An Investigation into Tooling Requirements and Strategies for FMS Operation

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 other Institution of Learning

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Abstract

A study of the minimum tooling requirements and strategies for efficient operation of Flexible Manufacturing Systems, FMS's, in Assembly set Production, ASP, i.e production in sets of parts to completely assemble one or more product units, is presented in this research work.

The main investigating tool is a simulation model. With this model the tool groups to be loaded into machines and fixtured pallet requirements were studied in conjunction with two scheduling rules. One is a FCFS rule and the other is a new rule, called MRPAS, which schedules work on the basis of the number of parts still unfinished belonging to an Assembly Set.

The results of the research work show that ASP can be efficiently carried out in FMS's. However this requires that a good system set-up and adequate operating strategies are used. In particular appropriate tooling levels and good tooling configurations,TC's, i.e. combinations of tools in groups to be loaded into the machines, must be established to achieve high FMS performance. Tooling combination and duplication heuristic rules and the simulation model can be used for achieving this aim. The heuristic approach is shown to be necessary due to the impossibility, in a reasonable time, of evaluating the performance of FMS's under the large number of alternative tooling configurations which are possible.

The level of fixtured pallets used can also have a great influence on system performance. Appropriate levels of these resources to operate FMS's for given TC's can be established using the methodology developed in this work.

It is also important that good scheduling rules are used. In the cases studied, the MRPAS rule produces the best performance expressed as the combination of FMS utilization and production of complete assembly sets.

Moreover a very small assembly set batch size, ASBS, i.e. number of AS released together into the FMS, is likely to be preferable. In the cases studied an ASBS of one performed best overall.

Synopsis

Flexible Manufacturing Systems, FMS's, are suitable for small batch production. The high manufacturing flexibility of these systems suggests that a variety of parts with different processing requirements can be produced together in the same manufacturing period, say a shift or a day. This indicates that Assembly Set Production, ASP, i.e. production in sets of parts to completely assemble one or more product units, can be efficiently carried-out in FMS. This production approach is considered in this work for studying minimum tooling requirements and strategies for efficient FMS operation.

An analytical methodology is presented for estimating the minimum number of tools and fixtured pallets to run an FMS. The values obtained may be useful as a first approximation to the required resources to operate FMS's for manufacturing a given part operation mix.

However the main investigating tool is a computer simulation model. A complex and considerably detailed simulation model of FMS's was developed. With this model the required number and type of tools to be exchanged in the machine spindles and different types of fixtured pallets were studied in conjunction with two scheduling rules. One is a FCFS rule and the other is a new rule, called MRPAS, which schedules work on the basis of the number of parts still unfinished belonging to an Assembly Set, AS's.

Tooling configurations, TC's, i.e. the combination of tools in groups to be loaded into the machines, are determined through the application of tooling combination and duplication heuristic rules and computer simulation. The heuristic approach is shown to be necessary due to the impossibility, in a reasonable time of evaluating the performance of FMS's under the large number of alternative tooling configurations which are possible. This number is shown to increase enormously as the number of different tool sets increases.

Two differently configured FMS's are considered. One is highly flexible with highly versatile identical machining centres, i.e all parts can be processed by all machines. The other is less flexible with less versatile and different machining centres. This second configuration has restrictions on the parts which can be processed in each machine.

The results of the research work show that ASP can be efficiently carried out in FMS. However this requires that a good system set-up and adequate operating strategies are used. In particular appropriate tooling levels and TC's must be established to achieve high FMS performance. Tool combination and duplication heuristic rules can be used for achieving this aim. The level of fixtured pallets used can also have a great influence on system performance. Appropriate levels of these resources to operate FMS's for given TC's can be established using the methodology developed in this work. It is also important that good scheduling rules are used. In the cases studied, the MRPAS rule produces the best performance expressed as the combination of FMS utilization and production of complete assembly sets.

Moreover a very small assembly set batch size, ASBS, i.e. number of AS released together into the FMS, is likely to be preferable. In the cases studied ASBS of one performed best overall .

It is also shown that an optimal work load level can be found after which system performance does not improve. On the contrary, performance deteriorates as the workload increases since work in progress and throughput time increase.

CONTENTS

CHAPTER 1 - INTRODUCTION

In general, a Flexible Manufacturing System, FMS, can be described as a set of Numerical Control, NC, workstations and possibly other auxiliary stations linked by a material handling system, to manufacture a variety of parts, with overall operation under computer control.

This new generation of Automated Batch Manufacturing Systems, ABMS, has been with us for more then two decades[137,30] However, although the basic technology used by such systems has been available for some time difficulties still exist in the integration of FMS elements, in FMS design and in the design of strategies and procedures for efficient FMS operation.

Part loading and control of the work and tool flow are major functions influencing the efficiency of FMS operation. The number of available tools and the way they are combined to be loaded into machines imposes restrictions on manufacturing control decisions which affect FMS performance.

There are quite a number of variations on tooling systems and tooling organization which can be adopted in FMS. However, many of them use the strategy of exchanging sets of tools in the magazines of machines or simply exchanging loaded magazines themselves.

In such cases it appears that the combination of the tools for replacement according to part processing requirements is critical to efficient system operation. This is due not only to the fact that tool availability and grouping configuration in conjunction with machine versatility ultimately defines the degree of part routing flexibility but also because the number of tools necessary to run a system and the tool replacement frequency can be dependent on the way tools are combined and organized.

It is pertinent therefore to investigate and find methods of deciding the minimum number of tools and their appropriate combination to run an FMS to carry out production of a given part-operation mix.

This is a problem which can be seen firstly as a detailed design one by defining the required number of tools of each type and secondly as a FMS operation problem encompassing the establishment of the best tool grouping configuration to manufacture a given part mix in order to achieve good FMS performance.

Thus this research work has the objective of designing a methodology to solve these two problems in the context of prismatic parts production with particular attention given to Assembly Set Production, ASP, chapter 4, as opposed to traditional batch production.

Moreover, the work studies the use of the potential diversity of part routing, usually provided by FMS, as a way of finding good schedules for FMS operation taking into account the objective of minimising the number of tools required for high levels of system performance.

Due to the great difficulty of determining all tooling configurations from the amount of tools available and evaluating their efficiency in contributing to FMS performance objectives, heuristics are devised to indicate good tooling configurations to process a given part mix.

The problem of defining the necessary type and number of pallets and fixtures is also investigated.

CHAPTER 2 - CONCEPTUAL FRAMEWORK

2.1 FMS CONCEPTS

2.1.1 Definitions

In 1967 Dozalek[114] used the term Flexible Manufacturing System to refer to a number of machines interlinked through common control and transport systems in such a way that automatic manufacture of different workpieces requiring a variety of different operations could be carried out. This definition still applies today as a general definition of a Flexible Manufacturing System, FMS.

Groover[42] centres his definition on the flexibility of part processing defining FMS as "A manufacturing system consisting of numerical control (NC) machines connected by an automated material handling system. It is operated under computer control and capable of simultaneously processing a family of parts in low to medium demand volume, different process cycles and operation sequences."

However Ranky[88] emphasizes the computer data processing aspect and extends the FMS concept to assembly, stating that "a Flexible Manufacturing System (FMS), may be defined as a system dealing with high level of distributed data processing and automated material flow using computer controlled machines, assembly cells, industrial robots, inspection machines, and so on, together with computer integrated material handling and storage systems".

2.1.2 Classes of FMS's

Broadly three classes of systems for flexible manufacture can be distinguished:

- Flexible Manufacturing Systems, FMS
- Flexible Transfer Lines, FTL and
- Flexible Manufacturing Cells, FMC

Figure 2.1 illustrates the applicability of the three general concepts in the context of productivity, defined as the part output per processing time unit, flexibility for easy adaptation to production of different part mixes, batch size of identical parts and workpiece variety which usually can be dealt with in the same manufacturing period of say one day.

FMS and FTL have important differences in their work flow structures. FTL's essentially process work in a sequential manner, i.e. parts follow one another unidirectionally from one machine to the next machine in a fixed sequence through all or some of the machines in the line. Schematic representations of FTL's are shown in figure 2.2 (a). FTL's most frequently use roller conveyors for transporting workpieces between stations.

Flexibility in FTL's is achieved through the use of NC stations, local workpiece buffers, and bypasses at some workstations in the line. NC machines are characteristic of all FMS's. However these FTL's may also include some conventional automatic, i.e. non NC, machines.

The class of FMS's is distinguishable from FTL's mainly because parts to be processed can access randomly any machine in the system. This is achieved through variations on the FMS work flow structure, as figure 2.2 (b) illustrates. Flexibility of the system is also enhanced through the wide use of machining centres, section 2.1.5.

A FMC is characterized by having a single versatile Computerized NC, CNC, machining centre, MC[125,97], either for rotational work, in which case is usually referred to as a turning centre or turning system, or for prismatic work. The FMC machining centre has its own dedicated local part/pallet storage, transport and handling system and also local tool storage and tool handling system. A reasonably large storage capacity for tools can be usually provided if necessary. This is necessary for maintaining unmanned work for long periods. FMC frequently have a local work storage capacity for one or a few shifts. When pallets are used usually a capacity up to 20 or more pallets can be available. Figure 2.3 shows typical FMC's for prismatic parts and figure 5.2[67] shows a FMC for rotational parts.

FMS's consisting of a few machines arranged in a circle like layout, with parts loaded/unloaded from machines by an Industrial Robot have also been referred to as FMC's.

2.1.3 Costs

Initial and operating costs of FMS's are usually high when compared with non automated systems. A complete FMS installation with 10 machines may easily cost $10 million[54] . Of the total cost, it is estimated that on average machines may cost 50%, fixtures pallets and tooling 25%, transport and material handling 10%, software and control 8% and engineering service 7%. Labor costs, tooling and maintenance are the most significant operating cost items in an FMS[54] . These cost estimations point to the importance of pallets, fixtures and tools in both the design and operation of FMS. This constitutes a central aspect studied in this research work.

2.1.3 Advantages of FMS

Advantage of FMS in achieving high levels of performance in batch manufacture and of providing high flexibility at many levels justifies the use of FMS by a firm. In relation to traditional batch manufacturing systems, TBMS, i.e. manufacturing systems manually controlled and operated with stand alone NC and other machines, typical advantages from using FMS are:

1 - Higher machine utilization, U.

A much higher utilization is possible in FMS than in TBMS, primarily because of reduced set-up requirements, and as a consequence a lower number of machines is necessary for satisfying a certain demand.

2 - Lower job throughput time.

Average job throughput time with an FMS can be very much shorter than with a TBMS. This can lead to substantial reductions in order delivery times.

3 - Low levels of work-in-progress, w.i.p.

W.I.P. can be substantially lower than in TBMS because of the possibility of FMS's being able to efficiently manufacture smaller batch sizes and also because the number of machines in an FMS will be much lower than in TBMS[62]

4 - Space savings

The smaller number of workstations required usually allows space savings and consequently savings in costs. In addition there are cost savings in transport of materials, e.g. as workpieces, pallets and tools, during the system's operating life.

5 - Unmanned operation

FMS's are more suitable for 24 hour a day operation because of the possibility of unmanned or partially unmanned production being carried out for one or more shifts a day.

When compared with a TBMS which may operate only on a one or two shift basis, this ability of FMS's to operate continuously provides more intensive use of the equipment. This helps minimize the pay back period on FMS's. Furthermore, these systems, which have the inherent capability of operating for substantial periods without human intervention, will be less affected by operator absence than TBMS.

6 - Consistent quality

This is a by product of the use of NC machines.

7 - Part mix and product design changes.

The flexibility at various system levels, primarily that provided by low set-up times and NC control of machines, means that changes in part mix and in product design can easily be implemented in FMS.

In general the advantages referred to above highly contribute to the overall better performance of FMS's relatively to TBMS's. This is due to the combination of aspects such as the possibility of delivering in shorter times at lower levels of w.i.p. and higher machine utilization, the flexibility of being able to change part mix and product design more easily and the ability to manufacture parts in a larger range of batch sizes. This potential for increased performance is an important factor in increasing company competitiveness.

2.1.5 FMS Elements

The main FMS elements are:

- Operators
- Machines
- Auxiliary workstations
- Fixtures and pallets
- Tools
- Transport/Handling devices
- Control, Monitoring Supervision Systems

Operators

Although FMS are essentially automated systems there is still a need for carrying out some manual operations, system supervision and to prepare general manufacturing schedules. For this a certain number of personnel is necessary.

Typical manual operations which are still carried out in FMS are palletising and depalletising work and tool replacement at the processing stations. These are frequently done at the start of well defined manufacturing periods.

Tool set-up and preparation is also an area where avoidance of the human intervention seems to be difficult.

Machines

A major division between types of machines is:

-Machines for rotational work

-Machines for prismatic work

Some machines can only perform a single type of operation, e.g. milling, turning, etc..In this thesis these are termed single purpose machines. They can be used in both FMS's and FTL's but are less suitable for FMC's, section 2.1.2 . FMS's with such machines are termed Multiple Stage Systems FMS's[83].

Machining Centres, MC's and turning centres, section 2.1.2, are versatile machines which can perform many different operations. These machines are typical of FMC's and widely used in FMS's. They are termed multipurpose machines in this thesis. MC's are usually provided with local tool storage and automatic tool exchanging mechanisms. Automatic part/pallet exchange mechanisms are also frequently incorporated. These versatile machines are frequently able to completely machine a workpiece. FMS's with these versatile machines have been referred to as Single Stage Systems FMS's[83] .

There is also a range of machines whose versatility is in between that of the two types of machines above referred to above. They are termed limited purpose machines. Usually a part rarely is completely processed in one of these machines. A system which includes both this type of machines and highly versatile MC's and possibly single purpose machines have been referred to as Mixed or Combined Stage System FMS's[83]

Other complex machining systems can also be seen which include tooling head changing machines or tooling head changers and tooling head indexing systems or tooling indexers, figure 2.4. Figure 2.4 also shows a schematic representation of an FMS which uses tooling heads changers[27].

Studies and descriptions of required features of machine tools for Automated Manufacturing have been published recently by a number of authors including Gatelmand[38], Yoshida[143] Ana Kochan[63] and Lord[71]. These emphasize the importance of the modular design of machines which allows a variety of machining system configurations to be built up from basic modules. Modular design towards standardization has been extended to many parts of FMS's[94] This highly simplifies FMS development and installation[124,97,2].

An overview of tooling systems for machine tools is given in chapter 4.

Auxiliary workstations

Auxiliary equipment is used mainly for quality inspection.

Inspection of quality and of dimensions can be integrated into FMS's in two main forms:

1 - through measuring and touch probes used at machining stations normally held in machine spindle

2 - through use of inspection and measuring machines strategically placed in the layout of the FMS.

The use of touch probes has been discussed by Lewenden[69] and a study on the measurement of tools and workpieces is given by Hermann[49]

Inspection machines can be of NC type, e.g. NC coordinate measuring machines[120] or other types.

Fixtures and pallets

Fixtures and pallets come together to form fixtured pallets on which parts will be held. Fixtured pallets constitute the physical interface between workpieces, the transport system and the workstations. Thus usually, in an FMS parts are carried on pallets. These are transferred from a palletising area or part/pallet storage area, by means of an automated transport system, to the machines for processing and then back to the palletising area for part depalletisation and refixturing if necessary. A range of palletising possibilities and work transport alternatives is available. These are described in some detail in chapter 4.

Palletising and depalletising are respectively the first and last tasks to be performed on parts in an FMS. These tasks, as referred above are still predominantly manually performed.

Pallets are usually loaded on machine tables. This is very typical of prismatic part production although these parts may also be handled individually at machines, and positioned in a fixturing system permanently resident at the machine, figures 2.3 and 5.5. However this approach to part clamping and positioning for machining is typical of rotational work where the part is loaded directly into a clamping device, e.g. chuck, fixed to the machine spindle. This may be a manual operation but in FMS is usually performed by an industrial robot.

Attempts have been made to try to simplify the clamping and unclamping functions through universal[47] flexible and automatic clamping or fixturing systems[96,121]. Such systems may be modular[141,70] or specially designed to accommodate a limited variety of identical parts. Fixturing systems can be flexible to accommodate a variety of different parts.

For parts to be produced in somewhat larger quantities, it might be advantageous to design specific and efficient fixturing systems for fast clamping of parts. These systems may be designed for clamping one or a few identical or different part types figures 2.3 and 5.5

Tools

Tools are used at the spindle of the machines for part processing and other auxiliary functions. Three types of tools may be distinguished:

-Replaceable single tools for machining

-Replaceable tool heads for machining and

-Touch and trigger probes used for measuring and monitoring functions

Tools are essential to carry out part processing and must be available at the machines when required. An adequate tool management system is necessary and a number of approaches to this problem are reported by Hankins et al[45].

Tool requirements and elements of tooling systems are considered in some detail in chapters 5 and 6. Additionally, most of this research work looks into the influence of a variety of tooling aspects on FMS performance.

Tools are still frequently replaced manually in FMS's but there appears to be a tendency of completely automating the tooling distribution system. This has been done in a number of existing FMS[125]. An approach becoming popular is to take tool kits to the machines on an Automated Guided Vehicle, AGV, and replace them into the magazine of the machine by meas of an automatic handling mechanism or industrial robot, IR, figure 2.5[47].

Transport and Handling Devices

Transport and handling devices, HD, are necessary to move parts and tools between workstations and central stores. HD's are important elements of the FMS material flow system.

Consideration of material flow and material flow systems is given in chapters 5 and 6.

2.1.6 Control, Monitoring and Supervision

2.1.6.1 Levels and Functions of Control

The control of FMS's can be viewed at two levels[142] :

- The Production Planning and Scheduling off-line level and
- The production control on-line level.

At the first level a production plan is determined where part types and quantities to be produced during a manufacturing period of a day or a few days are specified. This is mainly dependent on part demand requirements and available production capacity. A finite capacity plan or schedule is prepared where jobs or parts are allocated to machines or group of machines. The allocation can be aggregated or detailed. In the latter case an indication of the machine where and when should each part be processed is given and transmitted to the real time process control system. The production plan is frequently revised and adapted to take account of perturbed and changing system conditions.

For the preparation of the production schedule account is taken of the main manufacturing resources, i.e. machining and other workstations but also of manufacturing resource aids such as fixtures, pallets and tools. This is necessary when such resource aids can become constraints to part assignment to machines. This is most likely the case when they are available in limited quantities.

On-line control is directed to accomplish the production aims established at the previous production control level, i.e. the production planning and scheduling off-line level, through on-line commands based on control strategies for job releasing into the system, part assignment to and part/pallet sequencing at the machines for processing.

On-line control decisions may either be determined by an off-line detailed schedule[93,53] in which case the on-line control is mostly concerned with the generation of process control commands to carry out the schedule, or alternatively defined in real time, i.e. during real time operation of the FMS based on a aggregate schedule for the planning period[115,82]. Off-line detailed production schedules can be generated with the aid of a very detailed simulation model of the FMS operation a few hours in advance of the start of production for the manufacturing period. Scheduling in real-time may also use simulation for real time evaluation of alternative control decisions before they are taken[82].

Job dispatching or job releasing into an FMS is the highest level in a hierarchy of on-line control and can be performed based on a number of strategies. These are typically based on part due dates or part urgency, and factors which are related with machine load and machines idleness. In this releasing framework strategies can be used which attempt to balance work load among machines, release work for the idle machine or avoid work release for the bottle neck machine[106,6].

The assignment of parts to and sequencing at machines is aimed at achieving performance objectives. These typically consist of achieving high machine utilization, meeting due dates, minimizing throughput time and work in progress or a combination of these measures.

