is the time to select a cutting tool and load it into the spindle and $t_p[q_e]$ is the machining time for activity q_e.

16.6.13 Event 12 : Part Unloading from the Machine

The unloading of a part from the machine is in reverse to the loading of the part on to the machine tool. The unloaded part is returned to the part store in negligible time on a selected part transporter which is readily available or alternatively the pallet is just indexed to present the next part for machining. The time relation is given by :

$$^{12}T_s[P_j,MT_{m,c},PT_{v,c}]\,[q_e] >= {}^{11}T_f[r^*,MT_{m,c}]\,[q_e]$$

$$^{12}T_f[P_j,MT_{m,c},PT_{v,c}]\,[q_e] = {}^{12}T_s[P_j,MT_{m,c},PT_{v,c}]\,[q_e] + t_p[MT_{m,c},PT_{v,c}]$$

where $t_p[MT_{m,c},PT_{v,c}]$ is either of two times : Firstly, the time to unload a part into part stores from a part transfer device, $PT_{v,c}$, transfer it from a machine and unload it from a machine buffer or secondly to index the pallet to present the next part on the pallet for machining.

16.6.14 Secondary to Central Tool Store Algorithm

In parallel to the working of this algorithm is another which comes into effect when the number of worn tools in the STS reaches a predefined limit as specified in the STS tool retention rules. The algorithmic steps are repeated but with the CTS now acting as the STS and each cells STS acting as the individual PTS's in terms of loading, tranporting and unloading of tools.

16.6.15 Completed Activity

The completed activity, q_e, is now given an index of a=1 and deleted from the cutset, Q_{cut}. The activity succeeding q_e, if any, on the machining list is then added to Q_{cut} in its place. The process then recommences for the next selected activity till all activities in all machining lists are referenced with a=1.

16.7 Concluding Remarks

The algorithms presented in this chapter form the backbone of the tool flow modelling. They provide the infrastructure around which different operating strategies and decision rules may be selected and applied at different levels to influence events. The incorporation of these algorithms in the software is provided on high capacity diskette media or through a software listing available from the author.

Tool-oriented algorithms have been developed and are presented with flowcharts in chapter fifteen and seventeen. The simplified representation of the tool-oriented algorithm within the tool flow modelling is as for the workpiece-oriented algorithms. The essential difference comes in the initial determination of the *exceptional* parts from within a part cluster set. The subdivision of a part set into exceptional parts, the strategic selection of parts and the determination of the minimum tooling requirement is discussed in the following chapter.

The algorithms presented are developed around the tool flow representations built up in chapter six and follow the cellular flow decision rules specified in chapters seven and thirteen. The algorithms present a relatively quick method for evaluating tool flow systems. The method based on the heuristic procedures using the decision rules and strategies may also be used as a powerful tool to control the operation of a tool flow network in a practical sense. The algorithm has been examined and tested through computational experiments and validated with industrial case studies (see appendices three to five).

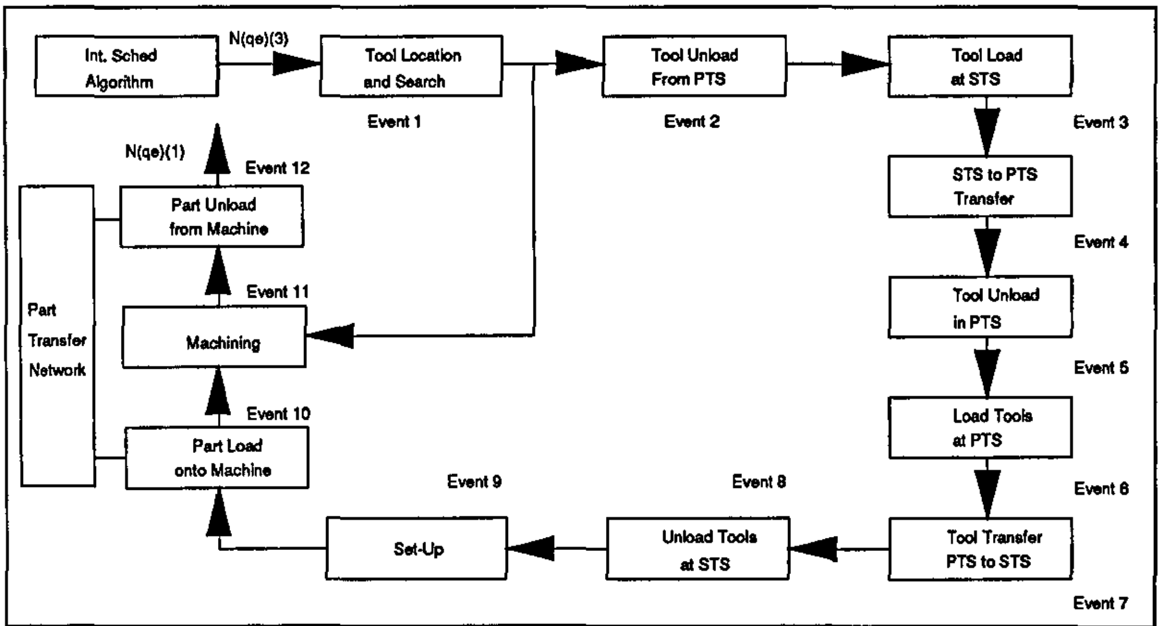


Figure 16.1	CELL TOOL FLOW ALGORITHM - EVENT CHAIN	LUT - FMS Research Group

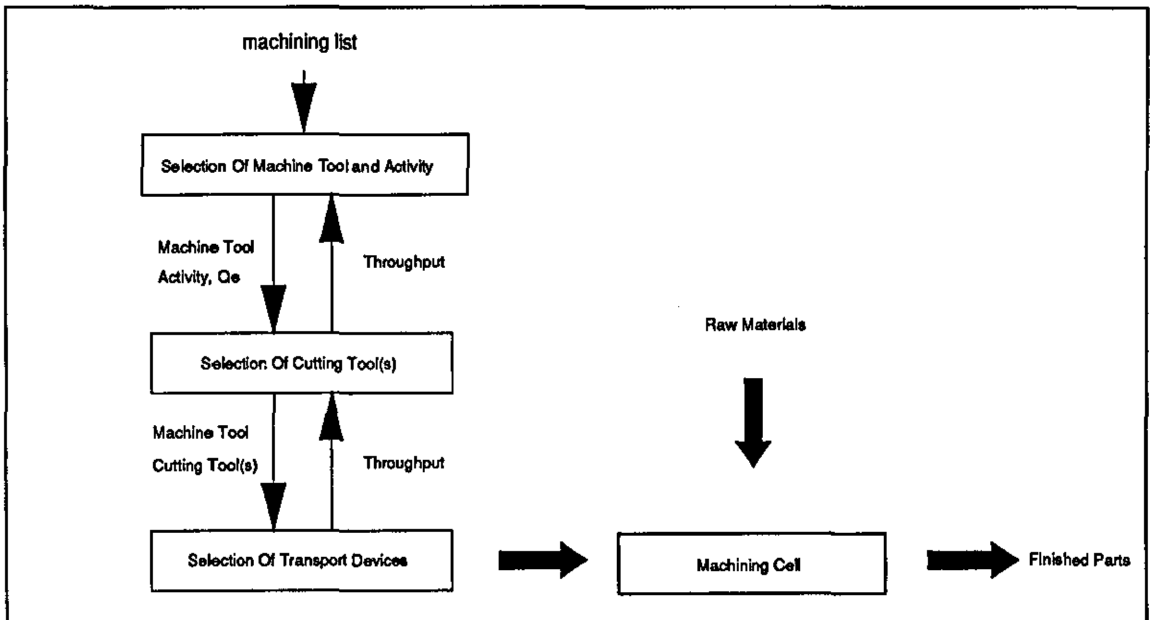


Figure 16.2	HIERARCHICAL ALGORITHM DECISION STRUCTURE	LUT - FMS Research Group

Chapter 17:
STRATEGIC ALGORITHMS

17.1 Introduction

This chapter describes the strategic algorithms which are a prerequisite to the general tool flow algorithms presented in the previous chapter. These algorithms are based on the tool management and tool issue strategies discussed in chapters ten and eleven and the tool life management discussion in chapter fourteen.

17.2 Role of the Strategic Algorithms

The strategic algorithms are so termed because they are based on the strategies for tool management and for tool issue to the machines rather than on the decision rules as is the case in the general tool flow algorithms. The algorithms are described for each of the tool management strategies viz. tool-oriented and workpiece-oriented.

The essential role of these algorithms is to determine from a tooling analysis of each machine's machining list, the minimum number of tools necessary for servicing of these lists according to selected tool issue strategies and the specification of tool life [64]. The determination of this minimum tooling requirement (MTR) is considered sufficient in many instances, in that a forecast is possible of the minimum number of tools (including sister and duplicate tools) that may be required to be held at, say, the secondary tool store (STS), for a given manufacturing period. The MTR also has value in the specification of *safety stock* or for the triggering off of order levels for tools, where long lead times for tool delivery or refurbishment are anticipated. This particular situation was examined, modelled and validated for the Automax cell at British Aerospace, Preston.

Alternatively, the MTR may be used as a means of specifying the tools to be assigned for the machining of activities within the machining lists. This consequently acts as a starting point for the general tool flow algorithms which in turn schedules the transfer of the tools preassigned in the MTR module. This has obvious implications in practice for the initial loading of tools into the STS and the subsequent assignment, management and tracking of tools around an installation.

Finally, the strategic algorithms will not only provide an estimate of the capacities required but also, and particularly in the case of the tool-oriented management strategy, provide for the specification of preferred tool cluster set, tool package and kit. This usage of the algorithms is illustrated, see appendix four, through the use of another industrial case study of a three machine Makino cell at Cummins Engines, Daventry.

17.3 The MTR Module and Tool Flow Modelling

The strategic algorithms are embedded within the 'front end' or user interface of the general tool flow modelling. The algorithms are implemented as a separate module, thus, permitting the use of the strategic algorithms on their own for determination of the MTR or as a predecessor to the general tool flow algorithms to model and examine throughputs and actual tooling requirements. The lathes may or may not differ from the MTR and takes into consideration tool flow factors such as availability of tools, tool transporters and multiple assignments of tools.

17.4 The Workpiece-Oriented Strategic Algorithms

The algorithms are presented, for simplicity and clarity, through the use of flowcharts rather than in the form of equations as adopted in chapter sixteen. The algorithms are presented for the different tool issue strategies described in chapter eleven and in respect to the tool rationalisation rules in chapter fourteen.

17.4.1 Tool Kit Assignment

The algorithm, *figure 17.1*, commences with the issue of a unique tool for each part operation on each job on each machine. This assignment, which in itself is a rationalisation rule, provides a 'maximum' tooling requirement. This requirement is the basis of the machine rationalised MTR for kits.

For each tool assignment to a particular job in a particular machining list, a search is effected across the activites within a job or palletised set of parts for an activity that may possibly use the same tool type. The objective is to extract the maximum usage of the tool across the job before the tool exhausts its residual life. If insufficient life is available, another tool of the same type is assigned. The tool number is assigned to the activity in this MTR module. The search may, and usually does, dramatically reduce the 'maximum' tooling requirement.

Several checks are necesssary to ensure logical usage of this tool, particularly in the case of machines possessing more than one spindle and involved in simultaneous machining of the same activity on the same workpiece. The checks confirm that the tool is not assigned to two or more of the same spindles or for machining of the same activity. A further check is made to ensure that sufficient life is available to machine the activity to which the tool is assigned. Other checks are necessary in the case of kits to confine usage of the tool to a particular part type, job or palletised set of parts. These checks are shown in *figures 17.2 and 17.3*. The checks so completed then confirm the tool assignment not only for each spindle but also for each operation, part, machine and cell. The summation of these tools so distributed within a machining list, or as the rationalisation rule and issue strategy may dictate, will specify the MTR for the servicing of the production requirements for the manufacturing period, *figure 17.4*.

17.4.2 Single Tool(s) Assignment

The consideration of the single tools issue strategy is as for the kit assignment except that the tools assigned are not restricted to the part type or job. The search is more detailed and focuses on each and every stage in a machining list in the case of the machine rationalisation rule and further extends the search to all machining list in the case of the cell rationalisation rule. The objective here is to specify the maximum usage of the tool if the residual tool life of the tool permits. Similar checks are made as for the kit assignment algorithm but additionally to confine usage of the tool to specific machines or to distribute freely across machining lists.

The MTR so determined in either of the rationalisation cases, *figures 17.5 and 17.6*, will almost certainly be less than the actual tooling requirement determined from modelling of the flow. This is particularly true in the case of cell rationalisation where although the tool inventory is low in the MTR module, flow factors and delays due to transporter and tool availability, will require further tools to be added to minimise delays and reduce throughput time. This situation can only be examined by running the tool flow model.

17.4.3 Differential Kit Assignment

The determination of a MTR for differential kit assignments is as for the issue of single tools as the concept of differential kits implicitly implies sharing of tools across part types but is restricted to assignments within a machining list. Thus the difference in this strategy evolves in the movement of tools to the machines (which emulates the kit transfer, but moves only the difference from the previous kit) and not in the determination of the MTR.

17.5 Cluster Tooling Analysis

The cluster tooling analysis specifies mutually independent tool-part groups (tool cluster sets) some or all of which may be independent, determines the MTR for a given order requirement, and specifies preferred tool cluster sets and their assignment to the machines which will subsequently determine the part assignments, the essence of a tool-oriented approach.

The cluster analysis technique employed for this algorithm is based on Kings *Rank Order Clustering* (ROC) approach [178]. This technique was selected for its simplicity and ease of usage. A whole host of other techniques are available ranging from similarity coefficient methods upto the analytical techniques [170]. The ROC method falls in the latter category.

The clustering method concentrates on commonality of tools as the criteria for cluster set formation. The philosophy, behind this method, is essentially that in any machining cell there will be quite a natural division of tools into sets and parts into families: what the analysis seeks to achieve is the identification of such sets/groups/clusters which will consequently determine the part assignments to the machines. The actual processing sequence of the parts is ignored in the formation of tool cluster sets, since once cluster sets are determined their assignment is a separate exercise, in accordance with the capacities and issue strategy described in chapter eleven.

The cluster tooling analysis (CTA) has been included within a separate module called the computer assisted cluster analysis (CACA) module. The analysis, *figures 17.7 and 17.8*, commences with the building up of a two dimensional array for parts and tools. The CTA 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 *1* entries into an arrangement whereby the *1* entries are contained in mutually exclusive groups. *Figure 17.9* , is an example, from an actual industrial case study, of an initial tool-part matrix involving tools (labelled 1-100) and eight components (labelled 1 to 8). The clustering algorithm is then designed to generate a specific pattern in which if the rows and columns are read as binary numbers, they will appear in the matrix ranked in decreasing numerical order.

The base of the binary system is *2* and successive digit positions from left to right of a row have respectively the weights 2^0, 2^1, 2^2, 2^3, .. 2^N . These weightings are used to convert the binary numbers into the more common decimal system. Thus, every row or column pattern of blank or unity entries can be considered as eqivalent to a binary word with a corresponding unique decimal number equivalent form. This equivalence is the basis for the algorithm.

Although, in the example provided, it is assumed that all tool-activity processing on a part is carried out at the same machine in the same assignment, this does not have to be the case. If a part is to visit several machines for processing, then each visit and its associated activities may be clustered, not necessarily the whole part and its processing. Thus in the former case several columns may represent a part type and in the latter situation a part is denoted by a single column.

17.5.1 The Tool Clustering Algorithm - Ranking Rows and Columns

The algorithm can be described as follows: The pattern of cell entries of each row is read as a binary word and converted to its decimal equivalent. The rows are then ranked in decreasing decimal value. Rows with the same value are ranked in the manner of the original matrix. A check is initiated to ensure that the current row order is different from the previous row order. If this is not so then no further ranking of rows is possible. A checking procedure has been written within the CACA module to perform this function, *figure 17.10* . The same procedure is then initiated but this time for the columns. *Figure 17.11* shows this ranking after one iteration. When no more ranking is possible for either the rows or columns, the reformed matrix is examined for clusters. *Figure 17.12* shows this reformed matrix.

It is assumed that the algorithm would normally begin with the original tool-part matrix, but the procedure is iterative and it is possible to start with any rearranged form of the matrix. The algorithm is efficient and will converge in a finite number of iterations. It has the added advantage that although primarily intended as a computer procedure, it can if necessary be used with manual computations for problems of moderate size.

17.5.2 The Tool Clustering Algorithm - Exceptional Elements

If the tool-part matrix can be divided into clusters then the ROC algorithm will do this. In practice, as shown for this example of a case study in *figure 17.12* , the data will not in general always be capable of division into such mutually exclusive groups. It is in this type of situation that the ROC algorithm is particularly effective as already described by King [168].

The procedure for dealing with these elements which provide overlap between clusters is to simply rerun the algorithm with the exceptional elements suppressed i.e. temporarily overwriting them as *0* , *figure 17.13*, until the final mutually independent tool clusters are generated, *figure 17.14* .

17.5.3 The Tool Clustering Algorithm - Reinstatement of Tools

The suppressed tools need to be reinstated in the final matrix. Thus, where particular cutting tool types are required by a large number of part types as is the case in practice, these tools may be viewed as *bottleneck* tools, to the extent that, if their number could be increased, then a mutually exclusive tool cluster solution may be found. Hence, if additional tools of the same type are considered for all cases of overlap of part machining requirements, then it will always be possible to find a satisfactory solution. Whether or not it is economically or practically feasible to provide for multiple tools of the same type required in each case is another matter.

A relaxation procedure is suggested by King [169], which has been translated for CTA, to determine the number of duplicated tools required to eliminate the bottleneck as well as their disposition in the block diagonal structure produced. This procedure may greatly increase the dimension of the matrix and is thus limited for use on problems of modest size. To this purpose King has provided an extension algorithm entitled ROC2 [170], discussed in section 17.7. It was not considered necessary to implement this extension as the CACA module, based on a highly interactive industry standard spreadsheet package, was sufficient for handling large tool-part matrices.

The general rule for reinstatement of tools is simply that duplicate tools of a particular type , may, if they occur in the same part set in the final solution generated by the CTA within the CACA module, be recomposed into a single tool type. At this, the last stage in CTA, the necessary tool type duplications required as well as the tool cluster sets are obtained, *figure 17.15* .

17.6 Sister Tooling Predictions for Clusters

The final solution yielded by the CTA, will generate tool cluster sets. It is necessary to determine the number of tools to be contained within each cluster to service a given order requirement. For this purpose a further algorithm has been developed.

The algorithm replaces each *1* or *0* entry with an accumulated tool usage time on a particular part type and with respect to the order requirement specified for the manufacturing period under consideration, *figure 17.16* . These accumulated times are summed for each tool type in each tool cluster set to obtain a cumulative tool use time. The specification of initial tool life and percentage of tool life available together with the cumulative use time, will specify the minimum number of tools required for this tool type which is in turn translated into the number of sister tools required for the tool type within a particular cluster. The further summation of the sister tool type and the number of basic tool types will give the number of tools required for the tool cluster set, *figure 17.17*.

17.7 The ROC2 Algorithm

In cases where the use of spreadsheet facilities are not available then as the computational complexity of the ROC algorithm is of cubic order, this imposes a severe limitation on the use of this procedure for problems of anything other than what can be handled by the spreadsheet software. The ROC2 algorithm then becomes a better alternative as King [170] claims that overall complexity may be reduced to $O(mn \log(mn))$ compared with $O(mn(m+n))$ achieved previously, where m and n are the rows and columns respectively. Considerable improvement in the computational efficiency can thus be achieved by this process which only has particular relevance where problems involving large tool part matrices are concerned.

The ROC2 Algorithm can be described as follows:

```
REPEAT
 FROM   the last column to the first column
 DO     (* row reordering *)
        locate the rows (tools) with entries; move the
        rows with entries to the head of the row list maintaining
        the previous  order of the entries.
 END DO (* row reordering *)
 FROM   the last row to the first row
 DO     (* column reordering *)
        locate the columns with entries to the head of the column list
        maintaining the previous order of the entries.
 END DO (* column reordering *)
UNTIL (no change) or (inspection required)
```

This implies the use of two hash tables. The first comprises a row list versus a column number and the second a column list versus a row number. The former is used for row reordering and the latter for column reordering. Those columns (rows) with entries are successively edged to the front of the list as described above till it is no longer possible to proceed. This then produces the final ranked matrix from which tool cluster sets may be derived. This procedure and application is described by King and Nakornchai [170].

17.8 Concluding Remarks

The strategic algorithms presented above have obvious implications in practice as well as in the modelling. Furthermore, they provide a predictive facility for examining capacities, tooling requirements and specifying short range schedules. The algorithms are primarily designed for use in prescheduled situations but can also be used in reactive situations such as is found in dynamic scheduling situations or in the environment in which the emulator is designed to operate. In these situations where the look-ahead for each machine is restricted to the next part, unlike a machining list where the look-ahead capability is the last activity of the machining list, then the CACA module or the MTR module, particularly operating with the cell rationalisation rule, becomes very effective in setting up the system for desired operation, ensuring that sufficient tools are available to fulfil the production requirements.

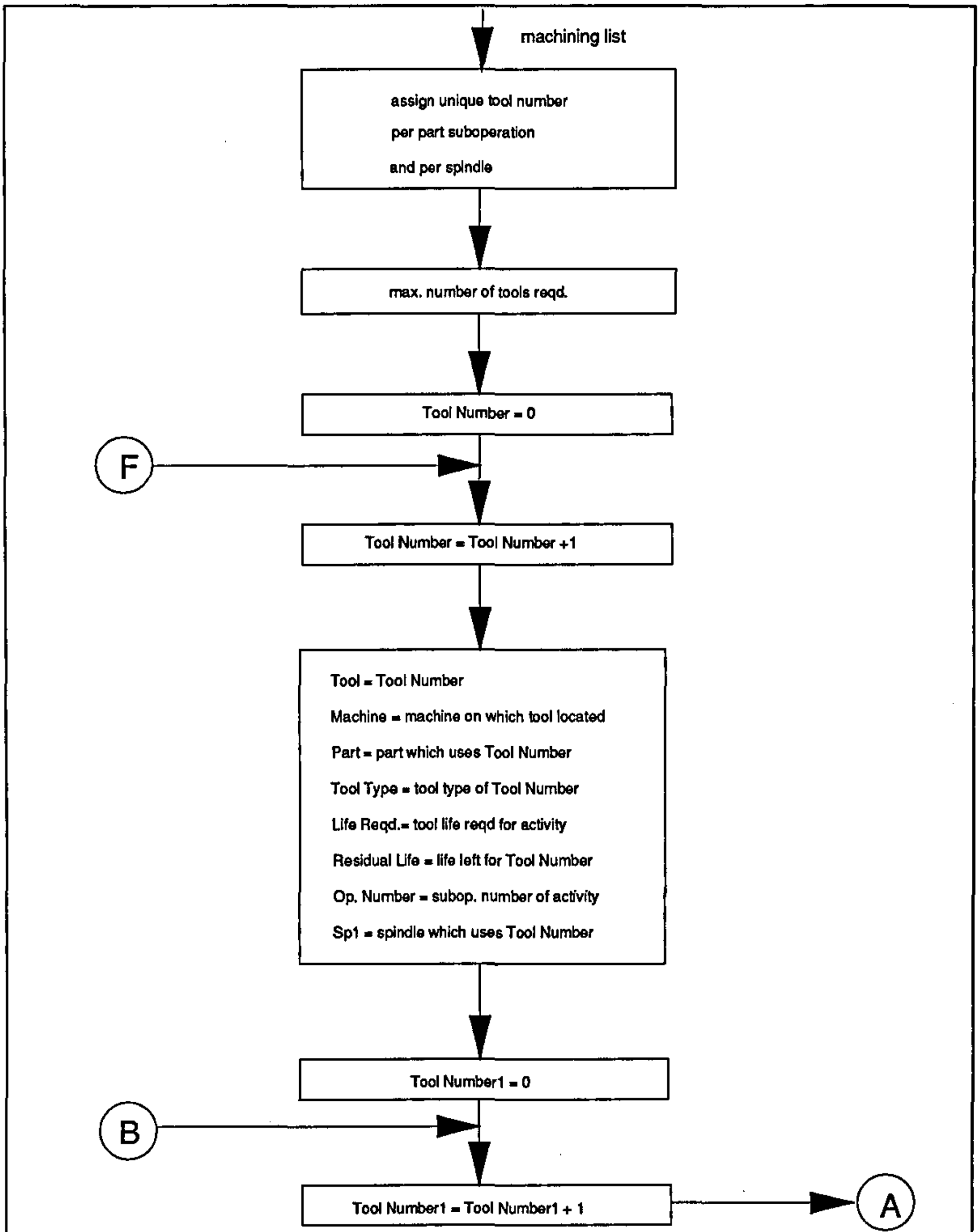


Figure 17.1

MINIMUM TOOLING REQUIREMENT FOR
TOOL KIT ASSIGNMENT WITH
MACHINE RATIONALISATION

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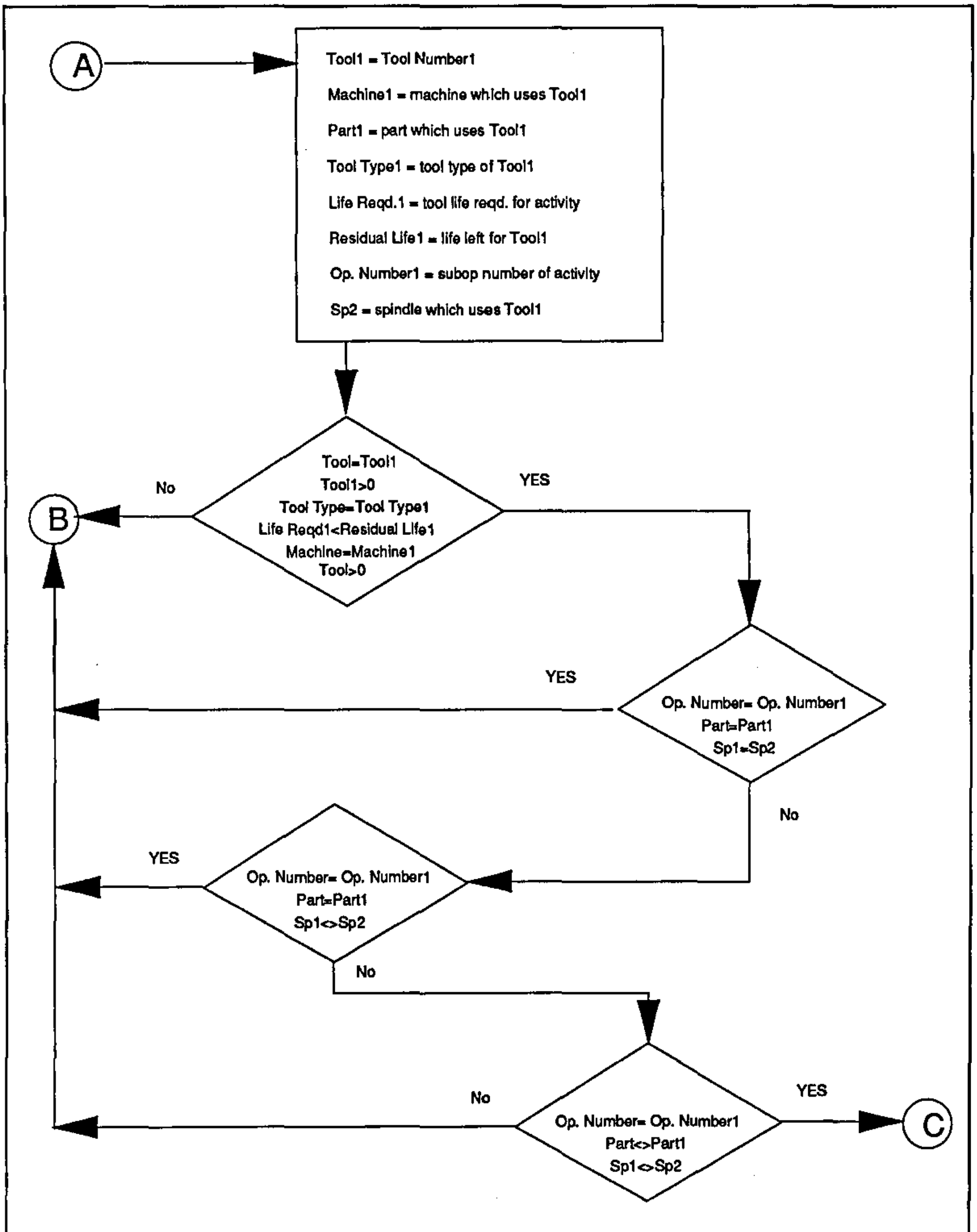