Part assignment and sequencing control must take consideration of real time availability of machines and manufacturing resources such as tools for allocation to and sequencing of parts at the machines in order to guarantee that part processing can effectively be carried out when scheduled. Such control is normally done basing decisions on priority rules. These may include First Come First Served , FCFS, rule, rules based on remaining processing time or number of operations of the job or still on many other factors. Once a part is effectively loaded onto and ready to be processed at the machine, the control system uses the appropriate NC part program for controlling the machining operations.

A classification of the FMS control decisions at various levels corresponding to different time horizons is given at the FMS Handbook[47] and are shown in figure 2.6

2.1.6.2 Hierarchical Centralized and Decentralized Control

The AMRF and AFMS Approaches

A methodology for overall control of automated manufacturing systems has been proposed, in the context of the Automated Manufacturing Research Facility, AMRF and Advanced Factory Management System ,AFMS,[82] where control of production is performed at different hierarchical levels in such a way that the input to one level is the output from the upper level of control realized for a larger time horizon, figure 2.7. The frequency of decisions are taken, at the lowest level on a second by second basis up to more than a monthly basis at the highest level of control. A two way information communication chain linking the hierarchical levels is necessary for control decisions, data collection and the monitoring of both the system conditions and the achievement of operational schedules.

Relative to the scope of decision control allowed at manufacturing cell control level two approaches can be considered[82]. One is the centralized approach. The other is the decentralized one. In the centralized approach most control decisions are taken at the upper level, i.e. shop level, and transmitted to the cell control to be carried out. Production control decisions are mostly not taken by the cell control in real time but simply the control of cell operation follows a pre-defined shop detailed schedule. This normally requires intensive two way data communication between cell control and the upper control level. In the decentralized approach great control autonomy is given to the cell control and in general to each control level in the hierarchy. Thus the higher levels usually define general control plans or schedules to which lower levels should base their own control decisions. Large disruptions of normal manufacturing operation and large deviations of pre-defined performance objectives, defined at the higher level, are likely to require action of this higher control level. This action essentially consists of general rescheduling and definition of new performance objectives. However small disturbances are dealt with within a control level. The need for information communication between levels in the decentralized control is smaller then in the centralized control due to the greater control autonomy of the centralized control.

Advantages of the centralized control are easier implementation, a broad view of the system control requirements by the central computer which can therefore make good control decisions due to large system status information which it can access. Interaction between decision makers in the control process is easier because of the simple control structure. These advantages are frequently overshadowedby the disadvantages resulting from difficulties which the central computer has in handling massive amounts of information in real time. Moreover difficulties may also arise for producing timely decisions due to the high frequency with which they are required.There is still the risk of total system disruption due to interrupted communications caused for example by computer failure.

An important advantage of the decentralized control is the provision for greater autonomy of the manufacturing systems to run itself with most of the control left to cell level. Only when major problems arise does the shop control level becomes involved in the control decisions. In this way the cell communication link with the upper level is less vital than in the centralized approach in such a way that if it is broken the manufacturing shop may well be able to carry out activities for some time.

Other Approaches

A different hierarchical decentralized FMS control system approach was developed by Stute[115], figure 2.8. Control hierarchy and decentralization is achieved by using different computers at different levels and at a same level using different computers for carrying out different tasks or functions. In this function based decentralization a main computer is used for main scheduling. Below this there is a manufacturing computer which is used for control and monitoring of the production process. The control is carried out on the basis of a schedule passed down by the main computer. Two other computers are used at the lower hierarchical level. One is used for carrying out geometry functions, such as interpolation for all the machines in the system, and the other is used for technological information handling. This includes decoding commands, produce output to programmable controllers, control pallets and tools' flow and data acquisition.

Fig. 2.9 shows the main control tasks to consider in a control system and divide them into groups to be treated by different computers[131]. For the centralized control only long term planning tasks are left to the main computer and the other manufacturing control tasks are carried-out by the centralized manufacturing computer. For the decentralized case four computers are considered each one with a reduced number of manufacturing control tasks to be carried out.

2.1.6.3 Monitoring and Supervision

Monitoring

Monitoring systems are aimed at avoiding large scale disruption of FMS operationally due to unexpected malfunctions of FMS elements.

There are many aspects to be monitored[1]. Amongst the most important are workpiece and tool conditions.

Important sources of failure in an FMS are wrong tool lengths set-ups, tool breakage and bad part positioning at the machines. Tool monitoring systems must be able to detect these deficiencies and lead to immediate preventive actions against undesirable consequences. When a tool breaks a logical measure is to retract the tool and replace it by a new one for further processing, either of the same part, if this has not been damaged, or of new parts. In the extreme tool breakage may cause the machine stop.

Another important aspect of tool condition monitoring is the monitoring of remaining tool life. This is important for tool replacement which due to economics of system operation may have to be done at defined tool replacement periods before tool fife ends. Tool life monitoring is frequently done by recording tool usage time which is compared with a predefined tool life time[64]. Other more sophisticated approaches take into account variation in some important machine, tool and workpiece parameters. These parameters may include temperature, noise and vibration, strain and forces, power and torque and workpiece quality data. Most of these are used for control and monitoring the level of tool wear in order to detect the right moment for tool replacement and also for adapting cutting conditions to achieve desired quality and increased tool life.

The presence or absence of workpieces at the machining area as well as the identification of the correct part and its appropriate positioning for machining are other aspects which must be monitored in a FMS.

FMS Human Supervision

Supervision is necessary to ensure that good operating and control conditions are maintained during system manufacturing periods.

Normally FMS supervision is concerned with verifying that all manufacturing functions are carried out as expected and that production schedules are met.

For small disturbances of system operation the computerized control system is usually able to take or indicate corrective action. however FMS supervisors may have to resolve problems resulting from unexpected disturbances of the normal operating conditions which cannot be tackled satisfactorily by the computerized control system alone. Thus, at breakdown of a machine or other major FMS element major rescheduling of work may be necessary which usually requires human interaction with the control system. A new scheduling plan for the manufacturing period may have to be prepared[93].

2.2 FMS DESIGN AND OPERATION

The overall design of FMS can be divided in two main stages:

1- Planning or general design of FMS

2- Detailed design of FMS

2.2.1 Planning of FMS

The main concern of FMS planning is to select the FMS equipment such as machines transport and handling devices, pallets and fixtures, and define the general system configuration to carry out production of a given part spectrum to satisfy a certain demand and therefore subject to a required production capacity. Moreover the general requirements and specifications of the control system and subsystems and operating principles are also defined at the planning stage. Thus FMS planning establishes the boundaries and constraints upon which both the detail design and system operation will depend.

At the end of this phase a few alternative systems may result which will be submitted to a "microscopic" study at the detailed design level.

2.2.2 Detailed Design of FMS

Almost every decision from and result of the planning phase can be seen as an input to the detailed design process. At this stage the alternative designs pre-defined at the FMS planning level are closely analysed in order to arrive at a final and operational FMS system. Aspects that may have to be determined are concerned with buffer sizes and their locations, the appropriate number of each type of pallet and tool and also magazine sizes. Moreover the efficiency and effectiveness of each configuration selected at the planning level is determined and required changes to improve system performance are put forward.

The detailed design of an FMS relies heavily on the performance evaluation of the system based on a range of operating strategies. In this sense much of the detail design of FMS can be regarded as a phase of designing the set of procedures and modes which will be used during FMS operation.

The design of the FMS operational strategy is concerned with finding the best ways of running the system to achieve production objectives. This usually requires the comparison of different strategies for releasing jobs into the system, the study of alternative processing routes, evaluation of different palletising sequences, analysing tool requirements and loading to machines, definition of modes of production e.g. Assembly Set Production or Batch Production, chapter 4. It also involves determining ways of obtaining good and feasible manufacturing schedules for the allocation of parts and shared resources such as tools and pallets in order to achieve high FMS performance.

2.3 FMS MODELLING

The process of finding adequate FMS configurations and refining them to obtain a final good solution is an iterative process[140] which can involve a range of planning and design tools and techniques. The most widely used are modelling techniques which can be classified under three headings:

- Analytical Modelling
- Computer Simulation
- Physical Simulation

"Analytical models represent quantities and relationships as mathematical variables and expressions, which are then manipulated (mathematically) to yield the desired information

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, transforms it into output measures

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"[101]:

2.3.1 Analytical models

The work on analytical models for FMS design can be classified under two categories:

- Mathematical programming
- Queueing network models

Mathematical programming models rely on Operations Research techniques such as Linear Programming, Integer and Dynamic Programming.

Queueing network models may combine both queueing network theory and some of the techniques of mathematical programming such as linear and non-linear programming and integer programming.

Analytical models find considerable use at the very beginning of the FMS planning stage. A variety of these models have been reported[136,98,12]

Newer analytical techniques such as Mean Value Analysis, MVA and Perturbation Analysis Method, PAM, have also been applied to study the performance of FMS, section 3.2.1.

2.3.2 Simulation

Although, as referred to above, a range of analytical models and modelling approaches are available, for FMS design and operation performance evaluation simulation models are by far the most useful, effective and reliable tools[130,74,5].

Simulation has become an integral part of design of FMS's. Almost all aspects of FMS operation can be modelled through simulation. Simulation can be used as an aid to FMS design and control at any level. Computer simulation was until recently available only on large computers but today realistic simulation work can also be developed on personal computers[43,22].

Computer simulation can provide valuable information both at early stages of the design of FMS and also during system operation to assist in the scheduling and assignment of parts and tools to machines.

In the early stages there is emphasis on studying alternative system configurations or concepts suitable for manufacturing a chosen part spectrum. It is important at this stage that the computer simulation model is able to evaluate different FMS types and material flow structures and general strategies for the operation of proposed FMS's. These strategies can be related with part mixes and batch sizes to be adopted, allocation of work to machines or groups of machines and job releasing strategies.

At a more detailed level simulation should be able to accurately evaluate any operating strategy for part and tool allocation to machines and part priority sequencing at different workstations. Moreover it should be able to determine the impact of varying levels of manufacturing resources such as tools and pallets on FMS performance.

In a simulation study the evaluation is based on output measures from the FMS model. These usually include, utilization of FMS elements such as machines, transporters and pallets, part and batch or product throughput times and also work in progress, w.i.p., expressed either as the number of parts in the system or the processing time already performed on such parts.

It is frequently argued that computer simulation models take a lot of time to develop but this is largely dependent on the approach to simulation used, language and also on the expertise available. Recent developments on graphical input/output and particularly on simulation program generators[60] are making the task of simulating FMS simpler and quicker. Things can be made even simpler if well tested and validated simulation models are available when necessary.

Well developed and tested detailed simulation models are good in accurately reproducing the system operation and behaviour. For this they require as input a large amount of system information in the form of deterministic data, such as part routes, processing times and also the representation of all relevant system elements such as parts, fixtures and pallets, machines and tools and handling devices. In addition stochastic data reflecting forecasted and historical information is usually also required , for evaluating the influence that aspects such as breakdown of system components and variation in demand and other variables have on system efficiency. A typical stochastic aspect which may be studied is the influence of statistical variation of operation times on system performance[53].

When the influence of operating strategies in a particular system configuration has to be studied, or detailed aspects of design are suspected to have a great influence on system performance, then fine simulations must be done. This requires that considerably detailed simulation models are used to evaluate FMS performance. Such models should provide the user with a range of detailed output information which may include aggregate and sometimes detailed performance measures about relevant system elements such as machines, transport units, operators, tools, pallets, fixtures and workpieces.

Simulation models may also be required for initial generalized studies of FMS performance in which the level of detail is somewhat restricted. In this thesis such models will be referred to as "global" simulation models.

When a physical system configuration is not clearly defined, a global simulation model can be used to evaluate a range of alternative global design configurations. Typical input data to global simulation models have a predominantly aggregate nature and are frequently stochastic. Thus, for example, theoretical probabilistic distributions may be used for defining processing times, work arrival to the system and unexpected stoppages. The usefulness of global simulation models is close to that of Closed Queueing Network models for FMS study, figure 2.10. An FMS analysis package may need to include not only simulation models for both global and detailed design but also a range of analytical models[17] including closed network models such as CAN-Q[102].

Evaluation of Existing and Proposed Systems

Simulation modelling is used either for studying existing systems or proposed systems. When simulating existing systems model development is simplified because even the most detailed information needed about system configuration and operating aspects, is in practical terms, readily available. The real system can also be seen as a test bed against which it is possible to compare the results of the simulation for testing and validation purposes.

By its very nature the modelling of new FMS's may have to be a more protracted process because some important data initially needed is not immediately available at the start of modelling. This includes processing times of parts, strategies for part and tool handling and part palletisation. Initially some of the data may have to be estimated which will be refined as modelling proceeds. Additionally the design of new FMS's has normally to be carried out in various stages. This usually requires first the use of global simulation and possibly analytical models for aggregate evaluation of a variety of alternatives followed by detailed simulation of a few selected FMS configurations.

Software for FMS simulation modelling

Simulation models can be written in normal high level languages such as FORTRAN and PASCAL or in specially constructed simulation languages such as SIMSCRIPT, GASP, SLAM and ECSL. The advantages of simulation languages are that they usually simplify the task of model development through simplified programming and they provide aids for model testing. They also frequently offer a comprehensive set of tools for aiding model input and model output, for simplifying simulation experimentation and analysing simulation results.

A third type of language which may be called a special purpose simulation language has emerged during the course of this research. Such languages are normally oriented to the simulation of specific types of problems and systems and are directed at simplifying the task of model building. Those that are used for the design of FMS are usually called FMS simulators although the term may also be used to mean a particular FMS simulation model. The three major FMS simulators are SKITAS[19], GISA[31], and MAST[68].

FMS simulators are normally provided with a form of automatic generation of a specific simulation model in a simulation language. Graphical aids are now used for input of some relevant data and also for presenting simulation results. In some recent cases the simulation can be visualized at a graphics terminal in a dynamic pictorial reproduction or animation of the simulated process. Varying levels of animated sophistication are offered by the simulators.

Artificial Intelligence techniques are now being brought into the design of such automatic program generation[99].

It is clear that as we move up in the level of a language, the application generality and flexibility of representing detail decreases. On the other hand simulation languages and FMS simulators simplify model development and testing. These are possibly the main aspects which should be taken in consideration when choosing a language for simulation. If a FMS simulator can provide the basis for developing an appropriate model of a specific system, then it is likely to be the appropriate modelling tool. For very detailed and complex FMS simulations high level languages like FORTRAN or PASCAL may be preferred to simulation languages or FMS simulators. This reasoning is supported by Cavaille[16] who in relation to a detailed simulation of the RENAULT FMS states: " The choice of a general language such as FORTRAN results mainly from the level of sophistication of the network and the control system whose modelling using a simulation language is too heavy ".

Experimenting with Simulation models

Simulation is essentially a non-optimizing technique. The amount of detail, complexity, stochastic and estimated nature of some data make optimization unrealistic[91]. Simulation can give good solutions, but no optimal ones, to many aspects of FMS design and operation and helps to avoid large risks and economically undesirable alternatives.

With rare exceptions the model user is usually an essential integrating part of the model itself in that he or she closes the simulation loop by being able to analyse the simulation output data of successive simulation experiments towards finding a good combination of relevant factors.

Simulation models may also include built in search procedures for determining good levels of particular factors or parameters based on a predefined required performance objective of a simulated system[15,77]. This greatly reduces the involvement of the model user in the simulation process and can lead to good values of the factors or parameters within a few simulation runs. One technique used by Carvalho[15] is based on the "Decentralised Gradient Approach-DGA". In this approach the simulation is run with an initial set of parameter values. A DGA analysing routine then examines the internal details of the run and attempts to recommend a better. set of values. The simulation can be automatically rerun successively for each new set of recommended values until the DGA has no more changes to recommend or its recommendation fails to improve performance.

In a similar way Mellicamp and Wahab[77] have supported the automatic generation of good FMS designs on an expert system.

2.3.3 Physical Simulation and Pilot Systems

An FMS physical model is essentially a scaled down physical representation of the real system through modelling components, like Fishertechnik components, of a proposed FMS system. Once ideas are clear about the FMS overall structure then a scaled model can be built in a few weeks[81].

Most of the FMS control hardware and software can be integrated with the physical model in such a way that testing and further development of control system software, interfacing and information processing system can be carried out. This real system emulation for the study of the computerized control is probably one of the greatest advantages of physical modelling. Another important benefit is the provision for training of personnel who will be supervising and operating the FMS in advance of the real system becoming operational. They can use the model to simulate system operation.

Pilot FMS plants[8] although very expensive when compared with simulation approaches, may also be used to study FMS. They are likely to be particularly useful for settling detailed aspects of design and control and in particular to try out system hardware and system control software. These plants approximate the real system and are seen as test beds for FMS installation.

The pilot FMS may represent an entire FMS plant or only a subsystem of a large system to be installed. It can be used as means of training people to use an FMS. Pilot FMS's can also be seen as the best "modelling" option, although the most expensive one, for studying system integration at all levels.

Physical simulation and pilot plants were not used in this research and will not be referred to further.

CHAPTER 3 - LITERATURE SURVEY

3.1 SURVEY OF FMS'S

3.1.1 Traditional Manufacturing Systems

Traditionally two main kinds of manufacturing systems could be identified:

-Job Shops, JS's and

-Transfer Lines, TL's

Job shops are labor intensive systems with, usually, one man operating one machine. Initially these were conventional machine tools but since the introduction of NC in 1950's[66] JS's also tend to include these latter type of machine tools. JS's are able to produce a large variety of parts requiring different processing sequences and technology.

JS's tend to have low productivity, section 2.1, low average machine utilization, large work in progress and usually very long product lead times which can easily reach months. These deficiencies lead to a poor use of manufacturing resources and therefore to relatively high cost of piece part manufacture.

TL's are manufacturing systems where processing operations are carried in a fixed sequence imposed by the line layout of the machines. Parts flow one behind the other, unidirectionally from one extreme to the other of the line, stopping the same amount of time at every machine for processing until the last stage of processing in the line is finished.

Transfer lines were first used for large scale production in the beginning of 20th. century in the automobile industry by Henry Ford[134].

TL's are very suitable for high volume and very low or zero part variety. Small variations on a part type may be accepted provided the same manufacturing process and sequence could be used. TL's usually produce identical parts at very high production rates, high machine utilization, low throughput time and low w.i.p. In simple terms w.i.p is only the work which is currently being processed at each of the machines and throughput time is the time a part takes during processing to move from the beginning to the end of the line.

Once a TL is designed and installed it is necessary that it continues producing a part type or small variations of it for many years.

So TL and JS's are two approaches to manufacture which are incompatible with present market requirements for low cost and high variability of product types with short life cycles and short lead times.

Ideally a manufacturing concept was required that had the flexibility approaching that of job shops for producing a variety of parts but with productivity, machine utilization and lead times which could approach those of transfer lines. FMS appeared just to fill these requirements.

3.1.2 Initial Developments of FMS

To achieve the aim outlined above a revolutionary manufacturing concept was proposed in the mid 60's. This proposed the computerized control of an automated manufacturing system consisting of the then new NC machining centres and an automated work flow system.

The first system to be designed in GB was the Molins 24 System[137,138], figure 3.1, for prismatic parts. Parts were to be manually clamped on pallets which would then be transported by an automated stacker crane and stored in a vertical store. A second stacker crane would then be used to transfer pallets between this store and the machining area. Finished palletised parts which had been returned to the store would be taken back to the operators by the first stacker for part unclamping. Each machining centre was provided with a magnetic tape on which a number of NC programs were stored. Each pallet was capable of taking a number of different parts. The overall manufacturing process was computer controlled. The Molins 24 System was in fact the first FMS do be designed.

Molins 24 System was ahead of its time. The concept required computer power which was not available at that time at sufficiently low cost. Although the concept was never fully built one partial system was however installed at Molins Deptford factory and another at an IBM factory in USA[7].