Figure 17.2 (Figure 17.1 cont'd)	MINIMUM TOOLING REQUIREMENT FOR TOOL KIT ASSIGNMENT WITH MACHINE RATIONALISATION	LUT-FMS RESEARCH GROUP

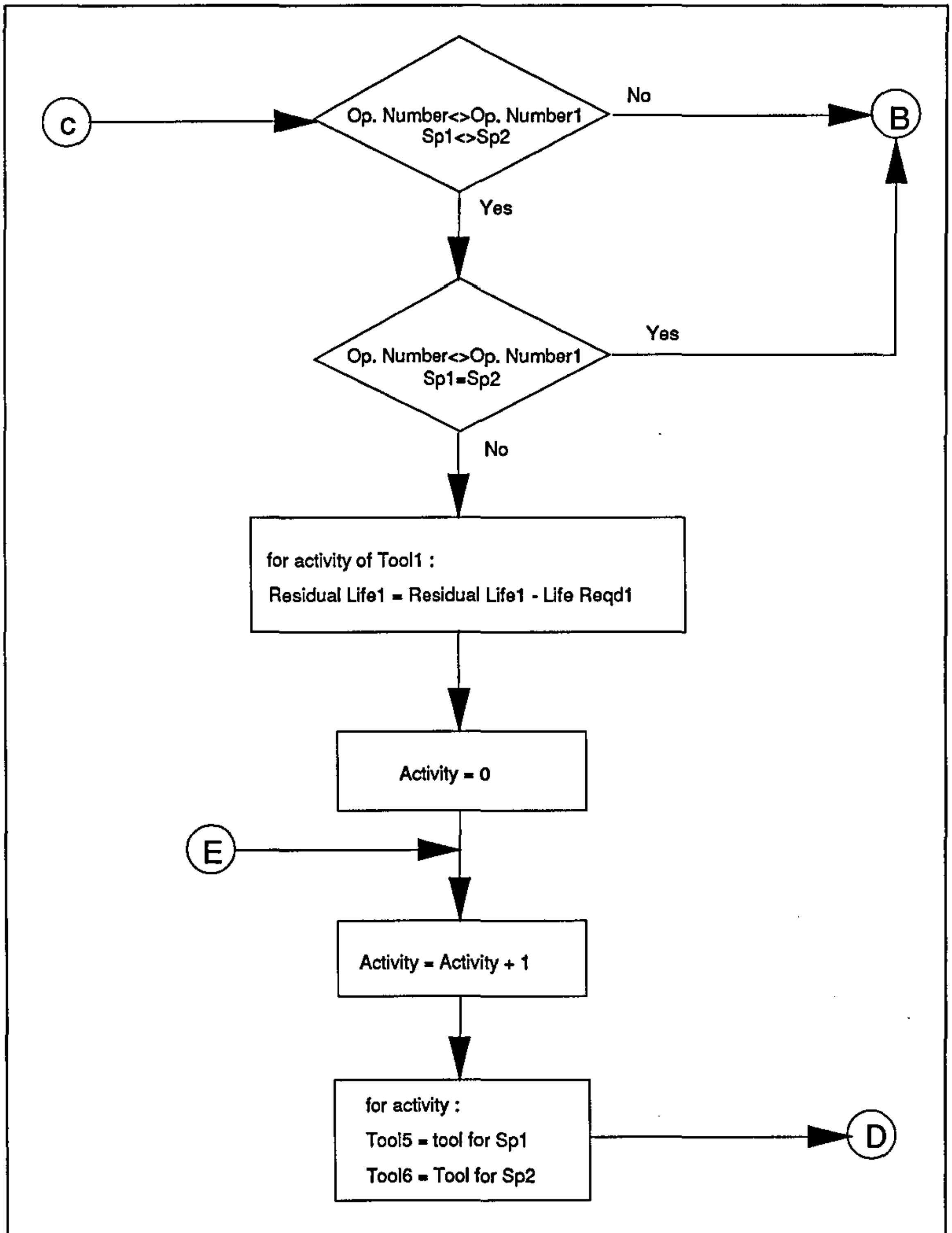

Figure 17.3 (Figure 17.1 cont'd)	MINIMUM TOOLING REQUIREMENT FOR TOOL KIT ASSIGNMENT WITH MACHINE RATIONALISATION	LUT-FMS RESEARCH GROUP

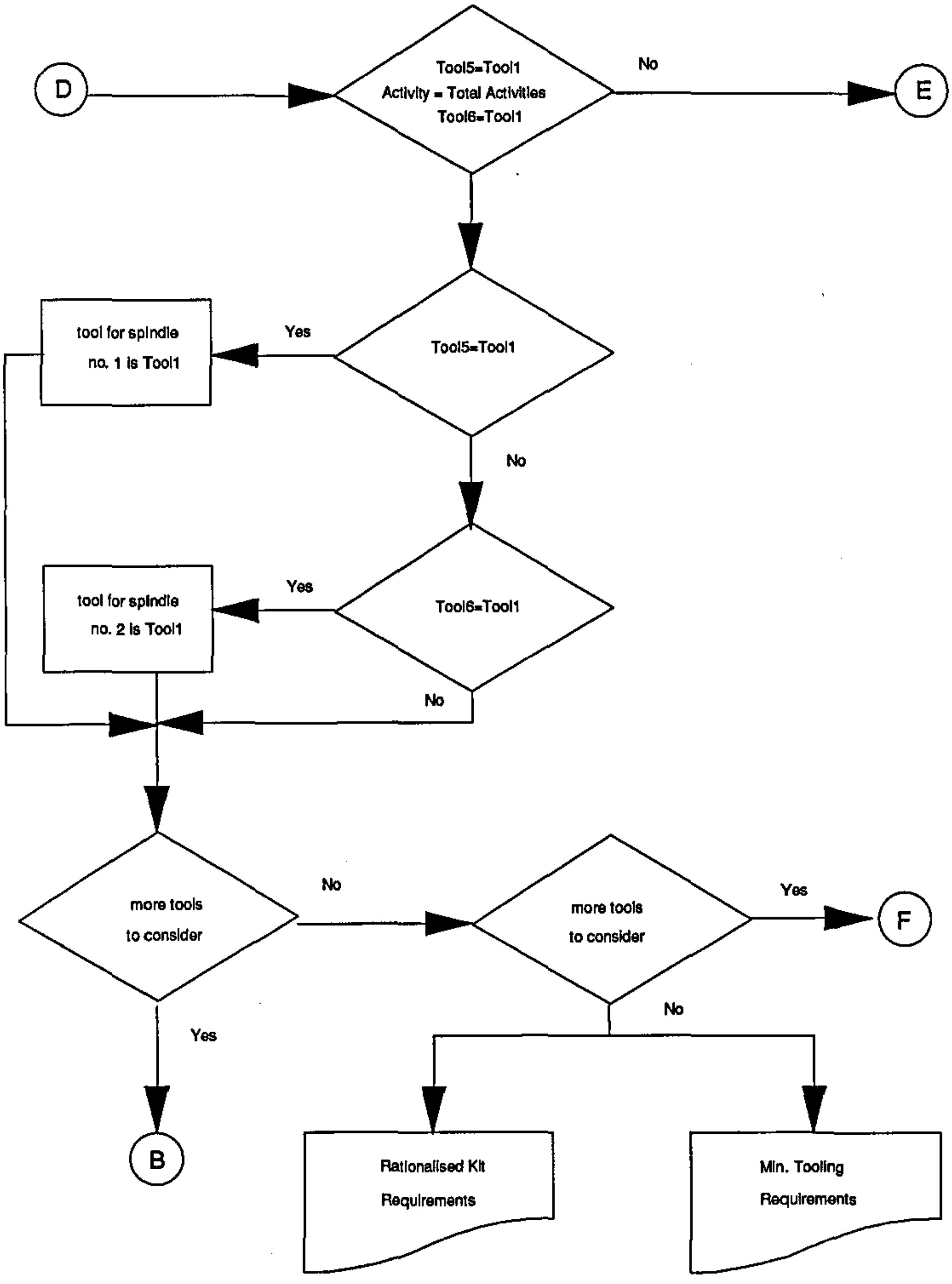

Figure 17.4 (Figure 17.1 cont'd)	MINIMUM TOOLING REQUIREMENT FOR TOOL KIT ASSIGNMENT WITH MACHINE RATIONALISATION	LUT-FMS RESEARCH GROUP

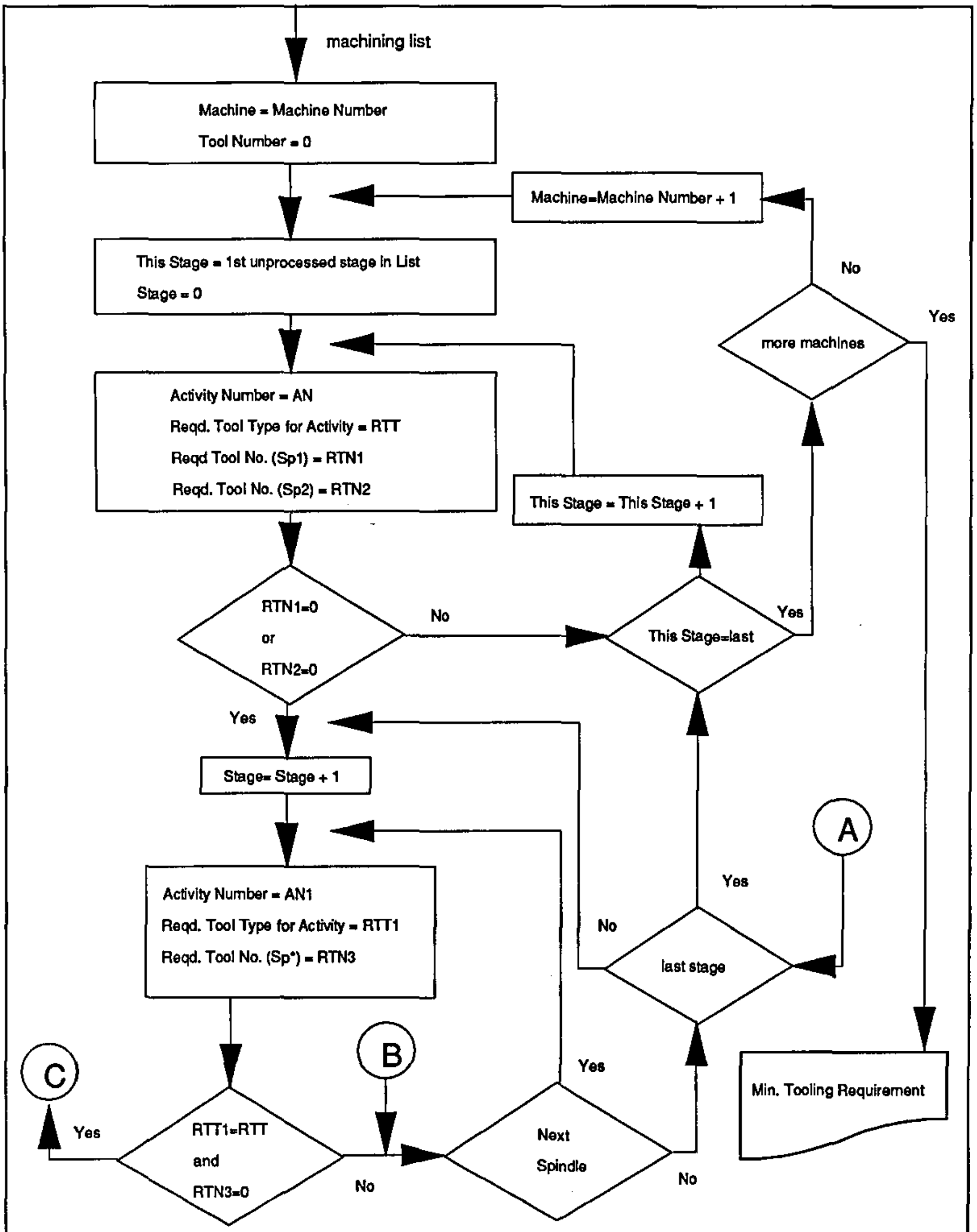

Figure 17.5	MINIMUM TOOLING REQUIREMENT FOR SINGLE TOOL(S) ASSIGNMENT AND MACHINE OR CELL RATIONALISATION	LUT-FMS RESEARCH GROUP