Another system developed in the mid 60's in USA, was the Variable Mission Manufacturing System, VMM[85,30], figure 3.2. This system was the designed answer by the Cincinnati Milling Machine Co. to manufacture a small variety of parts in relatively large quantities which were not enough to justify the use of TL's. Parts were also prismatic and individually clamped onto pallets. The work flow system was quite different from that of the System 24. A loop roller conveyor was used with the possibility for some storage buffer near a number of NC machines. A washing station was also included. The VMM manufacturing system was in fact the first Flexible Transfer Line to be built.

3.1.3 Present State of FMS Development

Presently more that 300 FMS may be available. In a 1987 survey 253 systems have been reported[26] only in Japan, USA, and Europe.

Surveys of existing FMS's have also been published by Spur and Mertins[104], Mertins[78], Wilhelm[135], Hutchinson[55,56], Kochan et al[65], Gatelmand[40], Steinmuller et al[109], Iwata[57], in the FMS Magazine of July 84, April 85 and July 85, Bilalis et al[6], Smith et al[100] and Enghill et al[29].

The growth of FMS applications since they have been firstly installed is shown in figure 3.3.

Type of FMS's

FMS are also divided according the type of parts they manufacture in:

- FMS for rotational, R, parts and

- FMS for non rotational or prismatic, P, parts.

In general R and P parts are not manufactured in the same system.

The USA FMS's are predominantly for P Parts. In fact, in USA, no FMS for R has been reported by Steinmuller and only two were reported by Mertins.

World wide only around 20 % of FMS's are for rotational parts. This is clearly shown in both the comprehensive survey of 87 FMS's by Spur et al and also in the recent survey of 107 FMS's by Edghill et al.

Size of FMS

From 80 FMS's of the FMS surveyed by Spur et al 40% of them have only between 2 and 5 machines and about 80% have no more than 10. Similar results are shown by other surveys. In the survey presented by Enghill et al it is shown that 45% of the FMS's have no more than 6 machines.

Work Flow System

The nature of the work flow systems can be classified in systems with discrete means of transport of parts or pallets and continuous transport systems. These include floor and overhead conveyors of many kinds. The discrete type transport include any kind of transport on floor vehicles such as tow line, track or rail vehicles, automated guided vehicles and still gantry type robots or cranes and industrial robots.

In the Spur survey about the same number of the systems use the continuous type of transport and the discrete type. A few FMS's use both conveyors and discrete type transport systems. However this not the case in the recent survey by Smith et al, of the USA FMS's, were conveyors accounted for 35 % and the discrete type transport and handling system was used in 87% of the systems.

Part Variety

Very few systems produce more than 200 different parts[104]. In the Enghill et al survey 24 out of 29 FMS's produce a variety no larger than 30 different parts and very large proportion of the FMS's, i.e. between 43%[104]

and 62%[29], manufacture at most 10 different parts. 34% of the USA FMS's manufacture a part variety no larger than 20.

About 50% of the parts fall within a 600 mm cube[29].

Batch sizes

Average batch size varies between 30[29] and 55[104]. In the Edghill et al survey 24 out of 41 FMS's produce in batches no larger than 30 and in the USA 50% of the surveyed systems[100] manufacture batches larger than 30.

3.2 MODELLING FOR FMS DESIGN AND CONTROL OF FMS

3.2.1 Mathematical Modelling

Most of the work on analytical modelling for FMS design based on queueing theory is direct or indirectly related to the Jackson[58,59] work developed almost three decades ago. Jackson developed a method for studying jobshop-like queueing network systems as a set of independent service stations.

Work on analytical models using queueing theory has since then been developed by many authors[39,136,98,12,61].

The models fall under two areas namely flow line type network with and without buffers and job-shop like network. However practical application of this work has been limited[136]. This is due to the too restrictive assumptions underlying analytical models which rarely apply in real FMS and due to the limited range of output measures that can be obtained.

Solberg[102] has developed a model, CAN-Q model, which has been shown to be useful to use at the initial stages of FMS design. The model can be used for determining the number of required stations to satisfy required production output.

The CAN-Q model is a queueing network "Jackson" type model which models an FMS as a closed queueing network system in which a single class of customers is considered and a number of customers (workpieces) N is maintained constant. This assumption can be seen to be quite realistic for FMS with a fixed number of pallets in the system. Further assumptions include exponential service times, infinite machine buffers, fixed transport times and perfect reliability. Central part storage is not considered nor is the possibility of studying time dependent sequencing priorities.

Although some of the assumptions within CAN-Q can be seen as very unrealistic compared with the complexity of FMS, this model which is easy to use is stated to provide acceptable initial system performance estimates[103]. These include production rate, mean flow time, utilization and work in process. The model can also show the effect of increasing process inventory on the production rate and flow time.

Some models based exclusively on mathematical programming were included in a software package[72] which also contains closed queueing network models destined to be use in the preliminary stages of FMS planning. One model, SELECT, is used to select machinery on the basis of machine cost, machine availability and part operation processing time in each alternative machine. Alternative routing arrangements can be considered by trial and error based on successive runs of a dual optimizing program called GLOBAL. The routing arrangement which combine "best" utilization and minimum total production time is selected. At a next step, by using a linear programming program called BATCH, a good combination of work loads is defined to achieve maximum utilization in a minimum production time to meet production demand. The queueing models, called QUICK, within the same package, are used to determine the appropriate number of pallets required per work load per part type and to define the approximate buffer sizes at machines. The package has been used to establish initial configurations for Flexible Transfer Lines.

Further work on analytical modelling was presented by Buzacott and Shanthikumar[11]. They have used a few simple analytical models to analyse the importance of different levels of control and the influence of local and central storage on the output of FMS-like systems. Major conclusions were that the models show the desirability of balanced workload, the benefit of diversity in job routing if there is adequate control of released jobs and the superiority of common storage over local storage at the machines.

Recent Techniques

A fairly recent technique called Mean Value Analysis, MVA,[89] which uses mean values of the variables, has also been applied to study FMS performance[117]. MVA which is oriented to study Close Queueing Network Systems uses an analytical recursive algorithm and a heuristic procedure which is considered to be reasonably accurate.

Another very recent technique called Perturbation Analysis, PAM[51], has also been applied to study the performance of FMS's[117]. PAM may be seen as combining an analytical stochastic methodology with computer simulation. Its main objective is to determine the values of performance measures without having to use the "brute force" of experimental simulation. PAM is based on a given sample realization, i.e. sample path, of a discrete event system obtained either from actual observation/experimentation on the real system or from a single simulation run of a detailed simulation. The basic question to be answered is how does change in the timing of events, firstly originated by the change, i.e. perturbation, in the value of a system parameter, change system performance measures? The analytical procedure based on the results of the single simulation run can then establish, within reasonable accuracy, the expected values of system performance measures caused by the change of the value of the parameter.

3.2.2 Computer Simulation

FMS are characterized by features which include highly dynamic operation, unique requirements, high interdependence among system elements, sensitivity to operational strategies, high complexity and high cost.

The need to obtain proper evaluation of FMS performance to avoid unnecessary expensive mistakes of inadequate system design and operation, suggests that the simplistic mathematical models of FMS may only be useful at the first steps of design and performance evaluation of such systems. It has been suggested by many authors[74,128] that computer simulation still is the most effective and realistic modelling technique capable of studying the complex interrelationships between FMS elements and operation control strategies at different levels of detail in order to find the suitable FMS design and operating procedures to manufacture a given part spectrum.

In the last few years there has been a growing interest among researchers in studying FMS. Additionally companies have become increasingly interested in using FMS's as figure 3.3 suggests. These two reasons have caused the development of a large number of FMS simulation models, Table 3.1. As can be seen from figures 3.3 and 3.4 , there is a correspondence between the increasing number of existing FMS and the number of simulation models developed indicating the necessity for the use of such simulation models for performance evaluation.

Due to this demand for simulation modelling it is not surprising to see that most recently there has been a tendency for providing the user who needs to evaluate FMS design and operation with tools which can ease the way to simulation model development[60,8]. These tools which may be based on Artificial Intelligence, AI[99,111], are essentially referred to as FMS simulation program generators. In general a program generator can be defined as "an interactive software tool that translates the logic of a model described in a relatively general symbolism into code of a simulation language[76]". Program generators for FMS simulation models may be referred to as FMS simulators although this term is also used to mean FMS simulation models themselves.

One of the earliest program generators for simulation modelling, CAPS, was developed by Clementson[21] in 1972. A 1980 CAPS' version is available. CAPS automatically generates an ECSL language[22] draft of a simulation model through a dialogue oriented data input description mode. However the generated model has to be enhanced to accommodate details which it is not possible to include at the automatic generation level. Typical of such details are particular scheduling and control procedures or priority rules which control the flow of entities such as parts and transporters through the system. It is clear that for full model development CAPS' users do also have to master the ECSL language. In a sense, in this case, the task of the model developer it is not particularly simplified.

It has been suggested[20] that usually it is not possible to generate the program segments for FMS scheduling through program generators. In addition it seems that many presently available FMS simulators do not satisfy basic design criteria such as that put forward by Jain[60].

Animated simulation, section 2.3, may also be available in a simulation model or a FMS simulation package. This may include a number of independent although integrable programs[68] among which may be a program generator. However animation is not essential to study FMS's although useful for "feeling" and explaining what goes on during simulation run time.

It must be emphasized that a FMS simulation program generator is not a FMS simulation model. It is a special program built on top of or linked usually with a simulation language or a main simulation model which has some degree of generality, i.e. of capability to configure a variety of specific FMS structures and control procedures. So the generator works as a pre-processor of a simulation language or a generalized simulation model and may be written in a programming language different from that of the generated simulation model[43].

Generated simulation models are usually obtained through data input of important parameters[80] and other data, usually in a dialogue mode and eventually graphically supported. A simulation model generated from a generalized FMS model has capabilities naturally restricted by the capabilities of this model. The problem that arises is that a good and detailed model cannot be generated from a bad and global one, i.e. one for FMS first stage design and performance evaluation. In particular if some aspects of relevance to FMS design and operation analysis, such as palletisation complexity and control procedures are not considered explicitly in the main model then it is very unlikely that this can be made a available in the resulting FMS model obtained through program generation. To avoid this, i.e. to avoid having to write code directly, the main models must be both very detailed and quite general and be able to configure a variety of modelling situations from first step design up to a very detailed analysis of FMS operational control.

FMS simulators or program generators which could satisfy the modelling objectives of this research work were not available at the time this research started.

3.2.3 Tooling Systems and Tool Management

Of the variety of existing simulation models given Table 3.1 only a few model tooling systems or the movement of tools within the FMS.

In some studies, e.g. Carrie[14], tooling aspects may be analysed after simulation of part assignment to machines has been performed not considering tools to be a resource constraint to part assignment.

Stute et al[113,116] have used simulation for the study of tooling· They investigated the performance of 16 tool storage structures in order to choose the "best" one to adopt in a pilot FMS developed and studied at the University of Stuttgart. A framework for the determination of the number of tools was also presented. Basically tools could be determined based on a planning period or based on batch sizes and batch types to be manufactured together in the same production run taking into consideration the strategy to machine loading.

Westkamper[133] in a comprehensive study of automation in batch manufacturing also used simulation for detail study of tool flow structures including tooling requirements in a particular automated manufacturing system with 20 multi spindle machines and 200 different tools.

A simulation model called PATHSIM was developed by Crite et al[25] with the main objective of studying the physical configuration of a tooling system, which consider the tool transport system, based on carts, to be independent from the work handling system and also considers tools to be allocated to machines on a tool kit basis, a tool kit being defined as "the set of tools required to process one part type at one station type".

Ho and ElMaraghy[28] developed a simulation model to study tool management in FMS. The model offers the possibility of both graphical output of performance measures and simulation animation with an advanced video option.

In a study on tool management by Hankins et al[45] advantages and disadvantages of four tool grouping allocation strategies, namely Bulk Exchange, Sharing Tools, Migration and Resident Tools have been put forward. The authors conclude that the best strategy to use is very much dependent on the user's production requirements and that tooling constraints can hinder the productivity of FMS, but significant problems can be minimized through a good overall management system. Again it seems that the study is based on the assumption that a part allocation to machines schedule is pre-defined in a way which does not take tools in consideration.

Bell and Souza[4] are also developing a comprehensive system for tool management in highly automated flexible machining systems. It appears that the system also uses as input a part allocation schedule to machines.

In this research work both machines availability and tools availability are necessary conditions for parts allocation.

3.2.4 Palletisation

An aspect which appears not to have had particular attention in simulation modelling is that of palletisation complexity and generality. This is presented in detail in chapter 6, figure 6.2 and section 9.4, figures 9.4.2 and 9.4.3. When such complexity exists in the real system under study it must be modelled unless evidence exists that simplifications can be made without affecting overall performance analysis.

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3.2.5 Just-in-Time Production for Assembly

To achieve low w.i.p. and low throughput time to overall manufacturing system there is a need for just-in-time production for assembly which can be achieved through adequate operational control of manufacturing on an Assembly Sets, AS, basis, chapter 4. It appears that this manufacturing strategy and the study of operating procedures for Assembly Set Production, together with tooling aspects have not been treated by previous simulation modelling.

3.2 RESEARCH ISSUES

There are a range of generalized tools which can reasonably satisfy the FMS general design level tasks. The main problems are more at the FMS detail design level and particularly in FMS operation. Thus difficulties can be found in correctly defining the number of pallets and fixtures of each type as well as tools. Concerning FMS operation, there is a need to look into ways and methods to control the effect that shared resources like tools and fixtures have on system efficiency[103]. In particular the influence which such resources can have in finding good schedules must be understood. These aspects are likely to affect the way FMS systems should be operated. For example resource constraints may delay a scheduled operation even though workpiece and machines are available because the necessary tools may be in use elsewhere. Resources can always be duplicated but even such a measure, which brings increased costs and possibly increased "confusion" within the system, does not necessarily guarantee a better system operation. This simply means that the effects of such resource duplication on system efficiency and behaviour should be understood too and subject to careful study.

Working on the study of the effect of fixture and tool resources on FMS performance Solberg[103] states that "the problem is considerably more difficult than it appears; some of our favored approaches failed utterly".

The research work reported in this thesis examines these aspects, in connection with the problems of control for system operation, giving particular emphasis to FMS system operation for minimum tooling.

Manufacturing control

In operating FMS the assignment, and sequencing of parts and tools to machines, i.e. the short term scheduling, is of paramount importance. There are a few techniques which can be used to study the problem but, in a practical sense, they are restricted to the use of simulation. In fact analytical models do not yet offer an explanation of the principles which govern the operating dynamics within FMS and seem to be unsatisfactory techniques for studying realistic operating problems in real size systems. For this reason digital simulation is the main tool used in this work for modelling aspects of design and operation of FMS

The power of digital simulation to emulate FMS in one or more models in order to study the dynamic relationships between system parameters and control strategies suggests that it should be used to help to establish new procedures and guide lines for the better understanding of FMS operation.

There could be a temptation to apply the findings of scheduling studies of conventional systems to FMS. However the main available useful guide lines, based on sequencing priority rules determined through experimentation with simulation models of conventional manufacturing systems simply may not be applicable to FMS. Working on the control of FMS Stecke and Solberg[107] studied the relationships between sequencing rules and loading strategies in FMS. They concluded that FMS behave differently from conventional systems by showing that the results obtained under FMS situations were "counter-intuitive and different from those of previous similar types of studies" referring naturally to conventional systems.

Machine loading

Machine loading is another aspects which deserves further investigation.

In simple terms machine loading is the assignment of workload to the machines of a manufacturing system. This task is apparently simple in flow shops due to the nature of sequential and directional parts processing in all or almost all the machines in the shop. In traditional job shops, with a predominance of single purpose machines such as lathes, mills, drills and grinders, the loading problem can be greatly simplified through the grouping of identical purpose machines. This leads to the process layout of manufacturing. Thus each group of identical or similar machines work as a pool of servers able to perform the same operations to which the work is normally assigned in a balanced way.

In an analytical study of the FMS loading problem Stecke[108] has demonstrated that a specific and unique loading solution exists which maximizes production rate. In particular when the sizes of the machine groups, i.e. groups of machines equally capable of performing the same set of operations, of an FMS are equal then balancing workload is optimal. However if the sizes of machine groups are different balancing is only optimal if the number of parts is infinity, i.e. very large. The optimal loading solution can be obtained as a function of the number of parts in the system, the machine grouping configuration and the number of machines in the system. In general a larger(smaller) work load must be assigned to the machines of larger (smaller) groups.

According to Stecke the best production rate is obtained when all the machines are pooled together, i.e. can be grouped together in such a way that every machine can simultaneously process any part in the mix to be manufactured. If this is not possible due to physical, technical or other reasons, the best solution is obtained for a pooling situation which creates the minimum number of machine groups possible with the maximum number of machines imbalance between groups. Thus for a system with 8 machines it is better to group them all than to make two groups of 1 and 7 machines and this is better than a 2,6 configuration which on the other hand is better than 1,1,6 and so on.

The conclusion that the fewer the machine groups the better is in line with the findings of queueing theorists which have proved that under steady state conditions and stochastic service times a pooled number of servers are more efficient than the same number of servers working separately.

These results are of practical interest because they give guide lines for setting-up an FMS for part processing. However they are of little use when determining how FMS's really perform under different scheduling policies and sequencing rules and how they should be operated and controlled to manufacture particular part mixes which have varying processing requirements and levels of tooling. This is further emphasized by the simplistic assumptions underlying much of the analytical modelling not only for production planning and control but also for FMS design. A common assumption of analytical queueing models used for such purposes is to consider the system to work under steady state conditions. However more often than not FMS do not work under steady state. One of the reasons is the short term running periods, shift or daily basis, which rarely are enough for FMS's to achieve steady state manufacture.

Moreover the FMS loading problem often is a problem which may be better solved during manufacturing control. In this case system state conditions are analysed at every instant part loading decisions are to be taken. For example, part processing needs and aspects related with tools and pallets availability, in addition to machine readiness, should be considered for decision at such instants. This means that decisions about part loading are delayed near to the instant of processing. This strategy leaves open a number of alternatives for part loading which result from the in built flexibility of FMS's which would be otherwise not considered if part loading was defined at production planning.

When part loading is solved at the planning level a fixed FMS tooling set-up would have to be used for the manufacturing period. In particular if the loading problem is firstly seen as the assignment of parts to machine groups assuming workload balancing between machines within the group then when the time comes any machine in the group should be prepared to process the parts. This requires considerable tool duplication, depending on the size of machine groups.

A problem can now be raised namely that of knowing if it is possible to achieve good system performance without tool duplication, or, if not, what would be the best degree of tool duplication to run the FMS. This problem, together with that of determining the number of fixtured pallets under different operating scheduling rules for ASP, is addressed in this research work.

CHAPTER 4 - SOME ASPECTS CONCERNING OPERATION AND DESIGN OF FMS

4.1 ALTERNATIVES TO TRADITIONAL BATCH MANUFACTURING

4.1.1 Batch sizes

Traditional Batch Manufacturing Systems (TBMS) are nonautomated systems for manufacturing of a variety of parts. Production is normally carried-out and scheduled in batches of identical parts which are transferred from station to station and loaded and positioned at a station, usually on a one by one basis, by the station operator.

This batch approach to production is mainly motivated by the need to reduce work station set-up costs which are considered to increase with the number of times batch types change.

The set-up costs are primarily due to the following reasons:

-Cutting tool preparation, transport, replacement and set-up at the stations.

-Fixture and jig preparation, transport, replacement and set-up at machines for part clamping and positioning.

-Preparation, routing and loading of information for task processing including NC programs.