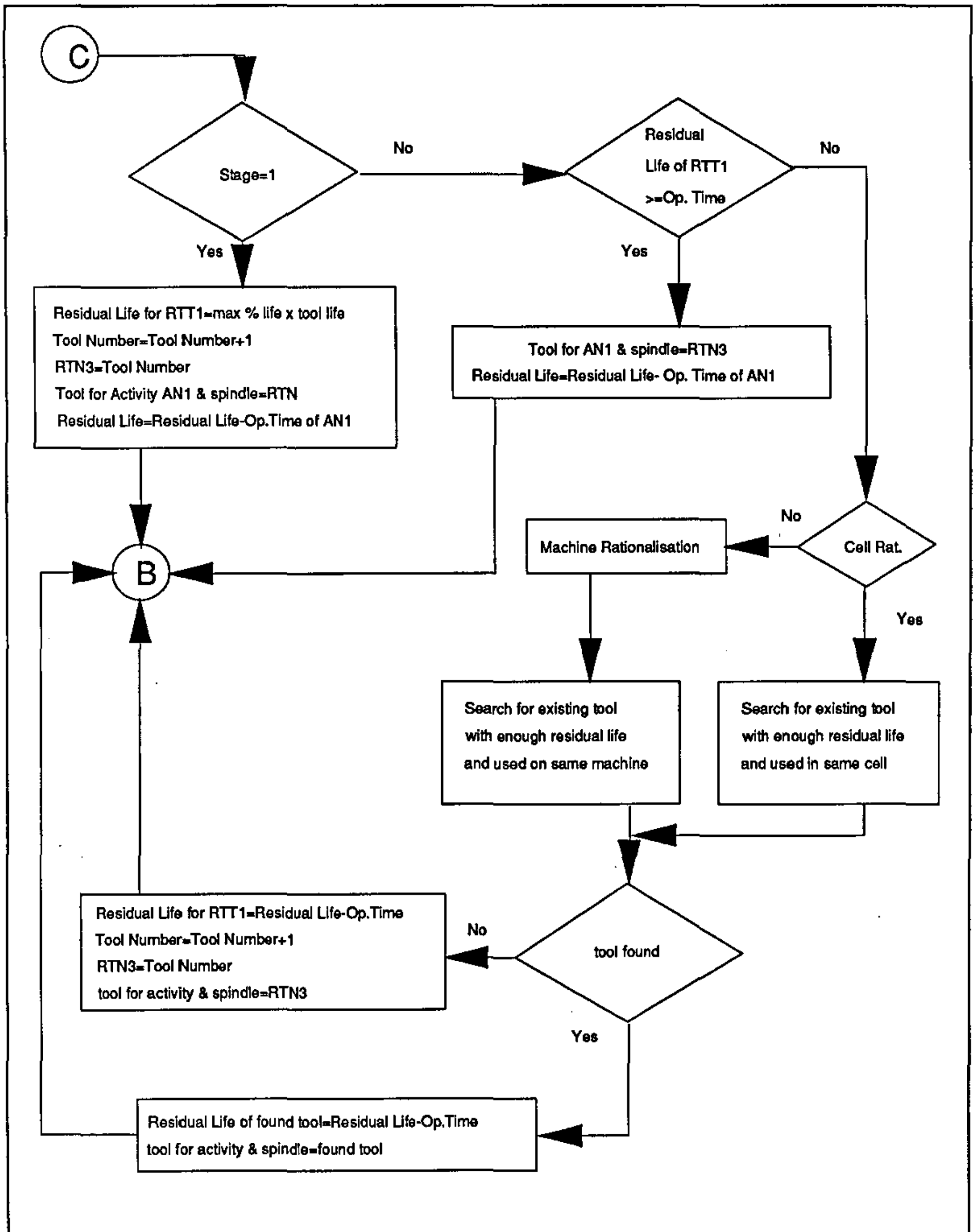

Figure 17.6 (Figure 17.5 cont'd)	MINIMUM TOOLING REQUIREMENT FOR SINGLE TOOL(S) ASSIGNMENT AND MACHINE OR CELL RATIONALISATION	LUT-FMS RESEARCH GROUP

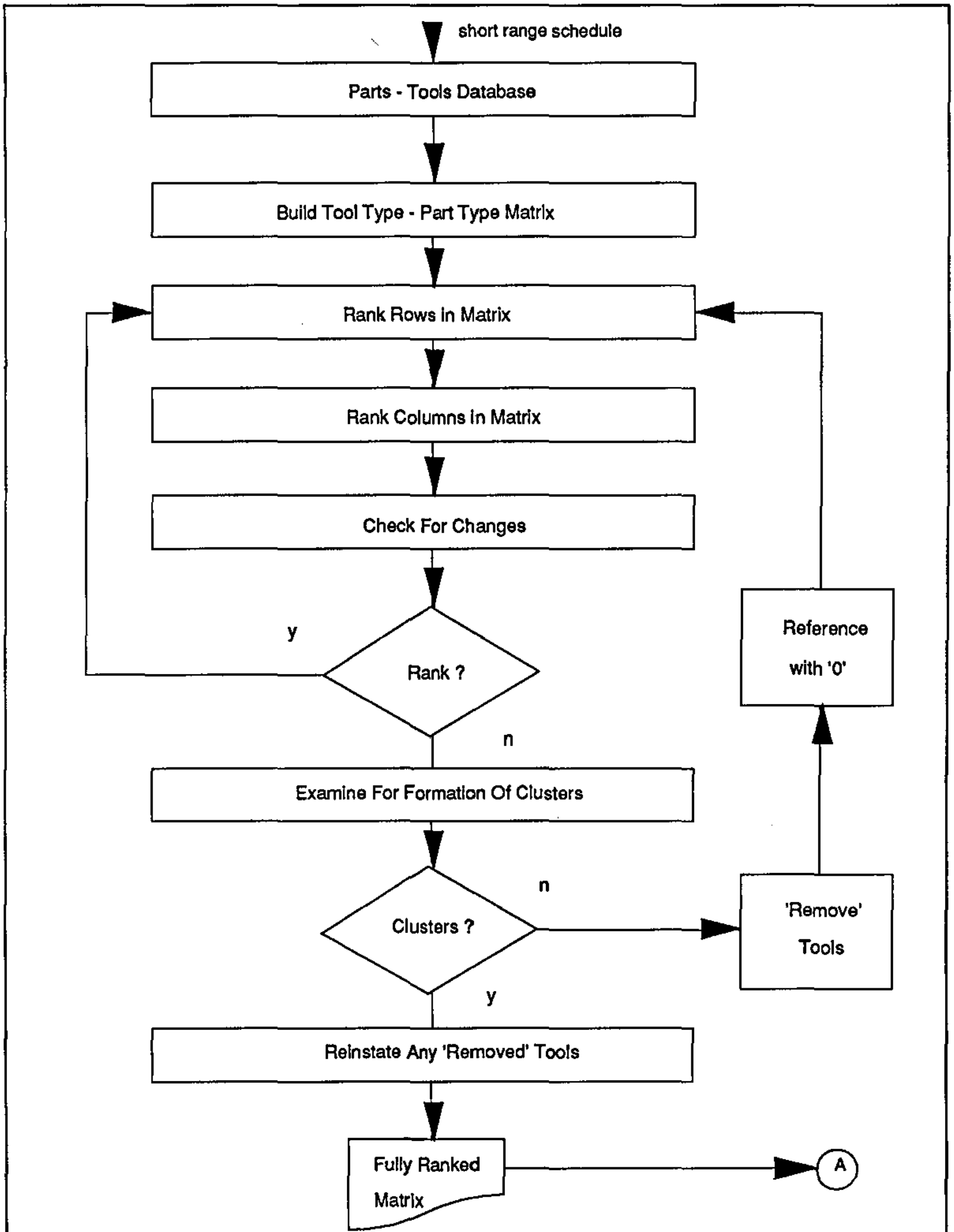

Figure 17.7	CLUSTER TOOLING ANALYSIS	LUT-FMS RESEARCH GROUP

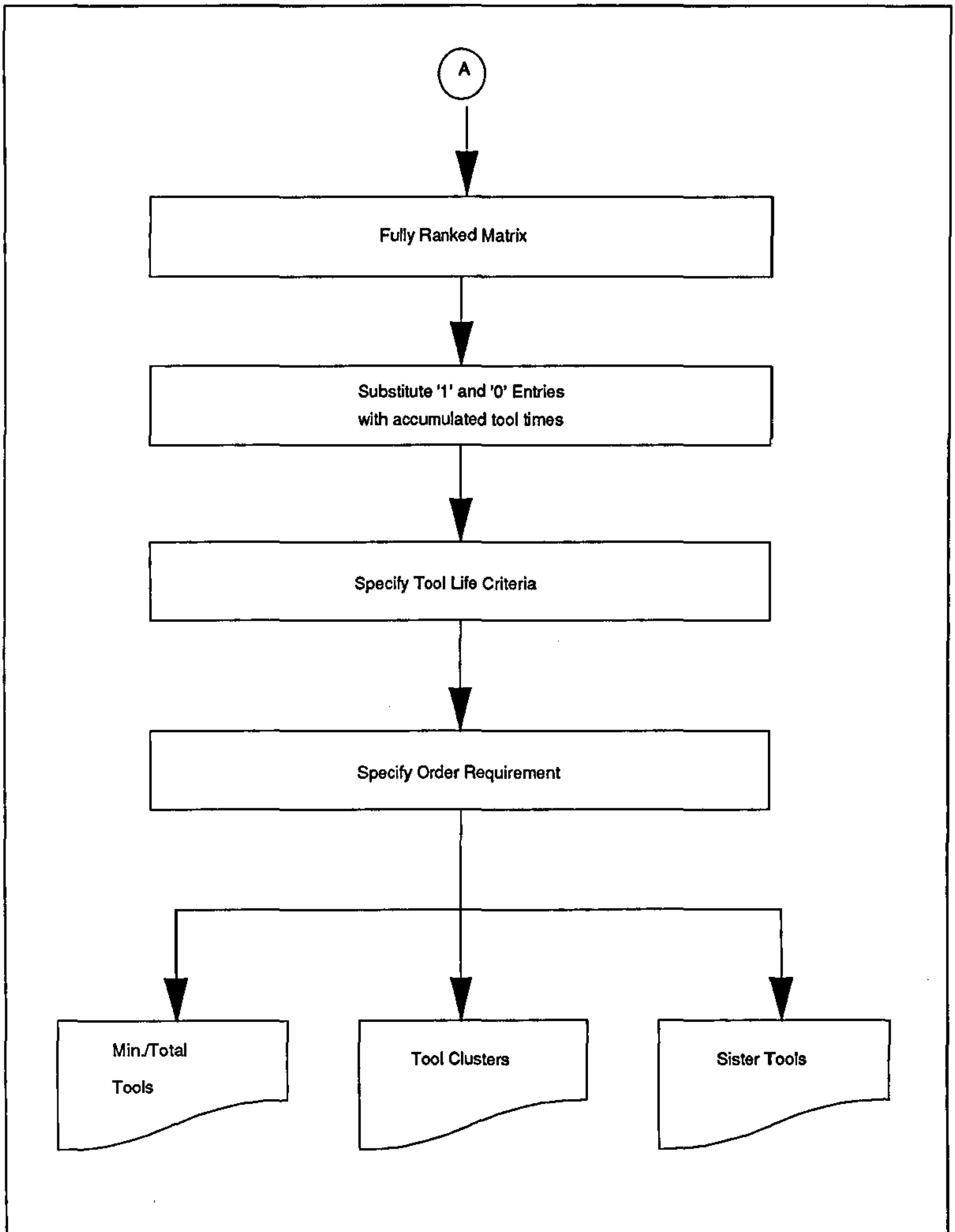

Figure 17.8 (Figure 17.7 cont'd)	CLUSTER TOOLING ANALYSIS - CONT'D	LUT-FMS RESEARCH GROUP

Cluster Analysis - Tool Flow Management - RdeSouza '88   Computer Assisted Cluster Analysis

I3=Macros A301=Checks OA1=Clusters A400=Help Q3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-O - Clusters

Original Matrix   8 Part Types - 100 Tool Types.