Although when batch size, BS, increases set-up costs decrease, it is also true that other costs increase. These are related to levels of work in progress, throughput times, space requirements and other factors.

Reducing the BS to one is apparently inappropriate in TBMS. But this may not be so in FMS's because these systems are considerably different from TBMS.

Therefore, it is pertinent to question the validity of the application of the batch production mode to FMS's. Such a mode seems be against some of the objectives of FMS which include the minimisation of work in progress and job throughput time keeping nevertheless high levels of machine utilization.

In FMS's for prismatic work machine, set-up costs are low for both production of identical or different parts since parts are preset before being delivered. The only set-up cost incurred is that due to tool replacement for different parts. It is possible that this can be carried out whilst the machine is engaged in processing parts. Thus little savings in cost can be expected from production in batches, particularly if we take into account that the higher the batch sizes the higher the cost of work in progress and the longer job throughput times.

It is important to point out that provided finished parts are not the end product, as it is most frequently the case in manufacturing systems, in practical terms the parts will remain in progress until they can finally be assembled into finished goods. This fact reinforces the idea that within FMS's the traditional batch production mode may not be appropriate. Such a view is also defended by some authors as the following comment by Warnecke[129] in relation to FMS flexibility, suggests: "The unit cost of a product is no longer dependent on lot size or number produced". Buzacott et al[11] has also emphasized the desirability for part diversity by stating that in an FMS " it is desirable to have a diversity of jobs with different routings". These views go against the traditional batch production mode and suggest that a one-off like production or at most very small batch sizes should be adopted in running FMS's.

4.1.2 FMS as Part of an Integrated Production System-Assembly Set Production

An FMS is fundamentally a subsystem of a larger production system. In general the manufacturing output of an FMS is likely to be the input to an assembly system. The assembly system, which may or may not also be automated, is usually provided with an area for parts storage. The size of such a storage area is very much dependent on the organizational strategy adopted to part production at the previous manufacturing level and is likely to be large if traditional batch production is used.

The amount of parts to be stored prior to assembly can be low if an adequate manufacturing strategy is implemented. This requires that part manufacturing is synchronized with the parts for assembly requirements. In other words, parts should be manufactured according the immediate needs of assembly, i.e. a "just-in-time" strategy. At best, the set of parts necessary for a single product should be manufactured simultaneously in the same production run and before any other part. This organizational form of production, based on assembly sets is called assembly set production, ASP.

Due to the rigidity of traditional manufacturing systems such a production mode has been proved to be uneconomical. However FMS are highly flexible and therefore are more suited to ASP .

ASP aims at finishing simultaneously all the required parts to assemble a single product. One way to achieve this is to palletise, in a single pallet, the maximum possible number of parts of an assembly set and process them together. This solution has been adopted to manufacture the set of parts necessary to assemble a small engine[139].

It is possible for ASP to lead to low assembly set throughput time and also low work-in-progress keeping FMS utilization high.

With ASP it is theoretically possible to conceive integrated manufacturing and assembly systems with no inventory of finished parts. The parts necessary for assembly could flow more or less continuously from the FMS into an assembly system fed at the FMS output rate. However, due to unavoidable variations in work flow rates between the FMS and the assembly system provision for some storage of finished parts at the assembly area is likely to be necessary in practice.

4.2 ORGANIZATIONAL AND DESIGN ASPECTS RELATED TO MANUFACTURING AIDS

4.2.1 Number and Type of Parts per Pallet

Parts may be palletised on one of two ways. Either a single part is carried by a single pallet or two or more parts can be palletised together.

When a single part is carried on each pallet the problem of part mix within a pallet does not arise. However if a number parts are to be palletised together, the problem of knowing the type and number of parts to palletised together has to be sòlved. The problem is primarily of an organizational nature although technical constraints must be taken into consideration for arriving at feasible solutions.

When batch production is adopted, the need to palletise together a number of identical parts is evident due to workflow and processing simplification which would result from such a measure. Ideally the whole batch should be palletised together for joint processing. Identical reasoning could be extended to split and averlapped batch sizes when batch splitting and batch overlapping is adopted. Similarly, in ASP, parts making-up an AS may advantageously be palletised together for joint processing provided this is technical and physically feasible.

4.2.2 Pallets and Tools Replication

Processing large batches of identical parts in an FMS can be undesirable as discussed above. This undesirability is reinforced by two main reasons related with the number of manufacturing aids required. One is the high number of identical pallets and fixtures which might be necessary. The other is related to tools, i.e. cutting tools and other tools to be exchanged at machine spindles. The last reason leads to two problems which must be solved. First the number of identical tools each machine must be provided with may have to be very high. The second problem is related to the large size of tool magazines or buffers which may have to be provided. The tool magazines would have to be large enough to accommodate not only the tool spectrum to process the appropriate part operation, i.e. a number of elemental operations each of which requires a single cutting tool, but also a considerable degree of tool replication. This replication results from the need for repeated processing in connection with tool life per tool. Moreover when machine pooling is necessary in order to increase part routing flexibility then the number of tools would have to be replicated not only in the magazine of one machine but equally replicated in other machines as many times as the number of machines pooled together.

4.2.3 Strategy to Reduce the Number of Manufacturing Aids

The problems mentioned above can to some extent be overcome if batch sizes are reduced to very low values and mixed with other batch types during the same production run. This would have the effect of reducing the number of tools required and also the number of identically fixtured pallets.

Taken to the extreme ASP, section 4.1.2, should be adopted. The main and basic difference relative to batch production is that in the ASP mode, the parts being processed together are predominantly not identical .

As compared to batch production, in ASP the number of parts which can go into a single pallet may also be one or more. However, ideally, the whole set of parts for a product or assembly set should be palletised together for joint processing.

In general we can conclude that, since tool replication in each machine is likely to be small in ASP when compared to batch production, then a large reduction in the number of tools to run an FMS can be expected. This is even more likely as the degree of machine pooling increases. However, if a full AS is to be completely processed in each of the machines then a full set of tools should be provided in each machine and therefore a tool replication at least identical to the number of machines in the FMS would be required.

4.2.4 Strategy for Fixtured Pallet Design

The ASP-palletising approach must take system physical constraints into consideration. Difficulties may arise due to the large number of different tools which it may be necessary to load together into a tool magazine for joint processing of the variety of parts palletised together. Tool magazine size may therefore put a constraint on the number of different parts which could be put together on the same pallet for joint processing.

The number and type of parts which may be palletised together for joint processing also depends upon the system physical capability for handling different tool types and on tool availability. Tool grouping possibilities will be determined by processing capabilities of the machines. There would be no clear justification to group tools, to be handled in a set if it could not be loaded into the machine's tool magazine.

Thus it is necessary to know:

-the number and type of tools required by each part operation;

-the amount and variety of part-operations which can be processed together;

-the total number of tools required to process together in a single machine a selected set of part-operations and

-the size of the tool magazines at each machine.

The following conditions must be considered when determining the number of pallets to accommodate the part mix:

-can the whole part mix be clamped together on a unique fixtured pallet

-can the part-mix be partitioned to be palletised in a number of different pallets and

-does each different part require a pallet

In the first case the minimum number of identical pallets should be provided to fully load the FMS. This can be initially calculated by equation (6.14), section 6.3.2, and later tuned through computer simulation of say daily production runs.

For the second situation a number of pallets can also be established, section 6.3.2.1 The difference is that pallets are not identical.

When a different fixtured pallet is required for processing each part-operation then the number of pallets is at least the same as pallet variety which is identical to the number of different part operations.

The problem of determining the number of pallets and tools is addressed in chapters 6 and 10. In chapter 6 simple analytical calculations are considered and adopted in chapter 10, section 10.2.9. In section 10.12 computer simulation is also used to determine the number of those manufacturing aids to guarantee high FMS performance.

CHAPTER 5 - ELEMENTS OF FMS MATERIAL FLOW SYSTEMS

5.1 INTRODUCTION

Material Flow Systems (MFS) are integral parts of FMS's and include the two following main subsystems:

-Work Flow Systems (WFS) and

-Tool Flow Systems (TFS).

Work Flow Systems are particularly concerned with the transport and handling of the workpiece through the system while Tool Flow Systems deal essentially with the transport and handling of tools which are exchanged at the machine spindles.

Work flow and tool flow may sometimes be carried out by the same Material Flow System [44,35].

There are a variety of work flow system configurations[126,123,112] and tool flow systems configurations[113,45] for FMS's which have been studied in depth and their advantages and disadvantages put forward.

This chapter focuses attention on the building blocks of MFS and presents a classification and brief description of tooling system structures.

5.2 WORK FLOW SYSTEM ELEMENTS

Work Flow Systems may be divided in two subsystems:

-Work Storage Systems and

-Work Transport and Handling Systems.

WFS components for such subsystems can be defined as basic elements whose integration determines the work flow system configuration.

5.2.1 Elements for Work Storage Systems Design

Figure 5.1 is a representative classification of the basic elements and approaches to storage and buffering. The elements shown can also be considered for storage of production aids such as pallets or fixtured pallets, fixtures and in most cases tools as well.

When large quantities of a variety of parts or pallets are to be stored the typical central store to be used is the static random access cell store whose schematic representation is shown in figure 5.1-element 1. The first FMS, the Molins 24 System[137,138], which was never completely built, had considered this type of store, for palletised work, laid-out vertically with cell access by a stacker crane.

Frequently this static random access cell store appears in a vertical form although horizontal and inclined versions have also been applied[90,34]. In this case industrial robots are frequently used to access the stored element.

If the number of part carriers or pallets in circulation is small then central storage can be efficiently provided by simple stands on the floor, figure 5.1-element 0. Such stands can be interfaced with part or pallets transport and/or handling devices of which the most frequently used are automated guided vehicles (AGV), carts and industrial robots (IR). A turning cell which incorporates an overhead robot for part and tool handling with local storage using static stands is shown in figure 5.2.

Pallet storage on static stands which are accessed by a vehicle carrier, figure 5.3, is one widely used concept for part storage and transport in FMS. Advantages of this method are aspects such as high reliability and random part and machine access. In this work flow configuration, part transportation is done in such way that a single part or set of parts can be clamped on a single pallet which is later loaded into a machine. Alternatively parts can stand loose on pallets and be loaded into the machine part holding device by an auxiliary automatic manipulator, as shown in figures 5.4 and 5.5.

When parts in a system are low in number but are large and complex needing long processing times in multiple stage systems, then the part or pallet vehicle carriers themselves, i.e. the transport 'track' may work as an in process work storage or pallet buffer. An example is the Kearney and Trecker FMS at Allis Chalmers[73]. This solution can however be expensive due to the high number of vehicle carriers that might be required. Additionally the higher the number of vehicles the more difficult the control of the work flow will be.

The mobile circulating random access vertical store, figure 5.1-element 2, can also provide large storage capacity. However it appears that this is not recommended for large and heavy parts. Due to the high number of moving parts of the store the risk of failure is large and reliability is low when compared to static stores.

In addition to central stores there is a need for localized storage areas. This can be achieved through buffers at machine areas and other places

For the storage of work in process, w.i.p., there can be many solutions. The use of pallet changers or two position shuttles, static stands near by work stations and rotating multiple pallet buffers, figure 5.1 elements 0, 3 and 4, are typical for both prismatic and rotational work carried on pallets as well as for sets of tools carried on pallets or tool magazines.

If parts are small and clamping on pallets is not required then storage systems made of multiple pallets racks are very common[50]. Rotating part or pallet buffers are another possible solution, figure 5.1-element 4, which can also be used in this case.

Circular random access stores, figure 5.1-element 9 are not so common for part storage and handling. When the store is static, it is functionally similar to the static random access cell store, figure 5.1-element 1. An example of application of the circular store solution can be seen in the ROTA-125 FMS[112]. When the store itself rotates it can be seen as a simplified version of the mobile circular random access vertical store referred in figure 5.1-element 2.

5.2.2 Elements for Work Transport and Handling Systems

Most of the known work handling and transport solutions are direct or combined applications of the building blocks shown in figure 5.6

Bar feeding mechanisms are widely used for manufacture of small rotational workpieces. The integration in FMS of machines fed directly from bar feeding mechanisms is not common although some applications can be seen in practice[3].

Bowl feeders are essentially used to feed parts into automatic machining or assembly stations. They are mainly applied to the handling of small parts for mass production. The need for flexible assembly automation directed research into flexible bowl feeders which can handle a diversity of parts. Flexible bowl feeders were developed at Institut für Produktionstechnik und Automatisierung (IPA)-Stuttgart and by Bosh[9,95].

Gravity storage towers have applications similar to bowl feeders. They are however better suited to feed processing machines[105] and to handling larger parts.

Both storage towers and bowl feeders, when applied to FMS, have to be interfaced with a part handling unit, which may be an industrial robot or other handling mechanism, for closing the handling cycle[39].

Floor conveyors have been used in FMS for a long time. One of the first FMS built in the USA by Sundstrand at Ingersoll Rand Company, used a floor conveyor for transport of palletised work to, from and between workstations[24]. Floor conveyors are very common for both pallet and part transport. They can allow adequate flexibility for integration into an FMS when provided with proper part and pallet recognition sensors and auxiliary transfer mechanisms at critical path interception points. Critical path interception points can be all passages at workstations and all points where a branch from the conveyor exists. A good example of use of a conveyor system for part delivery at FMS workstations can be seen at the SCAMP FMS[92].

Overhead conveyors have the advantage of keeping floor space unoccupied[84,145] which allows the free movement of people on the floor and complementary transport, at the floor level, by vehicles let them be automated or not.

The work handling and transport devices falling under the classification of traditional overhead cranes provide high flexibility but are rarely suitable to be used in an automated manner for FMS. The reason is that they are not much adapted to automated work and usually require the assistance of one or more operators. They are basically a means of extending the man capacity and ability for work handling.

Stacker cranes, figure 5.6-element 5, on the contrary, are very suitable for FMS. They are normally associated with static vertical random access cell stores, figure 5.1-element 1. They can usually access randomly any cell of the store. This combination of handling and storage is frequently seen as a FMS central store and handling of parts and pallets.

Rotating pallet changers in addition to being work storage elements, as seen in previous section, can also be seen as building blocks of the material handling system. They are typical of many FMS systems for prismatic work and to a less extent for rotational work FMS's as well. They can exchange the part or pallet with that on the machining place and can also function as a local storage area.

Rotating pallet buffers can be thought of as pallet shuttle changers of larger capacity.

Floor programmable robots are industrial robots standing on the floor having different degrees of programmability, flexibility and capacity. They can be presented in many different designs and have different levels of versatility. The access space varies according to the type of robot design, but above all is dependent on the maximum allowed movement of the axes. Although floor robots can be mobile[132], they are usually fixed either on the floor or at a firm stand.

Overhead robots, on the contrary are usually highly mobile in line[122] or over an area[67]. There is a wide variety of application cases of overhead robots for materials handling, not only for the handling of parts but also for tool handling[41,67].

Computer controlled transport and handling vehicles are being increasingly used. More frequently they are floor guided through tow line, induction currents and radio frequencies. Such vehicles can be pulled by chains or the like, in which case they are normally referred to as carts, or be self powered and automatically guided. In this case they are usually referred to as Automated Guided Vehicles (AGV). Other guiding alternatives include the use of light sensors and colour contrast sensors. AGV using infrared light sources for guidance are frequently used[46,87] and laser guidance has also been reported[36].

5.3 TOOL FLOW SYSTEM ELEMENTS

5.3.1 General Aspects of Tool Flow Systems

Tool flow in manufacturing systems in general and in FMS in particular, requires careful planning.

If machines are very versatile they are able to perform a large range of operations during the manufacturing period conditioned however by those tools which a machine can access. If the access is restricted to a few tools, the machine might only be able to function as a special purpose machine and therefore, its versatility is not used during the manufacturing period.

To take advantage of FMS machine versatility, short term scheduling may be prepared off-line . In this case a machine loading plan can be prepared for the manufacturing period, shift or day, where part processing sequence and part and tool assignment to machines can be established in advance of production. On the assumption that no machine breakdown happens during the planned manufacturing period then manufacturing according to the plan can be completely carried out by providing the machines with only the required tools. If big disturbances do occur during the planned manufacturing period then rescheduling the work is likely to be necessary. Small variances may be coped with by adequate on-line redisposition control[115].

Tool variety reduction

In FMS there is a predominance of multi-purpose machines, i.e. machines which are capable of performing a large number of different operations, due to a need for simplifying the control of tools and parts flow.

So, there is interest in establishing efficient tool flow systems with a coordinated tool supply to the different work stations. This is particularly relevant when tool variety and quantity can become large which normally means that there are both economical and organizational advantages in reducing the number of tools in the system. This can be achieved on the one hand by adopting an off-line preparation of FMS loading plans based on the tools available, as referred to above, and on the other hand through a variety of standardization and rationalization measures directed at tool variety reduction[52,144,45], figure 5.7.

Tool availability

One major aspect in the selection of the tool system configuration is the need to improve machine readiness as it is affected by tooling. Consequently, there is interest in separating, as much as possible, the tool set-up function from the machine cycle. To achieve this, new tool system configurations can be applied as will be discussed below. The best configuration to choose is influenced by the degree of automation in connection with the autonomous period desired for unmanned manufacture and by other organizational aspects and economical reasons.

5.3.2 Tool Storage and Replacement Configurations

Tooling system configurations can be developed from pertinent combinations of basic tooling system elements, figures 5.8 and 5.9. They include local and central tool stores, tool magazines, tool exchangers and tool and magazine transport and handling elements, namely vehicles, conveyors and automatic manipulators (AM) such as industrial robots (IR) widely used in TFS of many FMS's. A classification of basic tooling storage and replacement configurations which use the elements classified under figures 5.8 and 5.9 is shown in figure 5.10.

When tools cannot be automatically accessed for tool change at the machine spindle, manual tool change has to be used, fig 5.10-configuration 1. Such a solution allows some degree of flexible automation but unmanned working is not possible.

By providing the machines with an automatic tool change system, performed from a local and/or central tool store or magazine, different degrees of unmanned work are possible as indicated in figure 5.10.

Alternatively automatic access to a central tool store can be provided. This solution permits a high degree of automation and, for large central stores, can allow long periods of unmanned work. Moreover the solution can provide a good level of utilization of tooling resources through a continuous flow of tools from and into the tool magazines of the machines. This configuration is likely to require constant computerized supervision and control of the tool requirements, tool function and tool life. A further advantage of this system is that it may allow a reduction in the required number of identical tools in the manufacturing system. However with centralized tool storage configurations processing interference among machines may result, when real time machine loading and operations scheduling or sequencing is used. This is due to the fact that all machines are sharing the same resources, in this case the same tool central store. Therefore, at some instants it may happen that different machines are "fighting" for the same tools or at least simultaneously requiring the service of the tool exchange mechanism for tool change. This can largely be avoided if off-line manufacturing loading plans are prepared in advance and tools are accordingly and adequately provided. This means that some degree of tool duplication may be required in the store. Another disadvantage of this configuration is an increased risk of complete system stoppage due to breakdown of the tooling system. To reduce this problem, machines can be designed and prepared to also work standing alone and tools manually changed while the tooling system recovers.

Advantage can be taken from using centralized tool storage in single stage FMS's, figure 5.11. In this case high part routing flexibility can be provided even under minimum tooling requirements. This is possible because in such systems any machine is theoretically able to process any part-operation. However, such routing flexibility is not available under multistage FMS's, i.e FMS's where part processing usually requires the use of most of the machines in the system, either for local or central tool storage because machines can perform only a given type of process. In these systems a central tool storage is particularly justified for unmanned work. But in this case tool duplication is likely to be required to back-up tools which wear out.

If local tool storage is used under single stage systems, unless some degree of tool replication is used, part routing flexibility is not available.