BatchSize=

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1			1	1	1	1	1	1							
2	1	1	1												
3	1	1	1	1				1							
4	1	1	1												
5			1												
6	1	1	1												
7	1	1	1	1											
8	1	1	1	1											
9			1												
10			1												
11			1												
12	1	1	1				1	1							
13			1												
14			1												
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43			1		1	1		1							
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Figure 17.9 | INITIAL ROC MATRIX
8 PART TYPES – 100 TOOL TYPES | LUT - FMS Research Group

The information below is to check for changes if any after reordering

Check for changes in rows after sorting columns
Check for changes in columns after sorting rows

Row Order ========== Checking Rows for Changes
Enter Iteration Number in G307 : 2

Old Order :	3	7	8	12	2	4	6	19	20	21	22	55	56	59	60	62
New Order :	3	7	8	12	2	4	6	19	20	21	22	55	56	59	60	62

Column Order ============= Already Checked
Enter Iteration Number in G314 : 1

Old Order :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
New Order :	2	1	3	4	8	7	5	6	9	10	11	12	13	14	15	16

Press HOME key

63	90	57	61	91	1	43	17	18	5	9	10	11	13	14	15	16	23
63	90	57	61	91	1	43	17	18	5	9	10	11	13	14	15	16	23

17	18	19	20	21	22	23	24	25
17	18	19	20	21	22	23	24	25

30	31	32	33	34	35	36	28	29	24	25	26	27	38	39	44	37	40
30	31	32	33	34	35	36	28	29	24	25	26	27	38	39	46	47	48

41	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
44	42	45	50	51	52	49	53	54	37	40	41	64	65	66	67	68	69

81	82	83	84	85	86	87	88	89	92	46	47	48	49	53	54	42	45
70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87

50	51	52	58	93	94	95	96	97	98	99	100
88	89	92	58	93	94	95	96	97	98	99	100

Figure 17.10

ROC SAMPLE CHECKING PROCEDURE
8 PART TYPES – 100 TOOL TYPES

LUT – FMS
Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88 Computer Assisted Cluster Analysis
filename : CumRow2.Wk1
KEYS= F5 then I3=Macros A301=Checks OA1=Clusters A400=Help O3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-D - Clusters
Comment: Finished Reordering The Rows - Proceed To Columns ? Y=Select Macro Key N=Select Function Key
Input BatchSize=

Part No.=		2	1	3	4	8	7	5	6	9	10	11	12
ToolType=	3	1	1	1	1	1							
	7	1	1	1	1								
	8	1	1	1	1								
	12	1	1	1		1	1						
	2	1	1	1									
	4	1	1	1									
	6	1	1	1									
	19	1	1	1									
	20	1	1	1									
	21	1	1	1									
	22	1	1	1									
	55	1	1										
	56	1	1										
	59	1	1										
	60	1	1										
	62	1	1										
	63	1	1										
	90	1	1										
	57	1											
	61	1											
	91	1											
	1			1	1	1	1	1	1				
	43			1		1		1	1				
	17			1		1							
	18			1		1							
	5			1									
	9			1									
	10			1									
	11			1									
	13			1									
	14			1									
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	28				1	1		1	1				
	29				1	1		1	1				
	24				1								
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	44					1		1	1				
	42					1							
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Figure 17.11

ROC MATRIX AFTER ONE ITERATION
8 PART TYPES – 100 TOOL TYPES

LUT - FMS
Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88 Computer Assisted Cluster Analysis
filename : CumCol3.Wk1
KEYS= F5 then I3=Macros A301=Checks OA1=Clusters A400=Help O3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-O - Clusters
Comment: Finished Reordering The Columns - Proceed To Rows ? Y=Select Macro Key N=Select Function Key
Input BatchSize=

Part No.=		2	1	3	4	8	7	5	6	9	10	11	12
ToolType=	3	1	1	1	1	1							
	7	1	1	1	1								
	8	1	1	1	1								
	12	1	1	1		1	1						
	2	1	1	1									
	4	1	1	1									
	6	1	1	1									
	19	1	1	1									
	20	1	1	1									
	21	1	1	1									
	22	1	1	1									
	55	1	1										
	56	1	1										
	59	1	1										
	60	1	1										
	62	1	1										
	63	1	1										
	90	1	1										
	57	1											
	61	1											
	91	1											
	1			1	1	1	1	1	1				
	43			1		1		1	1				
	17			1		1							
	18			1		1							
	5			1									
	9			1									
	10			1									
	11			1									
	13			1									
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	34			1									
	35			1									
	36			1									
	28				1	1		1	1				
	29				1	1		1	1				
	24				1								
	25				1								
	26				1								
	27				1								
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	39				1								
	46					1	1						
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	44					1		1	1				
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Figure 17.12	FULLY RANKED ROC MATRIX AFTER 3 ROW & 3 COLUMN ITERATIONS	LUT - FMS Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88   Computer Assisted Cluster Analysis
filename : CumRenA.Wk1
KEYS= F5 then I3=Macros A301=Checks OA1=Clusters A400=Help O3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-O - Clusters
Comments The tool types referenced with a '0' have been removed from the analysis to try and force clusters
Input   BatchSizes=

Part No.=	2	1	3	4	8	7	5	6	9	10	11	12
ToolType= 3	1	1	1	0	0							
7	1	1	1	0								
8	1	1	1	0								
12	1	1	1		0	0						
2	1	1	1									
4	1	1	1									
6	1	1	1									
19	1	1	1									
20	1	1	1									
21	1	1	1									
22	1	1	1									
55	1	1										
56	1	1										
59	1	1										
60	1	1										
62	1	1										
63	1	1										
90	1	1										
57	1											
61	1											
91	1											
1			1	0	0	0	0	0				
43			1		0		0	0				
17			1		0							
18			1		0							
5			1									
9			1									
10			1									
11			1									
13			1									
14			1									
15			1									
16			1									
23			1									
30			1									
31			1									
32			1									
33			1									
34			1									
35			1									
36			1									
28				1	1		0	0				
29				1	1		0	0				
24				1								
25				1								
26				1								
27				1								
38				1								
39				1								
46					1	1						
47					1	1						
48					1	1						
44					1		0	0				
42					1							
45					1							
50					1							
51					1							
52					1							
49						1						
53						1						
54						1						
37							1	1				
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Figure 17.13

FULLY RANKED ROC MATRIX
WITH TOOLS REMOVED FROM ANALYSIS

LUT - FMS
Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88 Computer Assisted Cluster Analysis
filename : CumCol2A.Wk1
KEYS= F5 then I3=Macros A301=Checks DA1=Clusters A400=Help Q3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-D - Clusters
Comment: Finished Reordering The Columns - Proceed To Rows ? Y=Select Macro Key N=Select Function Key
Input BatchSizes

Part No.=		2	1	3	4	8	7	5	6	9	10	11	12
Tool Type=	2	1	1	1									
	3	1	1	1	0	0							
	4	1	1	1									
	6	1	1	1									
	7	1	1	1	0								
	8	1	1	1	0								
	12	1	1	1		0	0						
	19	1	1	1									
	20	1	1	1									
	21	1	1	1									
	22	1	1	1									
	55	1	1										
	56	1	1										
	59	1	1										
	60	1	1										
	62	1	1										
	63	1	1										
	90	1	1										
	57	1											
	61	1											
	91	1											
	1			1	0	0	0	0	0				
	5			1									
	9			1									
	10			1									
	11			1									
	13			1									
	14			1									
	15			1									
	16			1									
	17			1		0							
	18			1		0							
	23			1									
	30			1									
	31			1									
	32			1									
	33			1									
	34			1									
	35			1									
	36			1									
	43			1		0		0	0				
	28				1	1		0	0				
	29				1	1		0	0				
	24				1								
	25				1								
	26				1								
	27				1								
	38				1								
	39				1								
	46					1	1						
	47					1	1						
	48					1	1						
	42					1							
	44					1		0	0				
	45					1							
	50					1							
	51					1							
	52					1							
	49						1						
	53						1						
	54						1						
	37							1	1				
	40							1	1				
	41							1	1				
	64							1	1				
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	67							1	1				
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	98												
	99												
	100												

Figure 17.14	FULLY RANKED MATRIX 2 WITH TOOLS REMOVED FROM ANALYSIS	LUT - FMS Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88   Computer Assisted Cluster Analysis.
filename: CumAdd8.Wk1
KEYS= F5 then I3=Macros A301=Checks DA1=Clusters A400=Help Q3=Iterations ALT-B - Rows Macro ALT-A - Cols Macro
Comment: Tool Type which were previously removed from the analysis have now bewn reinstated within each cluster.
Input   BatchSize=

Part No.=		2	1	3	4	8	7	5	6	9	10
ToolType=	2	1	1	1							
	3	1	1	1							
	4	1	1	1							
	6	1	1	1							
	7	1	1	1							
	8	1	1	1							
	12	1	1	1							
	19	1	1	1							
	20	1	1	1							
	21	1	1	1							
	22	1	1	1							
	55	1	1								
	56	1	1								
	59	1	1								
	60	1	1								
	62	1	1								
	63	1	1								
	90	1	1								
	57	1									
	61	1									
	91	1									
	1			1							
	5			1							
	9			1							
	10			1							
	11			1							
	13			1							
	14			1							
	15			1							
	16			1							
	17			1							
	18			1							
	23			1							
	30			1							
	31			1							
	32			1							
	33			1							
	34			1							
	35			1							
	36			1							
end TCS#1	43			1							
TCS#2	3				1	1					
	7				1						
	8					1					
	12					1	1				
	1				1	1	1				
	17					1					
	18					1					
	43					1					
	28				1	1					
	29				1	1					
	24				1						
	25				1						
	26				1						
	27				1						
	38				1						
	39				1						
	46					1	1				
	47					1	1				
	48					1	1				
	42					1					
	44					1					
	45					1					
	50					1					
	51					1					
	52					1					
	49						1				
	53						1				
end TCS#2	54						1				
TCS#3	1							1	1		
	43							1	1		
	28							1	1		
	29							1	1		
	44							1	1		
	37							1	1		
	40							1	1		
	41							1	1		
	64							1	1		
	65							1	1		
	66							1	1		
	67							1	1		
	68							1	1		
	69							1	1		
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	73							1	1		
	74							1	1		
	75							1	1		
	76							1	1		
	77							1	1		
	78							1	1		
	79							1	1		
	80							1	1		
	81							1	1		
	82							1	1		
	83							1	1		
	84							1	1		
	85							1	1		
	86							1	1		
	87							1	1		
	88							1	1		
	89							1	1		
	92							1	1		
	58										
	93										
	94										
	95										
	96										
	97										
	98										
	99										
end TCS#3	100										

Figure 17.15	FULLY RANKED MATRIX 2 WITH REMOVED TOOLS NOW REINSTATED	LUT - FMS Research Group

Computer Assisted Cluster Analysis - Tool Flow Management - RdeSouza '88 Computer Assisted Cluster Analysis
filename: CumUpT18.WK1
KEYS= F5 then I3=Macros A301=Checks DA1=Clusters A400=Help 03=Iterations ALT-B - Rows Macro ALT-A - Cols Macro ALT-D - Clusters
Comment: Finished Inputting Operation Times? Y=Select Macro Key N=Select Function Key

Input	BatchSize	4	4	8	8	4	4	5	3				
Part No.#		2	1	3	4	8	7	5	6	9	10	11	12
ToolType=	2	5	5	5.8									
	3	4	4	4.4									
	4	10.5	10.5	1.5									
	6	1.95	1.1	0.9									
	7	4.5	4.5	5.6									
	8	1.2	1.2	4.43									
	12	0.4	0.4	0.58									
	19	0.5	0.5	1.32									
	20	0.8	0.8	1.93									
	21	0.45	0.45	0.88									
	22	0.45	0.45	0.65									
	55	0.4	0.4										
	56	0.3	0.3										
	59	1	1										
	60	3	3										
	62	2	2										
	63	4	4										
	90	1	1										
	57	1											
	61	3.4											
	91	0.9											
	1			28.55									
	5			0.75									
	9			0.75									
	10			11.83									
	11			0.5									
	13			0.55									
	14			0.42									
	15			0.37									
	16			0.58									
	17			0.48									
	18			0.5									
	23			3.42									
	30			2.1									
	31			2.07									
	32			3.23									
	33			2.17									
	34			2.53									
	35			2.42									
	36			2									
	43			0.5									
	3				0.92	5							
	7				1.42								
	8				1.2								
	12					1	3						
	1				4.2	27	16						
	17					5							
	18					4							
	43					10							
	28				1.28	2							
	29				1	1							
	24				1.95								
	25				2.23								
	26				14.53								
	27				1.7								
	38				3.42								
	39				1.1								
	46					6	3						
	47					3	2						
	48					2	1						
	42					7							
	44					10							
	45					6							
	50					4							
	51					3							
	52					1							
	49						13						
	53						7						
	54						8						
	1							0.8	0.8				
	43							1.3	1.3				
	28							2	2				
	29							1.2	1.2				
	44							0.9	0.9				
	37							3.1	3.1				
	40							1.5	1.5				
	41							0.6	0.6				
	64							1.2	1.2				
	65							2.3	2.3				
	66							3	3				
	67							2.2	2.2				
	68							1.2	1.2				
	69							2	2				
	70							2.2	2.2				
	71							3.2	3.2				
	72							1.4	1.4				
	73							2.3	2.3				
	74							2	2				
	75							9.3	9.3				
	76							9.4	9.4				
	77							6.3	6.3				
	78							5.7	5.7				
	79							4	4				
	80							8.3	8.3				
	81							0.75	0.75				
	82							3	3				
	83							1.2	1.2				
	84							2.1	2.1				
	85							1.2	1.2				
	86							2.8	2.8				
	87							2.75	2.75				
	88							14.5	14.5				
	89							2.2	2.2				
	92							4.5	4.5				
	58												
	93												
	94												
	95												
	96												
	97												
	98												
	99												
	100												

Figure 17.16

FULLY RANKED MATRIX 2
WITH CUMULATIVE PART TOOL_TIMES

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Computer Assisted Cluster Analysis

Press HOME key to return to start

Input : Tool Life , Max % Use and Tool Cluster Set Number

Press HOME key to return to start

Tool Type	Max % Use	Tool Life Minutes	Cumulative Use Time	Min. No. Of Tools	No. Of Sister Tools	Total No. Of Tools
2	90	60	86.4	1.6	1	2
3	90	60	67.2	1.244444	1	2
4	90	60	96	1.777777	1	2
6	90	60	19.4	0.359259	0	1
7	90	60	80.8	1.496296	1	2
8	90	30	45.04	1.668148	1	2
12	90	60	7.84	0.145185	0	1
19	90	30	14.56	0.539259	0	1
20	90	30	21.84	0.808888	0	1
21	90	30	10.64	0.394074	0	1
22	90	30	10.4	0.385185	0	1
55	90	30	3.2	0.118518	0	1
56	90	30	2.4	0.088888	0	1
59	90	30	8	0.296296	0	1
60	90	60	24	0.444444	0	1
62	90	30	16	0.592592	0	1
63	90	30	32	1.185185	1	2
90	90	999	8	0.008897	0	1
57	90	30	4	0.148148	0	1
61	90	30	13.6	0.503703	0	1
91	90	30	3.6	0.133333	0	1
1	90	120	228.4	2.114814	2	3
5	90	60	6	0.111111	0	1
9	90	30	6	0.222222	0	1
10	90	60	94.64	1.752592	1	2
11	90	30	4	0.148148	0	1
13	90	30	4.4	0.162962	0	1
14	90	30	3.36	0.124444	0	1
15	90	30	2.96	0.109629	0	1
16	90	30	4.64	0.171851	0	1
17	90	30	3.84	0.142222	0	1
18	90	30	4	0.148148	0	1
23	90	60	27.36	0.506666	0	1
30	90	30	16.8	0.622222	0	1
31	90	60	16.56	0.306666	0	1
32	90	60	25.84	0.478518	0	1
33	90	60	17.36	0.321481	0	1
34	90	60	20.24	0.374814	0	1
35	90	60	19.36	0.358518	0	1
36	90	60	16	0.296296	0	1
43	90	30	4	0.148148	0	1
3	90	60	27.36	0.506666	0	1
7	90	60	11.36	0.210370	0	1
8	90	30	9.6	0.355555	0	1
12	90	30	16	0.592592	0	1
1	90	120	205.6	1.903703	1	2
17	90	30	20	0.740740	0	1
18	90	30	16	0.592592	0	1
13	90	30	40	1.481481	1	2
28	90	60	18.24	0.337777	0	1
29	90	30	12	0.444444	0	1
24	90	60	15.6	0.288888	0	1
25	90	30	17.84	0.660740	0	1
26	90	60	116.24	2.152592	2	3
27	90	60	13.6	0.251851	0	1
30	90	60	27.36	0.506666	0	1
39	90	60	8.8	0.162962	0	1
46	90	30	36	1.333333	1	2
47	90	30	20	0.740740	0	1
48	90	30	12	0.444444	0	1
42	90	30	28	1.037037	1	2
44	90	30	40	1.481481	1	2
45	90	30	24	0.888888	0	1
50	90	30	16	0.592592	0	1
51	90	30	12	0.444444	0	1
52	90	30	4	0.148148	0	1
49	90	30	52	1.925925	1	2
53	90	30	28	1.037037	1	2
54	90	30	32	1.185185	1	2
1	90	120	6.4	0.059259	0	1
43	90	30	10.4	0.385185	0	1
28	90	60	16	0.296296	0	1
29	90	30	9.6	0.355555	0	1
44	90	30	7.2	0.266666	0	1
37	90	30	24.8	0.918518	0	1
40	90	30	12	0.444444	0	1
41	90	30	4.8	0.177777	0	1
64	90	30	9.6	0.355555	0	1
65	90	30	18.4	0.681481	0	1
66	90	30	24	0.888888	0	1
67	90	30	17.6	0.651851	0	1
68	90	30	9.6	0.355555	0	1
69	90	30	16	0.592592	0	1
70	90	30	17.6	0.651851	0	1
71	90	30	25.6	0.948148	0	1
72	90	30	11.2	0.414814	0	1
73	90	30	18.4	0.681481	0	1
74	90	30	16	0.592592	0	1
75	90	30	74.4	2.755555	2	3
76	90	30	75.2	2.785185	2	3
77	90	30	50.4	1.866666	1	2
78	90	30	45.6	1.688888	1	2
79	90	30	32	1.185185	1	2
80	90	30	66.4	2.459259	2	3
81	90	30	6	0.222222	0	1
82	90	30	24	0.888888	0	1
83	90	30	9.6	0.355555	0	1
84	90	30	16.8	0.622222	0	1
85	90	30	9.6	0.355555	0	1
86	90	30	22.4	0.829629	0	1
87	90	30	22	0.814814	0	1
88	90	30	116	4.296296	4	5
89	90	30	17.6	0.651851	0	1
92	90	30	36	1.333333	1	2
58	90	30	0	0	-1	0
93	90	30	0	0	-1	0
94	90	30	0	0	-1	0
95	90	30	0	0	-1	0
96	90	30	0	0	-1	0
97	90	30	0	0	-1	0
98	90	30	0	0	-1	0
99	90	30	0	0	-1	0
100	90	30	0	0	-1	0

Figure 17.17

SISTER TOOL PREDICTIONS AND TOOL LIFE UTILISATION FOR A 24-HOUR ORDER REQUIREMENT

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Chapter 18:
THE TOOL MANAGEMENT DESIGN FACILITY

18.1 Introduction

The purpose of this chapter is to introduce the reader to the hardware and software configurations used in the development of the tool management design facility based on the algorithms presented in chapters sixteen and seventeen. The modelling approach, techniques, data inputs and the supporting modules are also discussed.

18.2 The Computer Models

Three computer models are available for the modelling of workpiece-oriented tool management systems. These are the single machine model, the single cell model and to reflect the trend towards multi-cellular installations, a multi-cell model. A separate computer assisted cluster analysis model has been developed to consider the scheduling aspects and the formation of preferred tool cluster sets for tool-oriented tool management systems. An overview of these models is presented in chapter eight. This chapter focuses essentially on the workpiece-oriented tool flow models for prismatic parts manufacture. The computer assisted cluster analysis has been described in chapter seventeen and its user interface presented in appendix two.

The overall module configuration is illustrated in *figures 18.1* . The four levels in the figure refer to the *Initialisation, Input, Run* and *Output* modules respectively. The *Run* module provides the representation and workings of a manufacturing system. The other three modules are supporting programs. The *Initialisation* module sets up the datafiles to initial status values. The *Input* module provides the data necessary for the modelling and is described in appendix two, and the *Output* module provides the generated information from the modelling.

The *Run* module is the control module which acts as the interface between the various major stores represented as files. This module is further constructed of sub-modules like machining stations, tool transfer modules, decision modules, etc., which are assembled depending upon the *Input* module data, to represent the manufacturing system under consideration. Facilities are also incorporated to allow the study of selected operating and tooling strategies, tool cart, tool allocation and tool deployment algorithms.

Each tool store is represented by a file specifying and updating the contents of that tool store, e.g. the primary tool store contents is represented by the *Machine* file, the secondary tool store by the *STS* file and so on. The sub-modules within the *Run* module can thus be seen as controlling and representing the flow of the entities such as the parts, tools and transporters between these stores (files). Each of the procedures (blocks) relate to a particular activity. These activity cycles of search, load, transfer, unload and update are described in chapter sixteen. The use of this modular approach allows the programmer to quickly edit and represent a large variety of tooling systems, see chapter five. There are four module aggregates that simplify the control of these sub-modules, termed : *Pre-Modelling, Modelling, Call-Tools-from-CTS* and *Cut-Set.*

The *Pre-Modelling* aggregate represents the transfer of worn or unnecessary tools from the secondary tool store to the central tool store; and the *Call-Tools-from-CTS* aggregate works in the reverse direction, supplying tools to the secondary tool store from the central tool store. The *Modelling* aggregate controls the transfer of tools from the secondary tool store to the primary tool store and vice versa, as well as the loading and unloading of parts onto and from the machines. The *Cut-Set* aggregate primarily provides the control and calls for the other three aggregates, and includes the 'Next Step' scheduler discussed in chapter nine.

18.3 Modelling Assumptions

The following is a list of the assumptions and conditions attached to the running of the model. The assumptions and conditions, based on the disscussion in chapter fifteen, are subdivided into four distinct but inter-related classes.

18.3.1 Workpieces

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

(b) No other workpieces shall arrive during the modelling period, unless predetermined.

(c) Workpieces can be produced randomly or in batches.

(d) Pre-emption is not permitted, once started an operation must be carried out till complete.

(e) 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.

(f) The processing time for each operation and the technological order of the operations for each job is 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.

(g) No jobs included in the modelling period are allowed to be cancelled unless this was prespecified.

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

(i) Each operation / sub-operation is considered as a tool activity.

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

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

(l) Batch splitting is permitted, providing that each sub group is separately identifiable.

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

18.3.2 Machines

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

(b) Each machine is continuously available for assignment during the modelling period, and therefore breakdowns and maintenance stops do not exist.

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

18.3.3 Manufacturing System

(a) In-process inventory is not allowed.

(b) pallets, pallet-fixtures are always available.

(c) pallets and fixtures never separate.

(d) It is possible to mount more than one workpiece 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 machining centre.

(f) Transportation time for the part transporters is negligible.

(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) Each transporter route is separately identifiable and separate from other transporters which may be present i.e no blockages or breakdowns are allowed.

(l) The transporter operates at a predetermined speed.

(m) The transporter route is unidirectional.

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

18.3.4 Tooling

(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 constitute 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 tool activity on the tool list is known and fixed.

(e) The technological order of each 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 dependent upon the tool rationalisation 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 upon the schedule and hardware constraints.

(j) Tool life must always exceed or equal the 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.

Several of the above conditions and assumptions are very realistic and often are very desirable for the successful design and operation of tooling systems. These *constraints* are evident in many installations. Some of the conditions are unrealistic such as 18.3.1 (f) and (g), 18.3.2 (b) and 18.3.3 (f). These sort of conditions are included more for simplicity, ease and clarity of the modelling than for the introduction of realism.

18.4 An Overview Of the Workpiece-Oriented Model Data Inputs

An interactive menu-driven soft-keys communication program, has been written using *Turbo Screen*, to provide a user-friendly interface between the user and the model, *figure 18.2* . The user interface is described in appendix two.

The interface is based on the software design now commonly found on machine controllers which employ conversational automatic programming functions. The essence of this conversational language is the ability to prompt and assist the user in the design and operation of tool flow systems, leading him through the required steps by asking the necessary questions in the correct sequence and indicating the correct key to push. The conversational structure masks the workings of the program and only leaves transparent the necessary functions sufficient to give feedback to the user. This is particularly useful when the *RUN* key is selected. Without some transparency the user would be faced with a static screen for a considerable time. Instead, the user is able to trace the movement of carts, tools and parts around the installation via the constantly updated alphanumerics displayed on the screen. The conversational structure is employed in the *Interrogation* and *Interactive Data Input* phases.

The language is based on dialogue which comes either in the form of direct questions or multiple choice questions. In the direct questions the answer can be as simple as *Y* or *N* (for Yes or No) or numerical data values or character strings. The multiple choice questions often involve the selection of an appropriate operating strategy or the choice of a particular decision rule. The multiple choice questions are displayed in the form of a soft-keys driven menu. The user simply selects a number key or a letter key to make his choice.

Modelling outputs are done in the form of either graphics or alphanumerics. The graphics are interfaced via ASCII files to graphics software, whereas the selection of the appropriate results is via the built-in soft-key driven output menu.

The input structure is closely related to the specification of a tool flow network for a specified level of automation and is based on the use of interactive data insertion, see appendix two. This hierarchical specification involves the following essential elements :

- a tool transfer network,
- centralised and/or decentralised tool storage facilities,
- automated tool exchange mechanisms,
- a tool refurbishment facility,
- a control / operational logic for managing the technological, analytical and managerial activities.

The user is led through this hierarchical structure, *see figure 18.2*, via the menu driven software. The data required to carry out this input phase is usually prepared in advance on detailed information and parameter specification sheets. These sheets accompany the user at the workstation. The experienced or repeat user will be able to operate the model without these hardcopy prompts. A brief overview of each menu is as follows :

The *manufacturing system parameters* are specifed in the opening menu for modelling, such as the number of machining centres, cells and parts, and whether the tool flow system under consideration is manual or automated. This level determines which of the computer models is to be used. The *single machine model* represents a single unmanned machining station, the *single cell model* represents a cellular configuration of single machines and the *multi-cell model* represents a collection of flexible machining cells supported by a central tool store.

The *tool rationalisation* menu is of a multiple choice nature that prompts the user to select an appropriate rule, see chapter fifteen, for this modelling.

The *machine information* menu is virtually an echo of the input data for each machine specified to be included in the database, and selected for inclusion into each cell configuration. This provides a confirmation of the overall structure of the tool flow system.

The *cell tool transportation* menu is a combination of direct and multiple choice questions. The direct questions relate to capacity, type and number of tool transporters. The existence of a secondary tool store and the planning horizon for each cell, used for calculation of the utilisation figures only. The multiple choice questions relate to the method of tool transfer. The choice is between kit, differential kit or single tool transfer, see chapter eleven.

The *tool transfer* menu is a straightforward declaration of time values for inter-store transfer and tool refurbishment.

The *decision rules* menu is three-fold. The first prompts the user in multiple choice fashion for a scheduling rule to be used in the *Next Step* scheduler, described in chapter nine. The second and adjacent menu is another multiple choice menu that prompts for a cart selection rule to aid in the choice of a tool transporter for assigned transfers. The third menu is in the same vein as the former two and prompts for an operation assignment strategy, see chapter fifteen, for the machining of several parts on a pallet.

The *part information* menu, provides a similar function to that of the machine information menu but is relevant to part numbers and type only.

The *routing* menu is a transparent view of the static scheduling process carried out by the external scheduler (see chapter nine) in conjunction with the preceeding menus. This once again provides the user with feedback information of the part routing.

The *tool information* menu, like the previous menu, is another transparent view using the rationalisation rules and part routings. This informs the user of the minumum tooling requirement, the tool numbers and other ancillary information such as the initial tool life, sister tools, tool life limits, etc. (see chapter fourteen).

The *secondary and central tool store specification* menus prompt the user for simple answers to direct questions relating to capacity, load/unload times and decision strategy. The specification of these menus is essentially done at the keyboard unlike that for the parts, machines and tools; as the specification of capacities for these stores is critical in terms of disk capacity and run times.