Additionally, with minimum tooling, the centralized approach does not allow for independence of working units which in terms of reliability and flexibility can be considered a bad solution.

Automatic tool replacement can be enhanced to allow tools to be replaced during processing. Frequently however, tool replacement is still done with the machine stopped.

When tool magazines are an integral part of the machine, tool replacement at the machine is normally done on an tool by tool basis, figure 5.10.

A tool replacement back up tool store can be provided which, as shown in the same figure, can be accessed either manually or automatically by means of an industrial robot or other automatic tool handling device or manipulator.

A few versions of this arrangement can be found in practice. They are designed to accommodate the tools needed for part processing and reduce waiting time of the machine. Typically the tools in the tool magazine are replaced with the tools in the back up store to cope with next part processing requirements[37,75]. The tool buffer may function as a means of increasing the local tool storage size.

By using the exchangeable magazines approach, in a manner which is similar to part replacement at machines, tool magazine replacement could possibly be performed during processing, which means that productive time of machines can increase. In addition, since the tool magazine or buffer represents an increased capacity of the local tool storage, longer periods of unmanned manufacture can be achieved.

This multi-magazine replacement approach can be associated with two basic arrangements as shown in figure 5.10:

1 - Local tool magazine store

2 - Central tool magazine store

In the first case the tool store is local with one or more magazines on a buffer which can be replaced with that being used.

In the second case the bulk of tool magazines or pallets with tools, destined for more than one machine, are located in a central tool magazine store. They are transferred to the machine areas through mechanized or automated transport equipment. A small tool buffer might be provided at the machine area.

Multi-magazine replacement can be highly functional because tool magazines can be associated with the processing requirements of the parts on a pallet or pallet group. However, the solution is likely to require considerable investment in tool magazines. To reduce this, tool magazines should be simple and standardized.

When the flow of tool magazines is "linked" to that of part carriers or pallets the control of the flow of tools and parts is simplified and synchronized . In this case the same parts pallet carrier may also simultaneously carry the tool magazine for processing them.

CHAPTER 6 - INITIAL ASSESSMENT OF TOOLING AND PALLET REQUIREMENTS

6.1 INTRODUCTION

The development of an FMS requires technical, economical and performance analysis of the alternatives for control, machining and material flow systems[32,127,110]. Interrelated with these three main areas are the important manufacturing aids of tools to be used in the machine spindles and part carriers i.e pallets and fixtures. It is necessary to determine both the types and quantities of such aids, figure 6.1

For rotational work pallets are usually simple and parts are rarely clamped on them. In this case the fixturing system is usually an integral part of the workstation although this may also be the case for some prismatic work, figure 5.5 .

For prismatic work, fixtures and pallet bases are frequently combined in what can be called a fixtured pallet onto which parts are firmly clamped forming a compact unit. This unit is then transported, handled and positioned at workstations for processing. A classification and schematic representation of palletisation alternatives most commonly seen is shown in figure 6.2.

Among the most important FMS aids are the tools to be exchanged at machine spindles. The central part of this research work is the solution of the tool grouping configuration problem in connection with the determination of the best number of tools to manufacture a given part mix with the aim of achieving good FMS performance.

In this work, the assumption is made that tools are grouped based on part-operation processing requirements and transported in groups which are loaded into tool buffers at machining areas. This view of tooling transport and replacement accounts for many tooling flow configurations found in practice which were classified in figure 5.10. In particular the cases of magazine replacement fall within this assumption as do configurations 2, 3 and 4 shown in that figure.

A solution to the tool grouping problem consists of finding groups from the available tools to be loaded into machines based on part processing requirements and routing alternatives subject to tool magazine sizes in such a way that good FMS system performance can be achieved.

A methodology for the dynamic solution of this problem is approached in the following chapters. Here however an analytical methodology for initially determining the number of manufacturing aids, in particular tools and pallets, is given.

6.2 NUMBER OF TOOLS TO RUN AN FMS

6.2.1 Number of tools for an Autonomous Manufacturing Period

While tool variety is primarily determined by the variety of part operations, the total number of tools required is dependent on the length of the period for which tooling autonomy is desired, figure 6.3. A tooling autonomy period is a length of time of manufacturing during which no tools are fed or removed from the FMS.

In this case the average number of tools required is given by:

$$\bar{N}' = m \cdot T / t_l \qquad (6.1')$$

where:

$\bar{N}'$ is the average number of tools for an autonomous tooling period

T is length of the manufacturing planned period

t_l is the average tool life

m is the number of machines in the FMS

As an example, considering a manufacturing period of a 3 eight hour shifts, i.e. a 24 hour day work, and 10 machines in the system. For an average tool life of 20 minutes the number of "tool lives" required is:

$\bar{N}' = 10*(24*60/20)$ $\bar{N}' = 720$ "tool lives"

Therefore for complete tool autonomy during the 24 hour planning period a total of 720 tools would be necessary.

Thus for an FMS with m machines on average each machine would use $\bar{N}'/m$ tools.

This assumes that machines are fully and constantly utilized in actual machining during the planned manufacturing period T and that all tools are used to their full lives. If expected average machine utilization in actual machining is U than the required number of tools could be expressed as

$$\bar{N}' = U(m \cdot T/t_l) \qquad (6.1)$$

$\bar{N}'$ should be interpreted as the number of "tool life tools" which are required for a manufacturing period of length T.

6.2.2 Number of Required Tools in the System

When tools can be fed into the FMS during the planned period, as old tools wear out and are removed, then a much reduced number of tools is likely to be required in the system at any time.

To determine this number let us consider first that t_t is the average tool throughput time, inside the system, until tool life ends. This time will be called average tool cycle time, figure 6.4. After this time a tool tip may be replaced and the tool reused. Alternatively, for non reusable tools, tool replacement is required. In either case the average number of tools in the system at any time is kept constant. It is in fact as if the tools were reused with new tool lives. A dummy usage rate per tool can therefore be established as a function of the manufacturing planned period T and average tool cycle time t_t, and is given by:

$$TR = T/t_t \qquad (6.2)$$

where

TR is the number of times tools are used or substituted after tool life ends during a manufacturing planned period.

t_t is the average tool cycle time.

And therefore the average number of required tools in the system at any time is scaled down by the TR factor, i.e.:

$$\bar{N} = (\bar{N}'/TR)$$

or

$$\bar{N} = \frac{m(T/t_l)}{T/t_t}$$

and therefore:

$$\bar{N} = m \cdot t_t/t_l \qquad (6.3)$$

It is interesting to note from equation (6.3) that the number of tools required in the FMS at any time is not dependent on the length of the manufacturing period but dependent on tool cycle time and naturally on tool life and number of machines.

Tool cycle time includes not only the time the tool is involved in processing but also the time the tool is delayed in the system due to waiting, transport, handling and set-up or preparation.

t_t can be expressed as:

$$t_t = t_l + t_s + t_c + t_w \qquad (6.4)$$

with:

t_l - Average tool life time

t_s - Average tool set-up time per tool cycle

t_c - Average tool transport and handling times per tool cycle

t_w - Average tool waiting time due to storage and buffering during manufacturing per tool cycle

Therefore $\bar{N}$ can be rewritten as:

$$\bar{N} = m\,(t_l + t_s + t_c + t_w) / t_l \qquad (6.5)$$

or

$$\bar{N} = m + m(t_s/t_l) + m(t_c/t_l) + m(t_w/t_l) \qquad (6.6)$$

or

$$\bar{N} = \bar{N}_m + \bar{N}_s + \bar{N}_c + \bar{N}_w \qquad (6.6')$$

where:

$\bar{N}_m$ are the tools used at machining, m

$\bar{N}_s$ are the tools used at preparation and set-up, $m(t_s/t_l)$

$\bar{N}_c$ are the tools being carried or handled, $m(t_c/t_l)$

$\bar{N}_w$ are the tools waiting in system, $m(t_w/t_l)$

From equation (6.6) we can see that reducing tool waiting and the time of some activities such as transport and tool set-up can mean a reduction in tools required in the system. Dependent upon the amount of time this could be a substantial reduction.

6.2.3 Tools Removed Before Tool Life Ends

Equation (6.5) can be adjusted to take account of tool replacement before tool life ends.

Thus if, due to technical, organizational or economical reasons resulting from system operation, tools are not used-up completely the number $\bar{N}$ of required tools in the system increases and is be given by:

$$\bar{N} = \frac{m(\beta \cdot t_l + t_s + t_c + t_w)}{\beta \cdot t_l} \qquad (6.7)$$

where

β is the average proportion of used tool life.

It is as if the average tool life had become equal to $t_{l\beta} = \beta \cdot t_l$.

6.2.4 Minimum Number of Required Tools in an FMS

The minimum average number $\bar{N}_{min}$ of tools is obtained when tools do not wait, that is, they are constantly used for part processing, being transported or set-up. So:

$$\bar{N}_{min} = m(t_l + t_s + t_c) / t_l \qquad (6.8)$$

and for partially used tools it will be given by:

$$\bar{N}_{min} = m(\beta \cdot t_l + t_s + t_c) / \beta \cdot t_l \qquad (6.8')$$

This assumes that tools flow continuously between machines and tool preparation area and therefore theoretically no tool stores are necessary. This situation is similar to the flow of parts in a pure part flow line without intermediate storage buffers between stations.

6.2.5 Tool Requirements Considering Tool Life Differences

The number of required tools in the system has been determined considering that all tools in the system have identical values for average tool life and average tool throughput time. For tool life variations to be taken into account, we can write:

$$\bar{N} = \frac{1}{n} \sum_{i=1}^{n} m \frac{t_{li} + t_s + t_c + t_w}{t_{li}} \qquad (6.9)$$

$\bar{N}$ is the average number of required tools in the system

t_{li} is the average tool life of tool type i n - Number of different tools to be used during the planning period.

6.2.6 The Effect of Tool Cycle Time Variance on the Minimum Number of Tools Required

We have seen that :

$$\bar{N}_{min} = m(t_l + t_s + t_c) / t_l \qquad (6.8)$$

If time variances are to be taken into account and if the Normal Distribution applies to the minimum number of tools in the system, then:

$$N_{min} = \bar{N}_{min} + 2\, SN_{min} \qquad (6.10)$$

for about a 97.5 % confidence level, where SN_{min} stands for the standard deviation of the N_{min} variable.

It can be shown[79] that

$$SN_{min} = \sqrt{\frac{m^2 S_h^2}{t_l^2} + S_l^2 \frac{m^2 t_h^2}{t_l^4}} \qquad (6.11)$$

Where S_h^2 and S_l^2 stand for the variances of t_h, with the normal variable $t_h = t_s + t_c$, and t_l respectively.

When the coefficient of variance of the variables is less than 15%, (i.e. S/μ) the standard deviation SN_{min} can be obtained from the variances of t_l and t_h respectively S_l^2 and S_h^2 by[18]:

$$SN_{min} = \sqrt{\frac{m^2 S_h^2}{t_1^2} + S_1^2 \frac{m^2 t_h^2}{t_1^4}} \qquad (6.11')$$

6.3 NUMBER OF PALLETS TO RUN AN FMS

The analytical methodology developed for determining the number of tools can easily be extended to calculate the required number of pallets or fixtured pallets to run an FMS.

In fact the analysis is similar. The basic difference derives from the fact that pallets are practically always reusable within the manufacturing period while tools may not be.

6.3.1 Number of Pallets for an Autonomous Manufacturing Period

During a manufacturing period with pallet autonomy no pallets are fed into or removed from the FMS.

The number of pallets necessary to manufacture a given part mix in an FMS may be dependent on the length T of the manufacturing planned period and can be given by:

$$\bar{P}' = m \cdot T / p_p \qquad (6.12')$$

where:

- $\bar{P}'$ is the average number of required pallets
- p_p is the average processing time per pallet set-up at a machine or workstation
- T is the length of the manufacturing planned period
- m is the number of available FMS workstations

If for example

p_p=25 Min

T =24 Hour (three eight hour shifts)

m=10 workstations

then:

$$\bar{P}' = 10*(24*60/25) = 576 \text{ pallets}$$

If pallets could not be reused during the manufacturing period, say because the period was unmanned and repalletisation could not be carried out, then 576 pallets would be the average number of pallets necessary assuming that machines could be fully and constantly utilized in actual processing during the manufacturing period.

If an average machine utilization U is taken into consideration then the average number of required of pallets will be:

$$\bar{P}' = U(m \cdot T/p_p) \qquad (6.12)$$

In general $\bar{P}'$ is the average number of pallet set-ups for processing carried-out during the manufacturing period. The required average number of pallets can be much smaller if pallet reusage can be achieved.

6.3.2 Number of Pallets Required to Run an FMS

In general the number of pallets required to run an FMS is determined by the pallet cycle time. This is the average total elapsed time from palletisation to repalletisation which includes palletisation time itself, processing, handling and positioning, transport and waiting times, figure 6.5. This cycle time determines therefore the pallet usage rate per manufacturing period which is given by

$$PR = T/t_p \qquad (6.13)$$

where

PR is the average number of times a pallet is used during the manufacturing period

t_p - Pallet cycle time

Thus, the number of pallets actually necessary to run an FMS is given by:

$$\bar{P} = \bar{P}' / PR$$

or

$$\bar{P} = \frac{m(T/p_p)}{T/t_p}$$

and therefore

$$\bar{P} = \frac{m \cdot t_p}{p_p} \qquad (6.14)$$

This shows that the number of pallets required can be independent of the length of the manufacturing planned period and determined by the number of available workstations, 'pallet'-operations processing time and pallet cycle time.

Clearly if palletisation is manually performed and unmanned working for long periods is required, then the pallets' cycle time can become identical to the length of the planned period T and therefore the number of pallets continues to be given by expression (6.14) with t_p equal to T.

Pallet cycle time, figure 6.5, can be expressed as:

$$t_p = p_p + p_s + p_c + p_w \qquad (6.15)$$

where:

p_p is the average time a pallet is involved in processing per set-up at a workstation

p_s is the average time a pallet is used for part(s) palletisation per pallet cycle

p_c is the average pallet transport and handling times per pallet cycle

p_w is the average pallet waiting time due to storage and buffering during manufacturing per pallet cycle

Therefore $\bar{P}$ can be rewritten as:

$$\bar{P} = \frac{m(p_p + p_s + p_c + p_w)}{p_p} \qquad (6.16)$$

or

$$\bar{P} = m + m\,(p_s / p_p) + m\,(p_c / p_p) + m\,(p_w / p_p)$$

or

$$\bar{P} = \bar{P}_m + \bar{P}_s + \bar{P}_c + \bar{P}_w \qquad (6.16')$$

where :

$\bar{P}_m$ is the number of pallets used at machining, m

$\bar{P}_s$ is the number of pallets used at preparation and set-up, $m(p_s / p_p)$

$\bar{P}_c$ is the number of pallets being carried or handled, $m\,(p_c / p_p)$

$\bar{P}_w$ is the number of pallets waiting or stored in the FMS system, $m(p_w/p_p)$

6.3.3 Taking Account of Pallet Variety

When pallet variety is smaller than the value given by expression (6.14) then pallet duplication is necessary. On the other hand if the number of pallet types is larger than the average number of required pallets it may be assumed that on average no pallet duplication is necessary. The adequacy or inadequacy of such an assumption is very much dependent on the diversity of manufacturing operations, at any instant, in the FMS and can be evaluated through the use of computer simulation of manufacturing.

Due to variations of processing times per pallet set-up and other system variables it is very likely that in practice a larger number of pallets than the value given by equation (6.14) is required. The value obtained constitutes however a good design guide line which can be a starting value for FMS simulation.

6.3.4 Minimum Number of Required Pallets

The minimum number of required pallets $\bar{P}_{min}$ is obtained when waiting and storage of pallets is avoided, that is, pallets are constantly recirculating through the system and constantly renewing their load. Therefore:

$$\overline{P}_{min} = \frac{m(p_p + p_s + p_c)}{p_p}$$

or

$$\overline{P}_{min} = m + \frac{m(p_s + p_c)}{p_p} \qquad (6.17)$$

or, making $p_h = p_s + p_c$:

$$\overline{P}_{min} = m + \frac{m \cdot p_h}{p_p} \qquad (6.17')$$

Usually there is a need for a number of pallets larger than P_{min} due to two basic reasons:

1 - Dynamic losses due to scheduling constraints can occur. This causes pallets to wait in the system before they can be loaded into machines

2 - The need for some buffer work to keep machines running for some periods without the necessity to perform part palletising operations.

6.3.5 The Effect of pallet Throughput Time Variance on the Minimum Number of Pallets Required

We have seen that :

$$\overline{P}_{min} = m + \frac{m \cdot p_h}{p_p} \qquad (6.17')$$

If time variances are to be taken into account and assuming that the Normal Distribution applies to the minimum number of pallets in the system, then:

$$P_{min} = \bar{P}_{min} + 2\,Sp_{min} \qquad (6.18)$$

for about a 97.5 % confidence level, where Sp_{min} stands for standard deviation of the P_{min} variable.

It can be shown[79] that

$$Sp_{min} \approx \sqrt{\frac{m^2 S_h^2}{p_p^2} + S_p^2 \frac{m^2 p_h^2}{p_p^4}} \qquad (6.19)$$

Where S_h^2 and S_p^2 stand for the variances of p_h and p_p respectively.

When the coefficient of variance of the variables is less than 15%, (i.e. S/μ) the standard deviation, Sp_{min} can be obtained from the variances of p_h and p_p respectively S_h^2 and S_p^2 by[18]:

$$Sp_{min} = \sqrt{\frac{m^2 S_h^2}{p_p^2} + S_p^2 \frac{m^2 p_h^2}{p_p^4}} \qquad (6.19')$$

6.4 USEFULNESS OF THE ANALYTICAL APPROACH

The previous analysis gives a first approximation of the required number of FMS pallets and tools. The method is analytical and does not take into account the dynamic operation of the system. As a consequence, it offers values which can only be considered as a first estimation of the number of such FMS manufacturing aids.

The number actually required of each FMS component is highly dependent on system flexibility and on dynamic variables and aspects of system operation which naturally, due to complexity, cannot be dealt with analytically. Such dynamic aspects include operative strategies and sequencing priority rules which are used in the operation of FMS.

Tool variety and also pallet and fixture variety are closely related to machine types used, but are above all dictated by part variety and processing operations variety.

The number of these production aids is dependent on the number of machines in the system and on the average cycle times, as defined in the previous sections. This number can also be influenced by parts and operations variety.

Further, as seen before, the autonomous planning period for part production can also be important in establishing the right amount of production aids required.

To estimate the number of FMS components required and in particular, the number of pallets and tools, a study was presented in sections 6.2 and 6.3 .

CHAPTER 7 - SOME ASPECTS OF FMS MANUFACTURING CONTROL RELATED TO TOOLING

7.1 MACHINE GROUPING AND MACHINE POOLING

7.1.1 Introduction

Machine Grouping and Machine Pooling are usually seen, according to Stecke[108], as related concepts to mean that any of the machines in a group, said to be pooled together, can perform the same operations.

"In particular when it becomes time to perform a particular operation it need only find one of the pooled machines free"[108]. This assumes that the tools for the entire set of operations assigned to a machine group are available when necessary, i.e. tooling resources to be exchanged at machine spindle are not á constraint.

7.1.2 Machine Pooling as Tooling Dependent

In this work a distinction is made between a machine group and a group of pooled machines to take tooling resources into consideration.

A machine group, MG, is defined as a group of machines similar enough to process the same set of operations provided they are loaded with appropriate tools. A MG can therefore be established before production starts and is essentially dependent on technical and technological similarity or equalness of the machines.