18.5 The Database Management Structure

Two database modules have been set up, viz. the *Manufacturing Systems Database* and the *Tool Management Database*. The former is the major database used in conjunction with the *Manufacturing Systems Evaluator* described in chapter three. The *Evaluator* is a term used to describe a suite of software design aids for the initial assessment of a user's proposals for a manufacturing system. The Evaluator consists of a number of modules only one of these, viz. the *tool management interface* will offer the user the option of analysing tooling systems with the tool management software. The *Specification Build module* guides the user through the design and specification of a manufacturing system and incorporates a part-machine selection. The use of this module can automatically generate the data requirements for the tool management software. This data can be made directly accessible to the *Tool Management database*, which is directly accessible to the modelling. This applies if the model is to be used as a 'module' of the LUT Design Aid. *The Manufacturing Systems Database* structure is discussed in a complementary thesis [248] but essentially consists of the following :

- machining centre specification data,
- turning centre specification data,
- secondary tool stores specification data,
- material handling devices specification,
- part specification data,
- tool specification data,
- fixture specification data.

Much of the information contained within this database is not directly relevant to tool flow modelling. Thus, when run in stand-alone mode a much reduced subset of the manufacturing database is necessary. As such, a limited database for parts, machines and tools has been set up for use in conjunction with the computer models. The database, like the computer models, has been written in-house using the *Turbo Pascal* environment and communicates with the respective models through ASCII datafiles, see appendix two. The database has been constructed using three separate modules for part, machine and tool records respectively. Individual data records may be listed, deleted or added to this database. The records are accessed either sequentially or randomly by means of a search key. The data records which have been selected for use in the modelling are written down to the datafiles which in turn are readily accessible by the respective computer models. A scheduler has also been incorporated within the database to sequence the selected parts to the selected machines. The functioning of this scheduler is described in chapter nine and sixteen.

Although a database has been specifically written to accompany the models, any commercially available database capable of generating ascii files in the desired formats may be used. This provides for a wide usage and a facility for linking with established company databases.

18.6 An Overview Of the Workpiece-Oriented Model Outputs

One of the unique points about the tool flow models is their ability to record considerable amounts of user specific data on the operation of tool flow systems within an overall manufacturing system. If this generated data is subjected to proper analysis, it can be used together with the user's own experience to improve the overall performance and operation of a tool management system. Tool life can be more accurately predicted, and thus tool changes and tool inventory levels can be forecast with greater confidence.

The computer models offer solutions to problems within tool management systems, not only to the technological problems of how to store, handle, transport and load the tools but also to the analytical and managerial problems such as when will what tools be needed where, and how to best organise the supply of tools and their information, see chapter four.

A minimum level of tooling can be estabilished that could sensibly produce a given spectrum of components. A degree of rationalisation of tools within the modelling can be user selected without affecting the product design, by changing tool allocation principles, see chapter fourteen.

After a satisfactory *uptime* the model can be interrogated, either after 'n' time periods, 'n' modelling runs, after a user-specified time interval, on tool changeover or on user demand,for a comprehensive tool inventory and tool information at the *interrupt* time for particular tool stores. This enables tool handling capacities to be determined.

A prediction of the time taken to complete a given schedule and the final state of the tools with respect to tool life, frequency of tool usage, the number of duplicate or sister tools, etc., can be extracted from the model.

The output options currently available from the model include :

(a) *A tool transfer schedule*, i.e a timetable of tool transfer between all major stores

(b) A comprehensive *list of all machine and tool activities* over the modelled period.

(c) *Final tooling analysis*, tool usage, etc.

(d) *Cell performance measures* for a particular tooling system for the specified planning horizon. These figures are :
(i) *machine utilisation*
(ii) *tool transporter utilisation*
(iii) *system performance time* for a given production schedule.

(e) *Cell tool summary and status report* incorporating identification and analysis of peak demands and/or mismatches in tool inventory over the modelled period.

(f) *Final tool store contents* for each major store and changes from the initial tool assignment/arrangement.

(g) *Analysis of demands and capacities* of all major stores over the modelled period.

(h) *Measures and forecasts* of tool type demands.

(i) *Tool requirements* per batch, machine or cell.

(j) *Measures of transient capacity* of central tool store, with respect to supply and/or return of tools to/from the cell[s] over the modelling horizon.

An illustration of these outputs is provided by the case study material presented in Appendices three to five.

18.7 The Computer Assisted Cluster Analysis Module

The Computer Assisted Cluster Analysis (CACA) module has been added for determining preferred tool clusters. The CACA module has been described at length in chapter seventeen and through the use of case studies but reiterated, it specifies *tool packages* for each machine with or without sister tools. CACA gives the user the option of quickly adjusting, via the spreadsheet facilities integrated within *Lotus 123*, and specifying tool sets for each machine without going through the rigours of full scale modelling. CACA permits optimum tool set configurations for changes in batch sizes, maximum permissible tool life and different tool life specifications. This CACA module has excited a lot of interest among the collaborators and has been validated against a single cell example provided by a non-collaborator. The module has also been taken up by one of our major collaborators.

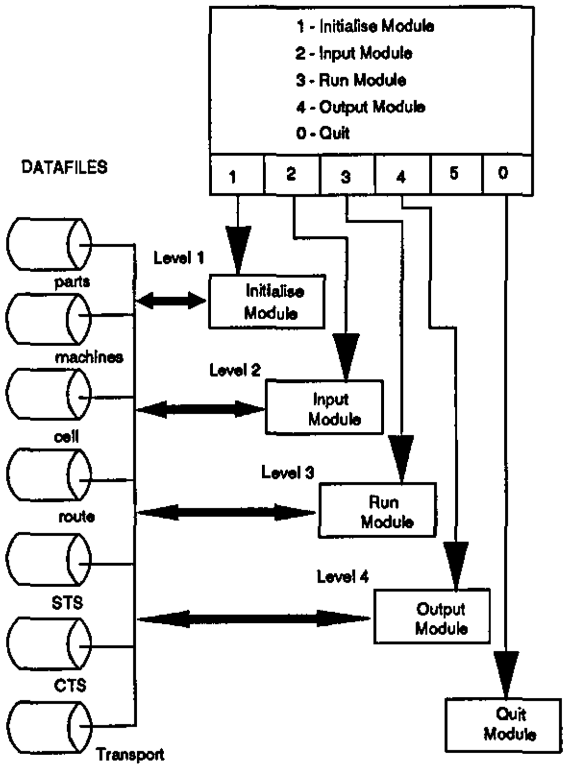

Figure 18.1	MENU DRIVEN SOFTWARE CONFIGURATION	LUT-FMS RESEARCH GROUP

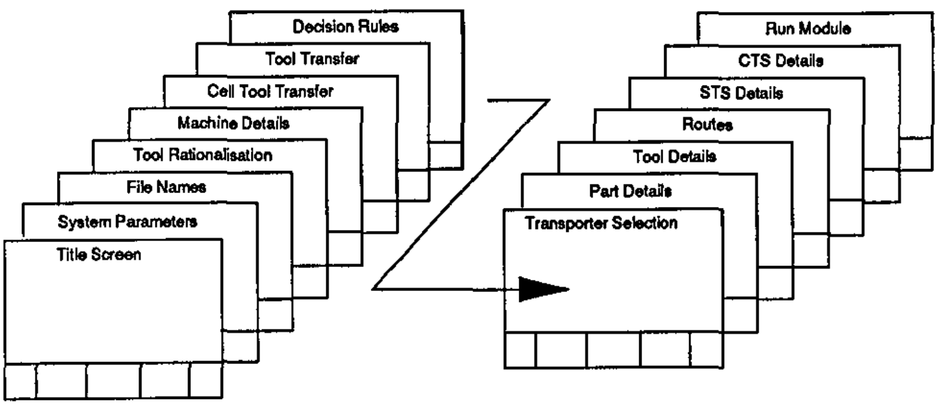

Figure 18.2	DATA INPUT STRUCTURE	LUT - FMS Research Group

Chapter 19: CONCLUDING DISCUSSION

19.1 Introduction

The discussion in this chapter centres on a critical review of the research work on the design, operation and modelling of tool management systems.

19.2 Cost Effective Solutions In Tooling System Design and Operation

The survey of literature , see chapter two, and the evidence provided in practice from current machining installations indicates the emergence of a distinct trend towards the provision of timely and cost-effective solutions for tool provision to the cells and machines. The study of installations such as Yamazaki, Worcester [44,189], has provided the impetus in the move from providing expensive hardware solutions to the provision of software control of tools at factory level accompanied by significantly faster and relatively cheaper tool flow automation at cell level. Werner and Kolb's QTC system extends this software control to the machine itself [116,232]. Yamazaki [189] and Cincinatti Milacron [207] are typical examples of installations that have updated their manufacturing strategy to allow for the evolution in their manufacturing systems design, over a relatively short period of time, from overhead transfer of bulky, expensive tool magazines, or the use of agv's upto the current single tool transfer tool highway (overhead gantry) systems.

The study, categorisation and assessment of these new developments, in chapters four and five, has provided the impetus for the research into tools to support in the design and operation, at minimum cost, of these complex tool management systems, ranging from the stand-alone machine to the newer multi-cell configurations [56] discussed in chapter three.

19.3 Generic Representations of Tool Flow Automation

The initial strategy of introducing algorithms in order to represent and examine a level of tool flow automation in a particular installation, coupled with the knowledge that the algorithms had to be modified for almost all of the case studies undertaken, provided the impetus to build generic representations capable of evaluating a broad base of flexible machining systems operating under a whole host of strategies and rules. This decision is reflected in the prototype software where a number of tooling system configurations, levels of automation and operating rules and strategies may be evaluated and their relative merits examined.

These representations, see chapter six, are constructed with emphasis on the tool flow. In many cases this generic approach is sufficient and powerful enough to examine and explore alternative rules and strategies for a selected configuration of tool stores as in chapter seven, but in some cases effort is necessary to modify these representations to adequately represent flexible turning systems and other forms of flexible machining. In other cases where the balance between the flow of tools and the flow of work is delicate, and where it is not possible to give priority to tool flow at the exclusion or relegation of the part flow, these representations may not be entirely appropriate. Research into methods of extending these representataions to include the competitive dual flows is currently underway in the laboratory [239].

19.4 The Heuristic Algorithms Approach

The generic representations provide the basis for the powerful, fast and effective heuristic algorithms. The algorithms permit rapid configuration and reconfiguration of a selected level of tool flow automation, thus providing a powerful tool for effective and economic tool management system design. The algorithms, presented in chapters sixteen and seventeen, have obvious implications in practice as well as for modelling. They provide a predictive facility for examining capacitites, tooling requirements and specifying short range schedules. The algorithms are primarily designed for use in prescheduled situations but can also be used in reactive situations such as is found in dynamic sheduling situations, where the look-ahead for each machine is restricted to the next part unlike in the former where the look-ahead capability of the machining list is the last activity of the machining list.

Use of this algorithmic approach has proved effective in use and has led to the consideration of more diverse areas in flexible machining. The emphasis on metalcutting does not obscure the potential of the algorithms for metalforming. In component manufacture, sheet metalworking has advanced to the stage where the level of automation and flexibility approaches that in metalcutting. A major factor has been the ability to use standard or easily exchanged tooling. Other forming techniques which are also less dependent upon single-purpose tooling will be able to be modelled along the lines of metalcutting. The challenge of representing a blanking press was sucessfully undertaken through a case study and the results presented in appendix five. This was not considered a serious test for the modelling but rather as an illustration of the capability of the modelling to other forms of flexible machining. Electro-physical machining processes, notably electron discharge machining (EDM), which also benefits from the ability to change simple tools and generate movement through CNC can also be considered for modelling with the algorithms.

19.5 Computer Assisted Cluster Analysis Module

The computer assisted cluster analysis (CACA) module specifies tool packages or clusters for each machine based on an initial *work-to* list. CACA provides the user with the option of quickly adjusting and specifying tool sets for each machine without going through the rigours of full scale modelling. CACA permits optimal tool set configurations for changes in batch sizes, maximum permissible tool life and different tool life specifications. CACA also has the added potential of determining or revising short range work schedules, assessing manual tool flow systems and specifying fixed or resident tools to be held in the primary tool store.

This module is currently only offered as a dynamic and versatile front-end, but has provided a useful insight into the priorities required at cell level, and a framework for control at the multi-cell level. Although this module has found favour and many possible applications, in its current form, with the collaborating companies, the implications of this tool-oriented approach have only been considered at a basic level in the prototype software and requires further development in order to realistically model the flow of tool cluster sets around a machining installation.

19.6 The Scheduling Function

The loading, scheduling and sequencing rules which complement the tool management package, see chapter nine, provide for adequate modelling of the activity flow networks, in chapter seven, at the exclusion of the part flow network. Detailed analysis of the effectiveness of the scheduling function on the performance of the overall system has not been undertaken, instead, and through collaborative work with other research projects, the work has been scheduled through simulation exercises and presented as presequenced machining lists. The scheduling function anticipates the current trend towards distributed scheduling in the design of modern manufacturing facilities and suggests an alternative to the static scheduling employed in the modelling. The alternative module is offered in this research (and examined through a case study in appendix four), viz. the computer assisted cluster analysis module, which not only explicitly considers tooling from the onset, unlike many other schedulers, but which also has the potential for dynamically assessing and examining the effects and the interplay between work and tools.

19.7 A Framework for Tool Management

A *bottom-up* approach is applied to rule and strategy selection, see chapter eleven, where at the lowest level, the primary tool store, decisions are required as to which tools are candidates for transfer, removal or replacement (see chapter thirteen and fifteen). At the cell level, rules for tool provision, transfer, exchange and return are necessary as discussed in chapter twelve; whereas at the factory or central tool store level the rules provide for the overall control and auxilliary functions such as refurbishment and cell level assignments. Hence, given a short term manufacturing task and emphasis of flow, then the rules and strategies can be iteratively applied till a complete tool management solution is achieved.

The rules and strategies included within the framework are drawn from a survey of current and anticipated practices, see chapters ten and eleven. The essential elements of these rules and strategies have been extracted, leaving no room for bad practice, and translated into modelling terms to manage the total combination of machining stations, stores and transfer devices and to supply all the control, management and tracking functions. All of the strategies offered, ranging from a selection of tool issue and assignment strategies down through the cell level rules for transporter, part and tool assignment to the more detailed machine level rationalisation, status and decision rules discussed in chapters twelve through to fourteen, have been validated through case study work and found to be effective.

This approach permits powerful tool flow solutions to be designed in vertical slices through the hierarchy of tool flow automation for long or short term manufacturing tasks and to explore the relative merits of and evaluate an existing or proposed tool flow network. Work is underway in extending this approach to factory level tool flow networks. The possibility of a rule based approach, to succeed this iterative approach, which converges in a finite manner on a complete tool management solution may be more appropriate.

19.8 The Prototype Modelling System

The modelling has focussed specifically on tool flow. This has proved to be adequate and sufficient for many situations as examined through the case studies. A limited number of situations do exist where the need to consider competitive dual flows of work and tools have been identified particularly within small complex cells where the balance of cost in the provision of these entities requires detailed study of the interaction between these flows. This is the subject of a complementary research programme [239].

The modelling system, presented in chapter eighteen, has been validated against several case studies and in different manufacturing environments. Each of the systems has a different basic requirement but all with the overriding objective of minimising tool delays and tool inventory. The forecasting capability of the modelling system, especially with regard to start-up i.e what basic tools to hold for example in the cell secondary tool store, was examined through a case study at the British Aerospace Small Parts FMS at Preston.

The prototype software permits powerful tool flow solutions to be achieved at cell level, but is only capable of limited modelling of factory level tool flow networks and of the detailed activities within the tool room or central tool stores, although a framework and decision structure is provided for the multi-cell facility supported by a central tool stores and refurbishment facility. A module is to be included for handling and tracking of fixtures. A user manual for the software has been written and is presented in appendix two.

The software is currently mounted on an extended version of the IBM PC-AT. The research has reached a point where the hardware configuration and the software employed is at a ceiling beyond which there is no realistic scope for enhancement. This configuration which is working at the extreme operational limits of the hardware ceases to be dependable when asked to operate for extended periods. This imposes a severe constraint on the usage of the system, the case studies that could be undertaken and what could be offered to industry. The imminent transfer of the software onto the more powerful SUN 386i workstation, prohibited previously because of cost and availability, with the capability for emulating DOS and the more powerful UNIX environments would not only significantly decrease run times by about 25 times but also remove the restrictions on the number of entities that can be handled.

Some of the initial shortcomings in the prototype software were overcome or minimised by four major modifications. The first was to specify tool locations within stores which significantly reduced search times which in turn reduced model run time by as much as seventy per cent. The inclusion of an array builder in the software provided a facility for modelling significantly larger tool stores beyond the 64K limit set by the compiler. The enhancement of the user interface and the dramatic improvement in the facility for specifying machining lists now enables the user to rapidly configure and reconfigure machining schedules.

Other restrictions in the current modelling include: the inability to animate traffic densities and hence examine blockages; the inability to reliably model situations where the number of entities is very large (as typified by the British Aerospace installation at Preston with a central tool stores capacity of around 80,000 and a secondary tool store capacity of the Automax cell at around 4,000); the inability to model turning centres other than as limited machining centres although the modelling of a blanking press was possible with minor modifications; and the ability to model mixed CNC and manual shops.

19.9 Case Study Experience

The experience gained through case study work has shown that in many companies, gathering of data can prove to be a mammoth task. The lack of a central pool of information or some level of factory control system implies a missing link between manufacture and production support, the very essence of a CIM strategy.

Tool data management, the collection and collation of tooling data and its subsequent maintenance is an all important function in flexible machining systems. Tooling information is found to be not only required at cell level for tool management and tool transportation but also in several other subsystems, including production planning, process control, dynamic scheduling, part programming, tool preset and maintenance, tool assembly, stock control and material storage [270e].

Four functions of a tool management system were highlighted from the case study work : ordering and storage of cutters; supply of tools to the machine and cells; disposal or refurbishment; and tracking of cutters. Each of these functions requires particular attention to be given to rules and strategy selection. Control is required to signal order quantities when stock falls below a specified level and to ensure the availability of tools within an acceptable response time. Simple and straightforward rules are necessary for the tracking of tools to ensure that the tool control system cannot only implement the decisions regarding the assignment / reassignment of tools but also the disposition questions about returning tools.

19.10 Concluding Remarks

The above discussion logically leads to specific conclusions being drawn in chapter twenty and further work being suggested in chapter twenty-one.

Chapter 20:
CONCLUSIONS

20.1 Introduction

Conclusions drawn from the case study work and from the modelling exercises are presented in this chapter.

20.2 The Algorithms and Generic Representations

The heuristic modelling algorithms, presented in chapters sixteen and seventeen, have proved to be adequate, fast and effective in the representation of highly automated manufacturing systems ranging from stand-alone machines to highly automated multi-cell configurations. The algorithms permit rapid configuration and reconfiguration of tool flow systems, thus providing the designer with a powerful tool in tool management system design and evaluation.

20.3 The Heuristic Algorithmic Approach

The use of an heuristic approach provides a powerful tool to design, control and operate tooling systems in a practical manner. The heuristic approach, unlike simulation, has the ability to record, manipulate and output considerable amounts of user-specific data on the operation of tool flow systems within an overall manufacturing system (see appendix two), other than the normal statistical based outputs obtained from simulation. The algorithms also allow the user to focus on particular areas of concern with fairly minor modifications.

20.4 Methodology for Data Collection and Collation

A methodology for rapid definition of prismatic parts as inputs to an FMS installation has proved not only to be an important part of the modelling but has also provided useful guidelines for users in the collection and collation of data, see appendix two.

20.5 The Tool Management Framework

The suggested tool management framework, in chapter eleven, provides a unique methodology for the design and operation of tool flow systems. The framework provides formal guidelines through rules and strategies selection for a complete and appropriate tool management solution to be achieved. The framework encompasses current thinking on tool management and provides technological and strategic options for the user at each level of the hierarchy. The multi-phase solution framework has been examined through case studies and has proved to be effective in communication and system design.

20.6 Performance Measures of a Tool Flow System

Many of the performance measures applicable to the overall machining system are also applicable to tooling system design. Two main additions to these standard figures are: the time to complete a given machining list which demonstrates the ability of the tooling system under different tool issue and tool management conditions, and the downtimes incurred through having to wait for tools to be made available. Case studies, see appendices three to five, have provided valuable insight into the relationships between these performance measures and machine and transporter utilisations, transient capacities of tool stores and tool handling capabilities.

20.7 Static Versus Dynamic Scheduling

The selection of scheduling rules, see chapter nine, appears to be in the main dependent upon the number of tools captive in the system versus the cost of holding such a tool inventory, the intrinsic value of the manufactured parts, the configuration of the tooling system, and the market response required. Machining lists with limited routing, obtained from simulation studies, have proved to operate very effectively as frozen schedules with the period of manufacture being the control variable. Limited tests carried out through case studies, and comparisons with other models, in the laboratory have shown the value in employing this approach in rapidly configuring machining lists for particular machines.

20.8 Influences of Machining Requirements on Tool Flow

Several parameters have been found to influence tool flow efficiency (see chapter eleven). Machining requirements, in terms of number of operations and tools required, plays a very large part in the selection of a tool flow system. Parts with very short operation times, demanding quick response times for tooling, may not render themselves easily, for example, to single tool transfer systems where although the transfer itself is fast the time to respond to multiple consecutive tooling requests is slow. Similarly long operation times render tooling systems inactive for lengthy periods and thus the cost of hardware solutions may have to be balanced against the cost of tool delays, see chapter five.

20.9 Influence of Process Plan on Tool Flow

The process plan for machining has a profound effect on performance times as was discovered through case study presented in appendix three, where the selection of operation assignment strategy made a dramatic difference to the time taken to complete a given machining list. The trade-off is between indexing of the pallet to present the next tool activity versus indexing of the tool magazine to present the next tool (see chapter fifteen). Thus careful planning has to be exercised not only at the tool selection stage but also in machine operations sequence plannning.

20.10 Influence of Other Parameters on Method of Tool Issue

The main parameters which influence the method of tool issue to the machines are determined to be: the number of parts fixtured on a pallet (which determines the number of table indexes required for machining versus the number of indexes of the tool changer); primary tool store capacity (where larger capacities favour single tool transfer and smaller capacities favour tool kit transfer); the number and mix of workpieces to be machined; the machining complexity (where the number of operations and the commonality of tools will influence the requirements and speed of response required); the sequencing of parts to the machines; and the tool flow network. The number of parts available at the machine (the part buffer capacity) and the sequence of introduction of parts was also found to be important in assessing the capability of the tool exchanger in meeting its requirements, see chapter fifteen.

20.11 The Secondary Tool Store Worn Tool Limit

The specification of a worn tool limit in the secondary tool store (STS), usually dependent upon the tool transporter capacity (see chapter twelve) so that the number of journeys between the STS and the central tool store is optimised, provides a powerful tool for scheduling refurbishment. The adjustment of the limit allows the examination of the effect of worn tools on the cell tooling requirements. The limit is also of particular value as discovered through the case study (see appendix five) in situations where the cost of particular tools is high and refurbishment should be scheduled as quickly as possible, thus implying setting the limit as low as one.

20.12 Tool Rationalisation Algorithms

The tool rationalisation algorithms (see chapter seventeen) and in particular the machine rationalisation algorithms was discovered to provide the best results. Its usage was particularly helpful in the case study work undertaken with British Aerospace to forecast the tooling requirements for the secondary tool store, due account being taken of tooling economics and handling.

20.13 Tool Status Values

Cell management systems usually operate on the assumption that there is an infinite supply of tooling or that the tooling requirements are given. This is often not the case and a study of the problem reveals a lack of effective rules to control tool flow at cell or machine level although attempts have been made to rectify this situation [232]. The status rules for the tools in chapter thirteen provide a useful facility as examined through modelling for servicing the production schedule by setting and resetting of these decision, transit, and supplementary values.

20.14 The Tool Life Limit

As data on abrupt tool failure is not readily available from tool users or suppliers and as it is considered inappropriate to include a random event, a correction factor or tool life limit has been offered in the software. This limit based on a user's confidence level, has proved to be a very useful and powerful tool in examining the tooling requirements under different limits for all tools, groups of tools or even particular tools. This allows the user to make the necessary allowances for tool breakage, see chapter fourteen.

20.15 Influence of Computer Assisted Cluster Analysis

The CACA module developed in this research work and validated through case studies (see appendix four) has proved its ability in bridging the gap in schedules which do not consider the tooling and tool flow explicitly. This CACA module has the added potential for selection and deployment of tools and for the scheduling of work in a workpiece-oriented environment.

20.16 The MTR Module

The minimum tooling requirement (MTR) module, in chapter seventeen, devised to solve the tooling problem in flexible machining systems is found to provide a good solution for minimising tooling. The MTR also pinpoints particular tools which should be duplicated and indicates possible configurations of tools which could constitute tool store loading and transport schedules.

20.17 Use of the Modelling Output

By selective change of the input variables and study of the resulting model output, (see appendix two), particular aspects of tooling system behaviour and the suitability of the tooling system configuration for certain work lists can be investigated and different operating strategies may be evaluated.

20.18 Novel Applications of the Model

The algorithms have also proved to be applicable not only in the limited modelling of turning centres but also in the rapid long term modelling of a blanking press, see appendix five, where tool life and machining times are measured in hits and the performance times measured in the number of laminations produced.

Chapter 21:
FURTHER WORK

21.1 Introduction

It is recommended that further work be carried out in the following areas :

21.2 Distributed Loading and Scheduling Functions

Some basic loading and scheduling functions complement the current total tool management package and provide a balanced prototype facility and cover the influences of short range scheduling. These loading and scheduling functions need to be extended for the current trends in distributed scheduling to give a more effective shop modelling.

21.3 Modelling of the Flow of Fixtures

Although fixtures are not entirely essential from the point of view of tooling system design, they are important in the operational sense. The tracking of fixtures is necessary in a manufacturing system to ensure there are no unnecessary restrictions on the part flow and hence the tool flow.

Due to the time constraint on the current contract, it is not feasible to give more detailed consideration to fixtures. For the fixturing rules to be effective, it would require limited modelling of part flow networks on a mutually exclusive basis from the tool flow network and the restriction that a fixture is limited to a part type. The tracking of fixtures and the determination of the type and number of these fixtures could then be more effectively monitored. The in-depth consideration of fixtures, free fixturing, pallet restricted fixtures, pallet requirements, buffer capacities and bottleneck predictions need to be considered.

21.4 Work and Tool Flow Under Tool-Oriented Tool Management

The effect of the tool-oriented rules and strategies on the actual flow of work and tools requires to be considered in more detail, particularly within dynamic scheduling environments. The basic rules and strategies are offered within the thesis and their suggested implementation defined, but not validated other than in the provision of the computer assisted cluster analysis module.

21.5 Extension Of Data Handling Capability Of Modelling

The modelling is currently being enhanced with the use of an array organiser which will provide capability for handling a larger number of entities than was previously possible. Although this facility has been included in the modelling, further work is necessary to fully integrate the data handler with the modelling algorithms.

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