A pool of machines, PM, on the other hand, is a group of machines such that any machine within the group can actually be a real time part-routing alternative to a number of identical part operations to be processed simultaneously by each of the pooled machines. This simply means that if, at a given instant, tools for a set of identical operations are made available simultaneously at two or more machines, provided the machines are equally able to process the operations, then such machines are said to be pooled together.

This situation shows that machine pooling can be both dynamic, i.e. time dependent, and also static. In this latter case tool loading configuration does not change during the manufacturing planned period. This can be established before production starts. In this case the machines would be tooled for each production planned period as if they were part of a rigid flow line in the sense that tools were not replaced during the production period

Dynamic pooling results from a continuous flow of tools, during the manufacturing planned period, between machines and between these and a tool central store. In this case the machine pooling situation is not established before production starts; on the contrary it is a consequence of the control of the work through the system, i.e. of the manufacturing control process. This dynamic view of machine pooling is adopted in a simulation model of FMS's, chapter 9.

7.1.3 Degree of Machine Pooling

When tool distribution or allocation among machines changes then the machine pooling configuration may change as well.

Different degrees of machine pooling can be established within each MG depending on the amount of tool replication available for each MG at a given instant in time.

Partial pooling - Partial tool replication

We can think of partial pooling as meaning either that only a subset of all part operations assigned to a MG can be simultaneously processed on the machines of the group or that only some of the machines in the group are able to simultaneously perform the part operations assigned to the MG or that only some of the part operations assigned to a MG can be simultaneously performed by only some of the machines of the group

In the first case tools for only some of the parts are replicated in the machines of the group. In the second situation tools to process all of the part operations are simultaneously available but only at some of the machines of the MG. In the last case tool replication exists only at some of the machines and only to process some of the part operations assigned to the MG.

Total pooling - Full tool replication

Total or full pooling is achieved when in all machines there are available all of the required tools to process the entire set of operations assigned to the MG. In this case there is full tool replication in every machine of the group.

Zero pooling-No tool duplication

If any single operation of the set of operations assigned to a MG cannot, at a given instant, be performed by two or more machines then a zero pooling situation is met. And if, due to tooling unavailability within the FMS such a situation always occurs then the system works under the lowest tooling level, i.e., there are not duplicate tools available to allow the alternative processing of an operation in two or more machines.

7.1.4 Machine Grouping and Machine Pooling Generation

Machine Grouping is both an FMS manufacturing planning problem and also an FMS design problem. Also, although it is possible to establish FMS Machine Pooling at the planning level, it is essentially a manufacturing operational control problem, i.e. one which is dependent on the control of the workflow through the system.

Machine Grouping is a design problem in the sense that the machines' physical and technological configurations, which are decided at FMS design level, impose restrictions as to which machines can be grouped together. If a high degree of flexibility for part assignment to machines is aimed at then machines should be identical or as similar as possible.

At manufacturing planning level MG's may be established to satisfy the processing requirements of a given part mix for a given part operation mix to be produced in a given manufacturing period. Eventually the machine grouping configuration may change with part operation mix changes for different planned manufacturing periods. When the machines are identical the machine grouping configuration is unchangeable by nature.

Machine pooling can be seen as a manufacturing planning problem in two ways. Firstly because pooling is likely to be conditioned by the machine grouping. Secondly because the assignment of tools to machines may be made before production starts and kept unchanged during production for the planned period. On the other hand machine pooling is a manufacturing operational control problem in the sense that during real time control of an FMS, tools may be exchanged between machines and also with the secondary tool store or stores. Therefore the possibility of machines simultaneously processing identical operations changes during the manufacturing period and with system state.

7.2 MACHINE LOADING AND MANUFACTURING CONTROL OF FMS

7.2.1 The Influence of Cutting Tool Resources

The machine loading problem is traditionally defined as the assignment of a given workload among the machines of a manufacturing system. In particular it can be seen as the "assignment of a given workload among a number of machine groups" whose machines within a group can perform the same set of operations[108]. This is considered a production planning problem and is therefore solved before production starts. This view of the loading problem assumes that the machine grouping has been performed and part mix selected.

A solution to the problem of assigning the work among machine groups does not solve the real FMS machine loading problem, i.e., the assignment of the work load among individual machines.

It may be argued that since machines within a group can perform the same set of operations then on-line manufacturing control of the FMS will naturally solve that problem in a way which loads the next part operation into the machine which becomes free first[108]. However, this requires that every machine within the group is provided with identical tools or, at least, with the tools which can process the whole set of operations assigned to the MG. Thus a considerable degree of tool replication would be required. But in FMS's this is highly undesirable due to additional cost of tools, tool storage and handling, tool organizational problems including tool life control and tool information handling. Moreover provision for storage of large numbers of tools within the system would be necessary. Eventually, if tools to be accessed by machines were to be stored in the machine areas, large tool magazines would probably be required.

7.2.2 Tool Savings

In a group of machines, potential tool savings offered by machine similarity or equalness can be explored. In fact the strictly minimum number of tools, without tool duplication, i.e., no duplication of tools to process one or more part operations, may be acceptable to run an FMS. In some cases a good level of system performance may be achieved under such minimum tooling depending naturally on part mix processing requirements and on manufacturing control. This would be particularly so when the tools could continuously flow between the machines of the groups and tool stores, in real time, according to processing requirements of parts.

Tool flow can be achieved either on an individual tool basis or on a tool group basis. These groups can include tools to perform respectively one or more different part operations. It is clear that the configuration of such tool groups could affect system performance. Thus careful design of the tool grouping configuration is desirable which should obtain configurations which minimize the number of tools for a proposed level of FMS system performance.

In an FMS, the provision for continuous replacement or tools interchange among machines during manufacturing allows full advantage to be taken of machine similarity and versatility in order to reduce tooling requirements for the planned period to a minimum. In such a case, even under no tool duplication, part operation routing alternatives can still exist, i.e. a part may be processed in the machine which first becomes free provided no other identical part operation is already being performed in another machine using the required tools.

7.2.3 Manufacturing Planning horizon

If the overall assignment of work to MG's can be performed during production planning, the assignment of parts and tools to individual machines is most likely better carried out during manufacturing control. This results from the knowledge that the probability of success of planned manufacturing control actions is larger as the planned period becomes shorter.

There are difficulties in attempting to solve the FMS machine loading problem before production starts. These difficulties arise from the fact that the work load assignment to individual machines is not only dependent on the machine grouping but also on the state of machines and tools availability at the moment part processing can start. This cannot easily be envisaged before production for the manufacturing planned period starts, i.e. at production planning.

The FMS machine loading problem may be seen therefore as both a production planning and a manufacturing control one. Manufacturing control includes the control decisions to achieve the control of the flow of work and flow of tools through the system.

This view of the machine loading problem has been adopted in this work and implemented in a simulation model to support the study of the influence that the number of tools and their possible combinations in groups can have on FMS performance.

7.2.4 The Influence of Pallets and Fixture

At this stage it is clear that work assignment to machines based on machine grouping alone does not solve completely the machine loading problem in FMS's. Any such assignment must have also the availability of manufacturing aids taken into account. This is true not only for tools, i.e. tools to be exchanged at machine spindles, but also for pallets and fixtures. Thus even under duplicated tooling simultaneous processing of identical parts in different machines is not possible unless duplicated fixtured pallets, or the like, are also available to be loaded into such machines. Therefore the control of the flow of work through the system must take tools and other manufacturing aids into consideration before actual loading of parts to machines can be done.

Tools and fixtured pallets have been considered in the simulation model, chapter 9, as constraints on the loading of work onto machines.

CHAPTER 8 - STRATEGY FOR DESIGNING TOOLING CONFIGURATIONS FOR FMS

8.1 THE NEED FOR TOOL GROUPING

The processing of parts in manufacturing systems in general and in FMS systems in particular is primarily dependent on the machines available and the tools to carry out the operations. It is necessary to group the tools to process the required part operations. Such groups may be loaded into the magazines of the machines.

When deciding on loading parts onto machines it is not only necessary to find a machine to process the part but it is also necessary to find the required tools which may or may not yet be loaded into the machine.

Whenever machines are special purpose ones, then a particular set of tools is permanently associated with a machine. In this case selecting tool groups to process the parts is equivalent to chosing the right machine on which the part must be processed.

In FMS's, the machines are usually fairly similar and multipurpose and in many cases are identical. Thus tool groups are not specifically associated with particular machines; on the contrary, many tool groups, within magazine size constraints, may be interchanged between machines. This however does not mean that parts can be processed anywhere at any time. The right tools must be available at the machines at the right time, or be ready at a central store to be loaded.

Usually there are a limited number of tools to run an FMS. For the sake of simplicity and system efficiency grouping is normally done, subject to magazine size constraints, to include complete sets of tools for one or more part-operations.

It is necessary to determine which tools to combine together to form the groups to be loaded into the machine in order to achieve good levels of system performance. This may depend on many factors among which are the processing requirements, the configuration of part-pallet loads, the number and type of available tools, the processing capabilities of the machines and magazine sizes.

If tool combination in groups can affect FMS performance so can the total amount of tooling available. In particular there is a need to know how FMS performance behaves for different levels of tooling including minimum tooling and maximum tool replication in every machine. There are many interrelationships between system elements and modes of operation which make it difficult to have an intuitive knowledge of this behaviour.

8.2 TOOL GROUPING COMPLEXITY PROBLEM

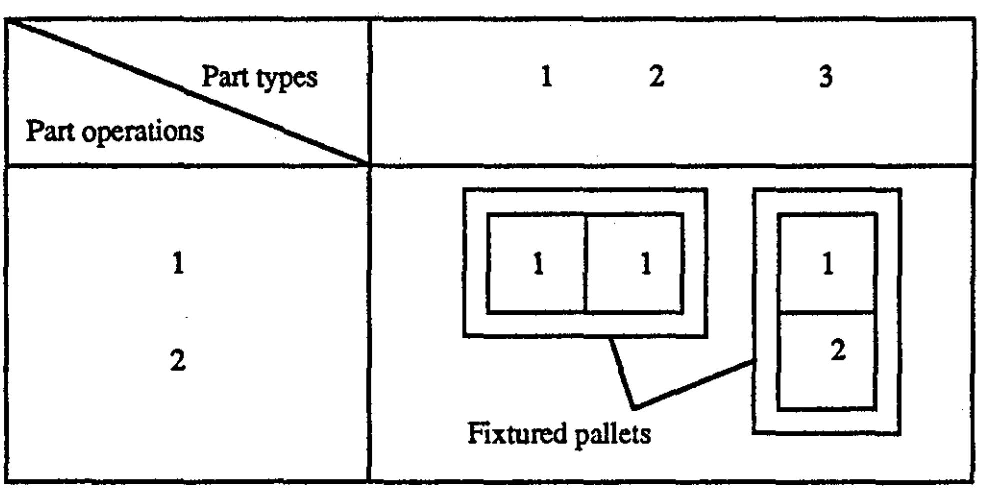
8.2.1 Introduction

In selecting the best final tool grouping configuration for minimum tooling to run FMS systems to achieve planned production objectives, many possible combinations of smaller tool groups, starting with a number of basic tool sets, can be considered.

A basic tool set is defined as a group of tools required to carry out a given part operation.

When some part operations are processed together in one pallet loading at a machine, a tool group made up from the necessary basic tool sets can be formed. In the example shown below a single tool group may be defined to process first operations of parts 1 and 2 if these are palletised and processed together. Similarly a group of tools can be defined from the basic tool sets to process operations 1 and 2 of part 3.

Example:



8.2.2 An Analytical Method for Determination of the Number of Tooling Configurations

A mathematical method for determining the number of possible tooling configurations has been derived by induction from the values shown in table 8.1 obtained from generated tooling configurations as shown in appendix 1.

In general the number of possible configurations G_n^t with n tool groups, containing t basic tool sets, section 8.3.1, is obtained by the following recurrence formula:

$$G_n^t = n\,G_n^{t-1} + G_{n-1}^{t-1} \qquad n \leq t \qquad (8.1)$$

With: $G_0^t = 0$ and $G_1^1 = 1$

Therefore the total number of possible tool grouping configurations of t basic tool sets is

$$G_t = \sum_{n=1}^{t} G_n^t \qquad (8.2)$$

It can be shown, table 8.2, that:

$$\sum_{n=1}^{t} G_n^t = \sum_{n=1}^{t} n\ G_{n-1}^{t-1} \qquad \text{with } G_0^t = 0 \qquad (8.3)$$

A graphical representation of G_t is given in figure 8.1.

n expresses the number of tool groups obtained from combining the basic tool sets required to process the work at the FMS.

Whenever n is less than the number of machining centres, m, in an FMS, then m-n of such machines are bound to stay idle. In such a situation a set of 'infeasible' tool groups would be obtained. Therefore the minimum number of tool groups to be configured must not be less than the number of available machining centres in the FMS. The set of all such possible tooling configurations with m or more tool groups each, say the feasible tooling configurations, which is a partition of G_t, equation (8.2), is given by:

$$G_{mt} = \sum_{n=m}^{t} G_n^t \tag{8.4}$$

Or , more generally:

$$G_{mt} = G_{m-1}^{t-1} + \sum_{n=m+1}^{t} n \ G_{n-1}^{t-1} \tag{8.5}$$

This formula is a generalization of formulas (8.2) and (8.3).

In particular for a FMS with 4 machining centres the combination of 9 basic tool sets, corresponding to an identical number of part-operations, gives 17866 configurations with at least 4 tool groups, table 8.2. If the number of basic tool sets increases by one the number of configurations is raised to 104747 and for another tool set the number of tool grouping configurations with at least 4 tool groups each are 637956.

It can be concluded therefore that for a real FMS system complete enumeration of all possible tooling configurations is usually unacceptable for finding the best tool group formation to manufacture a given part mix during a planned manufacturing period. The complexity of the tool grouping problem suggests the need for heuristic rules to simplify the task of obtaining good tooling configurations for efficient FMS operation.

8.2.3 Strategy for the Generation of Tooling Configurations

FMS performance under a particular tooling configuration can be evaluated through computer simulation and the results of the simulation be used as a stepping stone, to a new configuration which may lead to improved performance.

An iterative method can be envisaged which requires the joint utilization of both a simulation model and some form of heuristic decision method which, based on the results of the simulation, can help to generate tooling configurations. In particular a set of heuristic rules for tooling configurations design can be established.

A study of the performance of the heuristic rules for the tool combination process, developed in section 8.4, is reported in chapter 10.

8.3 BASIC TOOL SETS AND GROUPS

8.3.1 Basic Tool Sets - BTS

As a first step a number of basic tool sets can be defined from all available tools. The criteria used for defining the basic tool sets are based on the tools required by each different part operation of the part-mix to be processed within the FMS.

At an absolute minimum, a single tool may constitute a basic tool set. More frequently however a few tools will be required to carry out each different part operation in one set-up. Therefore at this tooling combination level a tooling configuration is defined by grouping individual tools into basic tool sets (BTS).

8.3.2 Basic Tool Groups - BTG

It is logical and advantageous from the point of view of FMS performance and simplification of manufacturing control to avoid unnecessary movement of parts or pallets during part processing. Normally it is good policy to process as many different part operations in a machine, in one single set-up, as possible[107,83]. This implies that pallets may carry a number of parts, identical or not, whose operations can be processed jointly in one pallet load at a machine. As a consequence the tools required to process the operations of the parts on a pallet in a single set-up at a machine, can be grouped forming what will be called a basic tool group.

The minimum number of basic tool groups necessary for processing a given part mix will be termed the Basic Tooling Configuration (BTC).

8.4 HEURISTIC RULES FOR TOOL GROUPING

8.4.1 Introduction

Tool combination in BTS's and BTG's are logical steps in the tool combination process which leads to the Basic Tooling Configuration. Heuristic tool combination can be applied to BTG's and possibly to BTS's for generating a variety of tooling configurations. During this process some tool duplication may be necessary when this can be proved advantageous.

In looking for a good strategy for tooling configuration design a variety of strategies were initially considered. These were based on the a priori belief that they could be effective in leading to tooling configurations under which FMS performance would improve. This is primarily measured as the combined objectives of high machine utilization and high assembly sets output per manufacturing period.

Examples of such strategies for tool grouping are to combine tool groups whose utilization is low and duplicate those which are highly utilized. A number of possible means of grouping were examined and some discarded owing to poor performance

One aspect which influences tool combination or tool grouping is the machine grouping configuration. A machine group is a partition of all available machines such that any of the machines in a particular group is able to perform the same subset of operations of the operation-mix, provided the necessary tools are loaded in each machine of the group. Two or more machines are said to be pooled together if they belong to the same machine group and are simultaneously provided with identical tools.

When machines are identical or similar enough to perform the same part-operations they are all grouped together.

An arrangement of all available tools in replaceable tool groups to completely process the operation-mix has been called the Tooling Configuration (TC).

The tools which are necessary to process the part-operations associated only with a specific machine group, can therefore be allocated only to the machines within that group. These tools constitute a partition of a set of tool groups formed to process the part-operations mix, i.e. of a tooling configuration. Such a partition is called a Subtooling Configuration (STC).

A tooling configuration therefore embraces its subtooling configurations.

One of the objectives of this work is to find ways of generating tooling configurations, i.e. the generation of all their subtooling configurations for high FMS performance.

8.4.2 General Tool Combination Heuristic Criteria

The tool combination heuristic rules have both:

-general, common criteria and also

-specific criteria.

Specific criteria are referred in the next sections, for each rule in turn.

The general and common heuristic criteria are:

1 - The tool group combination process ends when the minimum number, G_{min}, of tool groups allowed in a tooling configuration is reached. This minimum number is given by:

$$G_{min} = \sum_{k=1}^{g} n_{k_{min}} \qquad (8.6)$$

where:

g - is the number of FMS machine groups

$n_{k_{min}}$ - is the minimum number of acceptable tool groups in the STC

but $n_{k_{min}} = m_k$ with m_k being the number of machines in the machine group k

2 - Tool grouping starts with the basic tooling configuration, BTC, section 8.3.2, by combining iteratively and successively pairs of tool groups. As a result of each iteration a new tooling configuration is generated.

3 - Tool groups containing identical basic tool groups, BTG, must not be combined.

This is necessary to avoid forming tool groups with duplicated tools.

4 - The selected pair of tool groups to be combined must belong to the same subtooling configuration, STC.

5 - Tool groups whose utilization is larger than or near[a] to 1,0 are not combined with any other tool group.

Tool group utilization is defined as the proportion of the manufacturing time period during which the tool group is involved in machining parts.

8.4.3 Heuristic Rules Specific Tool Group Combination Criteria

8.4.3.1 RULE A - Least Utilized Tool Groups Rule

Main Criteria:

"The two least utilized tool groups are combined together".

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[a] In the experimental work a value as high as .92 is considered the maximum after which tool combination is not allowed.

Complementary Criteria

The main criteria is applied subject to:

1A - The combination of two tool groups which can both perform first operations on parts should be avoided when this results in a tooling configuration with a number, P_k, of tool groups for first operations on parts less than the number, m_k, of available machines in the machine group.

The motivation for this criteria is to avoid parts with unprocessed first operations be queueing in front of a machine, where the required tool group is loaded, leaving other machines idle.

Thus if

-TGUi , TGUj and TGUk are the utilizations of tool groups,

-TGi is the least utilized tool group,

-TGj is the next least utilized tool group. When TGi contains tools to process first operations then TGj is the next least utilized tool group which does not process first operations on parts and

-TGk is the next least utilized tool group which can perform first operations on parts when TGi can too.

Then if from combining TGi with the next least utilized tool group resulted to be $P_k < m_k$ then attempts should be made to find TGj such that:

$$TGUi+TGUj \leq 1$$

When this condition is not satisfied then the following condition should be checked:

$$(TGUi+TGUj) \leq ((TGUi+TGUk)+0.1)$$

If either the first or the second conditions are true then the combination of tool groups TGi and TGj must be performed. Otherwise the least utilized tool group TGi is combined with the next least utilized one TGk, irrespective of this being for first operations.

These conditions are aimed at combining two tool groups at least one of which, TGj, is not concerned with first operations. However if the sum of their utilizations is larger than 1 and also 0.1 larger than the sum of utilizations of the two least utilized tool groups for first operations, namely TGi and TGk, even for values of this sum larger than 1, than TGi and TGj, can be seen as having too a high sum of utilizations to be combined and therefore TGi should be combined with TGk instead.

In the second equation 0.1 was chosen because it appears to be a reasonable trade off value which avoids combining tool groups which have high sums of utilizations.

The flow diagram of figure 8.2 shows the tool group combination process under heuristic rule A. The process also takes into account the general heuristic criteria referred in section.8.4.2

8.4.3.2 RULE B - Lowest to Highest Parts Ratio,WPR, Rule

This rule is based on the concept of parts ratio, WPR, which is defined as:

$$\text{WPRi} = \frac{\text{Number of finished parts of type i}}{\text{Number of required parts of type i per Assembly Set}}$$

where:

WPRi - is the parts ratio of part type i

<u>Main Combination Criteria:</u>

"The lowest WPR tool group, i.e the tool group used to process parts with the lowest WPR, is combined with the highest WPR tool group"

Complementary and tie break criteria:

1B - The combination of two tool groups which can both perform first operations on parts should be avoided when this results in a tooling configuration with a number, P_k, of tool groups for first operations on parts less than the number, m_k, of available machines in the machine group.

Thus if

-TGUi , TGUj and TGUk are the utilizations of tool groups,

-TGi is the lowest WPR tool group,

-TGj is the highest WPR tool group. When TGi contains tools to process first operations then TGj is the highest WPR tool group which does not process first operations on parts and

-TGk is the highest WPR tool group which can perform first operations on parts when TGi can too.

Then if from combining TGi with the highest WPR tool group resulted to be $P_k < m_k$ then attempts should be made to find TGj such that

$$TGUi+TGUj \leq 1$$

When this condition is not satisfied then the following condition should be checked:

$$(TGUi+TGUj) \leq ((TGUi+TGUk)+0.1)$$

If either the first or the second conditions are true then combination of tool groups TGi and TGj must be performed. Otherwise the lowest WPR tool group TGi is combined with the highest WPR one, irrespective of this being for first operations.

2B - When a tool group can be used for processing both lowest and other parts ratio parts it should be selected first as:

a)-the lowest WPR tool group only if no other tool group for identically low WPR parts alone is available, or

b)-the highest WPR tool group when no other tool group exists which can process only parts with WPR larger than the parts with the lowest value of WPR.

Example:

Tool Groups (TG)	1	2	3	4	5	6	7	8
Part types	1	1	2,3,4	2,3,4	3,4	-	3,4	5 to 9

Part types	1	2	3	4	5	6	7	8	9
WPR	5	7	4	4	8	8	4	4	8

The analysis of the values of the two tables shows that:

-TG5 and TG7 are the lowest WPR tool groups and

-TG1 and TG2 are the highest WPR tool groups.

Thus, although tool group TG8 is used for processing both lowest and other WPR parts it is not chosen as the lowest WPR tool group because there are tool groups, i.e. TG5 and TG7, for identically low WPR parts alone. One of these will be chosen as the lowest WPR tool group. On the other hand, since there are tool groups i.e. TG1 and TG2 for processing only parts with WPR larger then the lowest WPR parts processed with TG8 , this tool group cannot be chosen as the highest WPR tool group in spite of some of the parts processed by it having the highest WPR. The choice will be therefore between TG1 and TG2 on the basis of the remaining rule criteria.

3B a)-For the same lowest parts ratio the tool group for processing parts required in the highest quantity in the assembly set, AS, is chosen first as the lowest WPR tool group.

b)-For the same highest WPR the tool group for processing parts required in the highest quantity in the AS is chosen last as the highest WPR tool group.

Example:

TG	1	2	3	4	5	6	7	8
Part type	1	1	2	2	3,4	3,4	3,4	5 to 9

Part type	1	2	3	4	5	6	7	8	9
WPR	4	4	6	6	6	6	6	6	6
Qty/AS	2	1	2	1	1	1	1	1	1

Based on a) TG1 or TG2 can be chosen first.

Based on b) TG5 or TG6 or TG7 is chosen last.

4B - When more than one tool group can be combined with another, based on WPR, then the tie should be broken by chosing the lowest utilized tool group first.

5B - When the sum of utilizations of two tool groups to be combined is larger than 1.05 then a new tool group should be selected able to process the next highest WPR parts such that the sum of its utilization with the first tool group chosen does not exceed 1.05. When this is not possible, the tool group is selected which produces the lowest value of combined utilizations. This should however take criteria 1B into account.

This is to avoid highly utilized tool groups being combined. If highly utilized tool groups were combined this would possibly prevent a part with a low WPR ratio from improving its value.

The 1.05 value is thought to be a good heuristic value. This value aims to minimize tool set-up, by enabling the combined tool groups to remain operational during one complete manufacturing period. Thus a value slightly in excess of 1 viz 1.05 was selected.

The flow diagram of figure 8.3 shows the tool group combination process under heuristic rule B. The process also takes into account the general heuristic criteria referred to in section 8.4.2.

8.4.3.3 RULE C - Highest to Highest WPR Rule

Main Combination Criteria

"The two highest WPR tool groups are combined together".

Complementary and tie Break Criteria

1C - The combination of two tool groups which can both perform first operations on parts should be avoided when this results in a tooling configuration with a number, P_k, of tool groups for first operations on parts less than the number, m_k, of available machines in the machine group.

Thus if

-TGUi , TGUj and TGUk are the utilizations of tool groups,

-TGi is the highest WPR tool group,

-TGj is the next highest WPR tool group. When TGi contains tools to process first operations then TGj is the next highest WPR tool group which does not process first operations on parts and

-TGk is the highest WPR tool group which can perform first operations on parts when TGi can too.

Then if from combining TGi with the next highest WPR tool group resulted to be $P_k < m_k$ then attempts should be made to find TGj such that

If TGUi+TGUj ≤ 1

When this condition is not satisfied then the following condition should be checked:

(TGUi+TGUj) ≤ ((TGUi+TGUk)+0.1)

If either the first or the second conditions are true then the combination of tool groups TGi and TGj must be performed. Otherwise the highest WPR tool group TGi is combined with the next highest WPR tool group, TGk, irrespective of this being for first operations.

2C - A tool group which can process both highest WPR parts, say parts Pa, and other parts, say parts Pb, should only be selected as the highest WPR tool group when no other tool group exists which can process only parts whose WPR is larger than the WPR of any part from Pb.

Example:

TG	1	2	3	4	5	6	7	8
Part types	1	1	2	2	3,4	3,4	3,4	5to9

Part type	1	2	3	4	5	6	7	8	9
case 1 WPR	4	7	7	6	8	8	5	5	8
case 2 WPR	4	4	5	5	8	8	5	5	8
case 3 WPR	4	4	7	6	8	8	5	5	8

The highest WPR tool group is:

case 1: TG3 or TG4

case 2: TG8

case 3: TG5 or TG6 or TG7

For case 1, although TG8 processes parts with the highest WPR, WPR=8, it also processes parts with WPR=5 which is less then the WPR of parts type 2 processed by TG3 or TG4. Since these tool groups process only parts type 2 one of these TG's must be chosen as the highest WPR tool group .

Case 2 only a tool group can be chosen as the highest WPR one, i.e. TG8

Case 3 is somewhat similar to case 1.

3C - For the same highest WPR the tool group to process parts required in the highest quantities in the assembly sets is considered to have the least priority to be chosen.

4C - When more than one tool group can be chosen to be combined with the first one selected then the tie should be broken by choosing the least utilized tool group first.

5C - When the sum of utilizations of two tool groups to be combined is larger than 1.05 then a new tool group should be selected able to process the next highest WPR parts and such that the sum of its utilization with the first tool group chosen does not exceed 1.05. When such a tool group is not obtainable, then the tool group whose sum of utilization with the first chosen one is minimum is chosen. This should however have criteria 1C into account.

The process also takes into account the general heuristic criteria referred in section 8.4.2

8.4.3.4 RULE D - Ungrouping-Regrouping Rule

A decombination eventually followed by a recombination of tool groups, towards finding better tooling configurations, may take place preferentially at the last stages of a tool group combination process performed by any of the three previous heuristic rules.

The three previous heuristic rules follow a sequential grouping process which ends when G_{min}, section 8.4.2, is achieved. Thus if G is the number of basic tool groups available, section 8.4.2, then:

$$n = G - G_{min}$$

iterations are necessary until the tooling configurations generation process ends.

With this new rule a total number of iterations larger than n may be required. This is because there is an additional number of combinations due to the decombination and recombination process.

Main Combination Criteria

A tool group may be selected for ungrouping when:

"The tool group has both the lowest WPR and high[b] utilization".

Complementary Criteria to Main Criteria

1D - When more than one tool group obeys the main criteria then that containing the basic tool group whose utilization under the basic tooling configuration is lowest is selected first.

2D - From all the basic tool groups belonging to the tool group to be decombined, that whose utilization under the basic tooling configuration is lowest is removed and:

a) recombined with the least utilized tool group from the remaining tool groups in the configuration or,

[b] 0.8 is the minimum value adopted in the experimental work

b) kept standing alone, forming itself a new tool group whenever its utilization, under the basic tooling configuration, added to that of the least utilized tool group in the configuration is larger than 1.05.

3D - Provided that the sum of tool group utilizations is less than 1.05 all basic tool groups, taken by decreasing order of their utilization, of the tool group submitted to ungrouping may be combined, one at a time, with the least utilized tool group of the configuration. Of the new tooling configurations which will be generated, the best performing one should then be selected.

8.4.3.5 RULE E - Tool Duplication Heuristic Rule

Main Criteria

Whenever a tool group is highly utilized[c] and the WPR of some or all the part types processed by it is the smallest, then a one at a time duplication of basic tool groups belonging to the tool group, and destined to process the lowest WPR parts should be adopted .

Complementary Criteria

1E - Only the basic tool sets for the parts with the lowest WPR may be duplicated forming a new tool group which can be combined with other groups formed using the previously mentioned heuristic tool combination rules.

2E - The first basic tool group to be considered for duplication is that which is most utilized in the basic tooling configuration.

[c] 0.8 is the minimum value adopted in the experimental work

CHAPTER 9 - MODEL DESCRIPTION

9.1 INITIAL MODELLING ASPECTS

The original modelling aim was to build a generalized but detailed data driven FMS simulation model which would encompass the possibility of studying the influence on FMS's performance of a variety of tool flow system and tool management aspects in conjunction with work flow systems. Tools pallets and fixtures were to be seen as resource constraints to part processing. The model should be able to study the performance of a variety of FMS configurations in conjunction with many operating control policies at different levels of FMS control.

This objective was aimed at reducing the need for developing new models whenever design and principally operation of new or existing FMS's were to be studied.

Part way through the research it was found that the restrictions of the simulation language used, ECSL[22], prevented the development of such a generalized model. The problem was only detected after a considerable amount of work had been done and much time spent in developing an initial version of the model which was then to be enhanced to deal with all the aspects detailed above. The required enhancements to the basic model were found to exceed the limitations on indentation and data storage which were found to be inherent in the language, section 9.3.2.

The problems were initially unforeseen due to the lack of information in published material on the limitations of ECSL and their implications on modelling complex and detailed systems requiring the handling of large amounts of data.

Despite promises by the ECSL supplier to provide the necessary language enhancements these were not supplied. It was then realized that it would be impossible to deal with the initial modelling objectives and that an alternative strategy should be adopted. This should maintain the main aim of combining modelling of tooling and work flow systems. A possibility was to use a suitable alternative language. Another was to simplify modelling without losing much of the generality and detail desired but using ECSL.

This would have the advantage of saving a large part of the work already done. The alternatives were discussed and the latter believed to be feasible and advantageous. This called for a new approach to FMS tooling modelling which essentially centred on removing the treatment of individual tools. Instead the tooling system was modelled only on a tool set and tool group basis, section 8.3. This reduced the complexity of activity tests[22] and also, enormously, the amount of computer storage required. Problems still arose later but model refinement allowed a working model to be constructed.

9.2 MODEL APPLICATION AREAS AND OBJECTIVES

The computer simulation model has been set-up to explore the relationships between FMS configurations, parts loading and tooling requirements. Initially it was based on the NGL-Crewkerne[139] system but was developed to provide the essential elements in most FMS.

Particular emphasis is given to modelling tooling and fixturing aspects of FMS with the main aim of using the model as an aid to find the minimum tooling and pallet requirements for effective FMS operation.

The model can easily allow alternative systems to be investigated. Alternative systems can be configured by data input changes of fundamental parameters. It provides system designers and managers with a tool for assessing design as well as operating aspects of FMS.

Considerable detail involving complex relationships between system elements has been built into the model. The intention of this detail is to reproduce as accurately as possible the real operating tasks to be carried out within the system.

There are important interactions between FMS variables. These can include the number of buffers and pallets, number of tools and degree of tool replication, processing priorities and loading strategies such as degree of allowable machine pooling. The model is set-up to allow the study of many of such interactions.

By selective change of the levels of the input variables and study of the resulting model output, particular aspects of FMS system behaviour can be investigated, the suitability of system configurations for certain part mixes can be tested and different operating strategies can be evaluated.

9.3 SIMULATION LANGUAGE-CHARACTERISTICS AND LIMITATIONS

9.3.1 General Aspects

ECSL (Electronic Control and Simulation Language) is the discrete computer simulation language used in this work.

The adoption of ECSL for developing the FMS simulation model was dictated firstly by availability. This was in fact in practical terms the only available discrete computer simulation language at Loughborough University at the time the research work started. There were some simulation subroutines and the possibility of accessing other simulation languages in other outside research centres through a national computer communication network but this was thought logistically not preferable when compared with the installed language ECSL.

The language was also chosen because of its facilities[22] for recording and output of results, data analysis, aids to program development and to simulation experiments, error discovery and testing, display facilities and above all due to its English like statements making for ease of understanding. This makes it user friendly and can be seen also as a further advantage during model development. Moreover the resulting model can be understood easily or at least an understanding of the model workings can be obtained, after a brief study or explanation, even by people who may have only a limited knowledge of the digital simulation technique as might be the case of some manufacturing managers.

ECSL is a Fortran based simulation language, with an activity structure[22], self contained and closed. It is closed in the sense that it requires the user to develop the models using only ECSL statements, i.e., no FORTRAN or other language code or subroutines can be added into the model. This can be seen as a disadvantage of the language. It is self contained due to the available range of facilities mentioned above which are necessary for complete model development, analysis and testing.

This last aspect can be achieved through a critical examination of the results but more particularly through a trace showing the changes, during successive simulated events, of all or some selected variables, which can be obtained automatically. This trace feature is a model development aid offered by ECSL which is indispensable through the development phases and also at initial stages of modelling.

9.3.2 Main Limiting Aspects

Display facilities

Although present microcomputer versions of the language have display facilities successfully implemented, the version used on mini or mainframe computers and installed on a Prime 700 at the Loughborough University Computer Centre, LUCC has never been enhanced to allow successful computer runs with displays of the simulation process.

Program size and data storage

One of the language's main limiting aspects is the size of computer models that can be developed and, as importantly, the amount of data which the simulation can deal with.It has been found that models with more than 2500 statements are likely to be difficult, if not impossible, to run.

In the 32k ECSL version, which is its maximum possible size as implemented at LUCC, about only 16K words of information can be stored and handled. This restriction creates some difficulties in configuring as a large variety of FMS's and part spectrum configurations as it might be desired in the FMS model development. Moreover it is very unlikely that entity classes larger than 200 can be modelled.

Indentation steps

Another restriction is what in the language is known as the number of indentation steps. These are limited to a maximum of five.

Usually the indentation steps are necessary at the beginning of an activity during the testing of the condition for an activity to succeed. This may involve testing a large number of decisions and a large variety of entities, which tend to increase further as the modelling detail of real systems increases. Such complex test decision processes may require more than the available five steps of indentation. When this happens and cannot be overcome by intelligent and simplified programming then ECSL cannot be used for such simulation work.

9.4 SYSTEM OVERVIEW

FMS systems are configured through input parameters and other input data to the model. Typical systems that can be studied with the model are shown in figure 9.4.1[33,146]

9.4.1 System Physical Entities

The main physical entities for system configuration are:

-Workpieces

-Pallets and fixtures

-Tool sets

-Tool groups

-Machines

-Transport devices

-System operators

Workpiece Spectrum

It is assumed that physical and geometrical characteristics of the parts or their technical suitability are appropriate for the system. These characteristics are considered to have been analysed at a previous stage of system design and at process planning. The model can however be useful in aiding the selection of appropriate part mixes .

The number of individual parts simultaneously in process at any time is limited to 200. This is not a model constraint but simply imposed by data manipulation limitations of the language used. This figure however covers many real part production situations in FMS[48].

Specification of workpieces requires the following information:

-workpiece type

-number of part operations per each workpiece

-tools to process each part operation

-machines able to process each part operation

-processing time per part operation on each of the machines

-pallet type required

-location of workpiece on the pallet if any in particular

A part operation is understood as a processing operation which requires a set of tools and an associated NC part program.

On the basis of workpiece data and machine data input both FMS for rotational and prismatic work can be evaluated through the model. The main aspect which distinguishes the treatment of the two types of part spectrum is the nature of pallet configuration. Rotational parts call for fairly identical and simple pallet bases while prismatic ones usually require a diversity of complex fixtured pallet types which frequently are unique for each different part operation or set of part operations.

Pallets and Fixtures

The model does not distinguish between pallets and fixtures. When fixtures have to be used to clamp or hold parts in place on pallets then fixtured pallets are considered. In this case a detailed description of the functional characteristics of the fixtured pallet is required. This description must include the type and number of part holding positions on the fixtured pallet as well as a clear specification of which part operations are carried out at which holding positions.

Pallets can be routed to any machine as long as this has been specified by data input.

Pallets can be single, multiple or combined purpose, chapter 6, figure 6.2.

Reclamping on the same pallet is a feature of some FMS's, e.g at the Normalair Garret FMS[139] (NGL-FMS), and this aspect has also been modelled.

A schematic representation of some typical pallets and palletising cycles is given in figure 9.4.2.

Tool sets

Tool sets are referred to as sets of cutting tools, or other processing tools such as automatic measuring probes or touching probes, which are required to perform single part operations. Fixtures and related manufacturing aids are not included in the so called tool sets.

The modelling approach used for the tooling system of an FMS is based on tool sets. A tool set is used to carry out a part operation consisting of a number of elemental operations each one requiring the use of a single tool or probe which can be exchanged at the machine spindle.

There is the possibility of defining a one to one or a one to many relationship between tool sets and part operations. This simply means that the same tool set may process different operations. If more than one tool set of the same type are loaded into more than one machine then simultaneous alternative part routing is available.

Tool groups

Tool sets may be combined together to form tool groups which constitute magazine loads. However the size of tool groups must not be larger than the magazine size.

Such groupings may be capable of processing a restricted number of different pallet loads and would be loaded into the magazine prior to the delivery of the first pallet load.

Alternatively tool groups, i.e. basic tool groups, may be associated with the processing of specific pallet loads. In this case, when pallets move to machines the appropriate tools move with them. This loading strategy has been used by some FMS's, from which a British Aerospace FMS[35] and the NGL-FMS[139] are examples.

Machines

FMS's usually integrate a number of fairly similar and versatile machining centres, MC. These have been referred to as multipurpose machines, section 2.1.5. The model is configured to accept the definition of not only such machines but also other more limited purpose machines.

Machine configuration is defined through machine data. This includes:

-type of machine

-tool magazine size

-number of pallet buffers and

-types of tools which can be used by each machine.

These characteristics allow the definition of single, limited and multiple purpose machines, section 2.1.5. Therefore multiple stage, single stage or combined stage FMS[83] can be configured by the model. Moreover FMS's for both rotational and prismatic work can be configured.

Typical machining stations which can be configured result from the combination of a range of part-pallet loading arrangements and local tooling approaches are shown in figure 9.4.3

Auxiliary equipment such as automatic washing or inspection stations can also be defined.

Transport system

Simple transport systems where delays due to congestion do not occur can be configured with the model.

Transport carriers may have one or two carrying positions. Examples of transport or handling devices that can be modelled are:

- -Automated guided vehicles
- -Industrial robots:
    - -overhead or
    - -standing on floor
- -Rail carts
- -Gantry type devices

The model is less suitable for systems with complex material flow networks. FMS's with such transport systems can be configured within the model as long as the transport system itself is not the main object of analysis and the sequencing constraints within it can be relaxed. In this case the results of the simulation are likely to be approximate and their use can only be adequate for a first step analysis of design aspects not highly dependent on transport system. Such aspects might include the determination of an adequate set of machines and tools suitable for the manufacturing of a given part-demand spectrum including estimates of the necessary number of buffer places at the working stations.

Operators

In FMS's operators are mostly used for palletisation work and tool preparation. They are also usually allocated to tool transport eventually followed by tool replacement.

The model allows operators to be allocated to palletisation, tool transport and tool replacement whenever necessary. Any of the operators is supposed to be capable of performing any of these functions.

9.4.2 Operating Characteristics

Part production modes

The model considers workpieces to be produced either individually, in sets of identical parts or batches, or in sets of a mix of part types, i.e. AS, section 4.1.2.

A pallet can be designated to be able to accommodate all or some parts of a complete assembly set to allow them to be processed together as with the NGL-FMS[139].

Parts are treated individually and each part has its own identity. This happens both in individual part production and AS production.

A more detailed discussion of aspects of set assembly production is given in chapter 4.

Part routing flexibility

Two basic forms of part routing can be considered:

1 - Single part route

2 - Alternative part route

In alternative part routing the same part can be processed following different routes. This implies that at some stage the option for two or more machines to perform a particular part operation is available .

Workstation breakdowns

This feature is not included in the model. One of the reasons for the exclusion of this aspect is that the model is designed to analyse FMS operation for short operating periods of a few working shifts only during which it is assumed no workstation breaks down.

Machine loading constraints

Machining with preemption is not allowed, i.e. once machining starts on a part it has to be completed before a new part starts processing on the same machine.

Parts can be assigned simultaneously to more than one machine before they are actually loaded into a machine. In general they are assigned to all machines in a pooled machine group, section 9.5.4. However when a pallet is loaded into a machine or machine buffer for part operation processing, any other assignment of the same part operation to other machines is dropped. This is because pallets with parts loaded into machine buffers only leave the machine after processing has been carried out. This assumption is realistic since FMS machining stations frequently have a single pallet buffer place or none. A large number of pallet buffer spaces is typical of unmanned machining stations and, even in this case, once pallet loading is performed it is unlikely that unloading takes place before processing finishes.

Shift based working

A feature of the simulation model is the shift based working possibility. With this the simulation period can be divided in shifts. At a shift change there may be a need to update shift related recording and controlling variables.

9.5 MODELLING FEATURES

9.5.1 Dispatching the work into the FMS

The arrival of work into the system is dependent on the following variables:

Main Variables:

-The job orders plan for the planned production period

-System workload level

Optional variables:

-Job priority

-Batch or AS type ratio requirements in the production mix

The job order plan is an input to the model. This plan is assumed to have been prepared by the Production Planning Department, and includes detailed information about the orders to be processed during a short time period of one or a few shifts or days. Batches, parts or assembly sets can then be released.

Information about the jobs to release includes the number of batches or AS's, their sizes and types and eventually the value of a job releasing priority parameter. When this parameter is not used then the First Come First Served, FCFS, scheduling rule is used, i.e. the first job in the job order plan is released first into the system.

The job releasing priority parameter has a value which is either external and defined by management or dependent on batch or AS intrinsic data such as batch size and total batch processing time and is therefore static, i.e. not dependent on system state conditions.

Part loading and part sequencing after job release can have both static and also dynamic priorities, i.e. priorities dependent upon system state variables.

A simple job releasing mechanism is used based on the releasing priority parameter and on the system workload level. When the load falls below a given value a new job is released into the system.

The model allows the definition of a number of identical assembly sets or identical batches to be manufactured with the same priority in a given production planning period. This feature is used in the experimental work to study the influence of the number of assembly sets to be released together in connection with different levels of tools and pallets for different processing priority rules.

The other available option mentioned earlier is to control the release of jobs based on batch or AS ratio requirements of the loaded work mix. This ratio endeavours to ensure that, on average, a given mix of batches or assembly sets is kept in the system. This ratio is in fact the only dynamic control parameter for job release.

9.5.2 Palletisation Features Modelled

In general pallets can be configured for one or any number of identical or different parts to be processed in one part-pallet set-up and completed in one or more machine set-ups .

Parts palletisation is done on a part priority basis which the user can specify, section 9.7.2. Frequently the priority is dynamic defined by a parameter up-dated at successive system state changes.

In the model pallets and fixtures move together and therefore a single entity has been defined to accommodate the two. Moreover, pallets can also be seen as simple bases on which parts can stand loose or seen as complex sets incorporating both pallet and clamping fixtures.

Palletising stations are associated with the number of available operators. As long as palletisation is required and an operator is available a palletising station is considered to be available.

There are three basic tasks an operator or palletising entity can perform, as shown in figure 9.5.1:

Task 1 - Depalletisation of parts and

Task 2 - Depalletisation followed by repalletisation on the same pallet

Task 3 - Palletisation of selected parts,

In practice any combination of the three tasks may be performed together by the same palletising operator, palletising mechanism or device. Therefore the most complex task that can be performed includes part or parts unclamping followed by reclamping in the same fixtured pallet finishing with the clamping of new parts in positions left empty by the unclamped ones. The model is designed to take account of any possible palletisation combination within this framework. It is therefore possible keep track of individual parts, their state of processing and their position on each single pallet.

A feature which is not included is the simultaneous use of more than one operator or palletising entity for palletisation of parts *on the same pallet.* Nevertheless, if additional operators are assumed to be always available the model can still be used. In this case however performance of palletising operators cannot be completely evaluated.

Palletising cycles are implicitly defined within the model by specifying the values of the configuration parameters related to pallets and part palletising requirements as described in detail in the model input data, section 9.7.2.

9.5.3 Work Assignment to Machines

Parts are assumed to be palletised before they are routed to machines.

The assignment of parts to machines is dependent on the availability of adequate tools to load or already loaded into machine tool magazines.

The acceptability of tools by the machines is dependent on machines' processing capabilities and on the sizes of tool magazines. Moreover, the decision to load tools at the magazine of a machine is linked with the priority of part processing. This priority can be dependent on part characteristics or on assembly set or product related variables to which the part belongs to. Examples of priority regulating variables of a part, dependent on product or assembly set, are the remaining processing time and remaining parts to completely finish the set. Most of these variables defining the priority of part assignment or part loading are dynamic priority variables, i.e they vary with system state.

In assembly set production mode, although parts have an individual treatment within the system, they are normally associated with the assembly set they belong to from the dispatching moment until the set is completely processed. When all of the AS parts are finished the set of parts is considered to be finished.

9.5.4 Machine Pooling-Part Loading

Machine pooling is achieved by loading identical tools into more than one machine. These machines must, of course, be able to carry out identical part operations and therefore accept identical tools. For these reasons it is clear that such machines must be identical or fairly similar.

Pooling is performed when the workload of one or more machines is beyond acceptable limits. Such limits can be defined by the user. In the case of machine overloading, attempts are made to find another machine with processing capabilities identical to an overloaded machine. Tools will be loaded to this machine to process all or some of the parts assigned, but not yet loaded, to the overloaded machine. Thus total or partial machine pooling is achieved in a way which allows parts to be processed in either of two or more machines.

A machine can be seen as overloaded if the workload associated with the parts at the machine buffer and parts still in the central store but already assigned to the machine although not yet loaded, is larger then the acceptable machine workload limit defined by the user.

The pooling capabilities of an FMS is specified to the model by defining the machine characteristics and capabilities through input data. This is done by specifying the type of each machine in the system and also which types of machines can be used with each type of basic tool group.

9.5.5 Tool Replacement and Transport

The model presents a range of alternatives for tool replacement and transport that are representative of past and present FMS's.

Tools can be replaced by:

1-Replacing magazines or pallets of tools and

2-Tool by tool replacement at the machine magazine.

Tool transportation can be by:

1-Dedicated tool transport systems:

2-Operators who also do palletisation work. They can move tool groups to the machines aided by trolleys or any other kind of transport vehicle:

3-The transport equipment used for part-pallet transport.

These last two transport solutions are modelled in considerable detail, but detailed modelling of dedicated tool handling systems is not included in the model. However the time for tool transport and for tool replacement taken by this kind of system are input variables to the simulation model. This is a simplified way of modelling dedicated tool transport which is assumed to be always available when required.

Combinations of the tool transport and tool replacement alternatives described above can be simulated by the model and studied at systems design level.

In addition the entity carrying out the transporting can either:

-be held at the machine while tool replacement takes place, or

-simply leave the machine as soon as the tool group for replacement has been deposited in an adequate place at the machine area. Immediate replacement into the machine magazine by an automatic manipulator or direct changing into machine spindle can then follow.

Tool replacement at machines is assumed to be done with machine stopped.

9.5.6 Part-pallet transport

The movement of pallets between stations and the pallet central store is essentially dependent on part processing requirements of the parts on pallets and also on the number of required set-ups/reset-ups at the palletisation area.

Parts flow through the system by means of the material handling system. The movement time between stations is specified through a transport time matrix of the type shown in figure 9.5.2 .

Stations are considered to be not only the processing machines but also the area where the palletising operations are carried out and also any stop and start points on the transport path accessed by the transport carriers.

Part transport is achieved by pallet carriers or handling devices. Examples of types of handling devices which can be used have been referred to previously in section 9.4.1.

In the model palletised parts are transported to machines and handed over to machine tables or machine buffer places. Once processing has been carried out the pallets are transferred back to the handling devices and transported either to the next machine for further processing if required or to the palletisation area for part depalletisation which may be followed by repalletisation.

9.5.7 Material storage

The size of the pallet central store and its contents, i.e. number of pallets of each type, can be specified by data. However the tools central store is considered to be able to accommodate the tools required for running the system. This can be seen as a pool of tools. Pools for parts waiting palletisation and for additional pallets, i.e. back up stores, are also considered in the model. These are assumed to be able to accommodate all such waiting parts and pallets. Empty pallets can be exchanged between the back-up pallet store and the pallet central store.

The number of pallets to run a particular system is dependent upon a variety of parameters such as part processing requirements, pallet design, batch sizes and tool system configuration. A study of the problem of determining the optimum number of pallets of each type is presented in section 10.12.

9.5.8 Part Spectrum and Related Aspects

Parts are specified to the model through their operating characteristics. These include part type to which is associated a number of different global operations, each requiring a given set of tools and a given processing time. A batch size must be specified, also, and an assembly set size must be given when production is carried out on an AS basis. In this case the types and number of parts which make up an AS must be specified also.

9.5.9 Groups of tools

Grouping small sets of tools into larger sets to load at machines is a requirement to reduce waiting time due to both tool replacement and tool transport. With such a strategy, much of the travelling time of tools to stations and repeated tool and part load-unload can be avoided. This strategy has been modelled.

The way in which tool sets are combined is likely to affect considerably FMS performance. A study of this problem is presented in chapter 10 and indications to best tool grouping are put forward.

9.6 PROGRAM DESCRIPTION

9.6.1 Program Structure

A simplified and general view of the ECSL simulation program and structure is shown in figure 9.6.1. Figures 9.6.2 to 9.6.16 are the flow diagrams of the main modelling aspects considered. The model cycle diagram is shown in figure 9.6.17.

The overall model structure, figure 9.6.1 is mainly imposed by the simulation language used.

Seven sections can be identified.

First there is a variables Definition section where every variable, integer or real, histograms or entities, attributes and queues of entities and a number of simulation functions are defined. Single integer variables may also be defined in the body of the simulation program itself.

After variables are defined a Data block must be entered. This assigns initial values to all system variables which may still be overridden by the values assigned to the variables in the next section of the simulation program, namely the Initialisation section. In the coded model the Data block or Data section appears at the end of the program just after the Finalisation section.

The Initialisation section is used to define the starting values of some variables and in particular those related with scheduled initial time events. This is a way of defining the initial state of the system to be simulated. The system state at the start of production is such that all machines are available and empty and tools and parts are in their stores ready to be allocated to the system working stations, i.e. machining and palletisation stations.

Moreover data may also be initialized through READ statements. In this case the values of the variables to be read are given in a separate input data file and appears on that file after the EXECUTE control card of the simulation language[22] at program execution. An example of such a file is shown in appendix 2, figure A2.1.

This feature is particularly useful during experimental work because the factors or variables to be changed can be initialized through such READ statements and input without having to change the simulation program including its data section or any other section. Thus only this data input file needs to be changed to carry-out a number of computer simulation experiments.

After Initialisation there is a statement which defines the value of the length of the simulation duration. When the simulation clock has been advanced to this value the so called Finalisation section is performed.

The Finalisation section is mainly a section which formats and outputs the simulation results based on the performance recording variables. Some calculation is also normally required in this section to transform the recorded variables into a more useful form for information purposes.

Values of any system variable can be printed out. Therefore to complement the results, other relevant variables, such as those defining the FMS configuration and manufacturing control strategy, are also printed out in the Finalisation block.

The clock advance time routine, provided by the ECSL simulation language, performs the so called A-phase of the simulation up-dating the clock time to the next time event. After this a new simulation cycle starts and when the last activity is tested and simulated the simulation cycle ends.

However, before activities start recording can be performed. If the switch ADD, provided by ECSL, is put on then every recording statement involving it is obeyed.

Recording may also be performed at the Activities section without having to use the ADD facility. This is frequently done in the developed model .

At shift changes there may be a need to update shift related recording and controlling variables, figure 9.6.3. This is modelled just before the activities section.

9.6.2 Activities Section

This part of the simulation model can be seen as the body of the simulation process. In the Activities section a number of activities are defined which simulate the internal workings of the FMS system configured by input data. The activities are classified into seven functional groups.

The first group is concerned with the arrival of entities into the system and contains a single activity called ARRIVE, figure 9.6.4. According to a releasing plan and releasing priorities, section 9.4.1, the activity ARRIVE controls the flow of the work into the system by releasing into the system the parts to be processed as well as the assembly sets or batches to which they belong.

The second group also involves a single activity called UPDATEFACTORS, figure 9.6.5. It uses information generated during the simulation up to the present clock time and compiles the present values of system state dependent variables, which are used for manufacturing control purposes, namely those related to the priority of part loading, part processing and part palletising.

The third group of activities achieves both part and tool assignment to machines. The group is a large and complex one, consisting of four activities, i.e. SAVEMAG, CHANGTOOLS, UNPOOLMCS and POOLMCS, and could have been considerably simplified and reduced if more than 5 steps of indentation, section 9.3.2, were provided by the ECSL language.

SAVEMAG, figure 9.6.6, performs the assignment of parts to machines which have the tools to process them. The parts will then be processed by one of these machines provided that they are actually loaded into the machine or machine buffer before higher priority parts, which must be processed first in the same machines, become available and require tools in the magazines to be replaced.

CHANGTOOLS, figure 9.6.7, assigns a new set of tools to a machine on the basis of part priority for processing.

UNPOOLMCS, figure 9.6.8, ensures that a machine pooled with another, i.e, provided with tools to process one or more part operations which can also be processed by that other machine, is unpooled in order to be able to process a new palletised part operation. The tools required to process the new part are immediately assigned to the machine to be unpooled .

POOLMCS, fig.9.6.9, chooses an unpooled machine to be pooled together with a second machine for the processing of one or more part operations. The first machine is chosen on the basis of the most loaded machine and the second on the basis of the least loaded machine. The need for pooling occurs when either a machine is overloaded, section 9.5.4 , or there is an empty one, i.e. with no pallets loaded waiting processing, able to process the same kind of part operations already assigned to a machine. In either case pooling is dependent upon the availability of both the necessary tools to process the parts and the pallets on which the parts are palletised

Machine pooling always implies that at least two identical tool sets and two identical pallets are available to be loaded into two identical or fairly similar machines to process the same type of part operations. Thus when there is no tool set duplication and/or pallet duplication for identical part palletisation then machine pooling cannot occur.

The fourth group has two activities. One is called UNLDMAGAZ and the other LOADMAG. These simulate the loading and unloading of tools into the machines. It was intended initially that these two activities were to be treated as a single activity. However the simulation language restrictions did not allow this to be done.

UNLDMAGAZ, figure 9.6.10, performs the replacement of tools of the machine with a new set of tools which has been assigned to the machine for processing new parts.

LOADMAG, fig. 9.6.11, performs the tools loading only. This activity is only used when tools replacement is not necessary.

A somewhat similar strategy to this load-unload strategy for tools is also used for simulating both the parts load into and unload from pallets as well as pallets loading/unloading into machines.

A fifth group simulate the activities of unclamping and clamping

Activity UNCLAMPING, fig.9.6.12, simulates the unclamping, or more generally, the depalletisation of processed parts eventually followed by reclamping of the same parts on the same pallet and/or clamping of new parts on positions left empty on the pallet, section 9.5.2.

CLAMPING, fig. 9.6.13, simulates the clamping of parts on pallets which do not require part depalletisation.

The action of unloading/loading palletised work from/onto machines is simulated by the sixth group of activities

UNLDMC, figure 9.6.14, tests the possibility of pallet unloading from machine or machine buffer and the test success implies that the activity succeeds. In this case pallet unloading is carried out. This may also be followed, in the same loading cycle, by a new pallet being loaded into the same machine or machine buffering area. A test is carried out to check the possibility and the need to do this. The unloaded pallet may then either go to the palletising area where part unclamping may take place or to another machine if further processing is required without repalletisation.

LOADMC, figure 9.6.15, is an activity which is carried out whenever only machine loading is required, i.e. a pallet must be loaded into a machine but no pallet is required to be unloaded from the machine.

The eighth and last group of consists of only one activity which simulates the actual machining of parts

MACHINING, figure 9.6.16, is performed by checking, for every pallet on every machine, if parts machining can start. For every test success, the activity is carried out and associated control and recording variables are up-dated.

Provided the simulation duration has not been reached recording takes place and a new simulation cycle restarts after this last activity is performed. When the time of the "clock" equals the simulation duration the simulation process ends and the Finalisation section is performed. After this if new blocks of Data are available the simulation restarts with a new Data block, otherwise the simulation finishes.

9.7 MODEL INPUT/OUTPUT

9.7.1 General view

Data input is carried out initially by the model Data block and complemented by the so called Initialization section, as mentioned above in section 9.6.

Input data is necessary for establishing the FMS physical configuration, specifying manufacturing organizational data and clearly defining manufacturing control procedures for job releasing, part loading and part processing sequencing.

It is therefore possible through input data to make a computer model representation of the physical configuration of an FMS system as well as the representation of the most relevant organizational and operating aspects of the manufacturing process.

Performance measures are the main model output results. Other data which is considered relevant to complement information for system evaluation may also be included in the model output. Thus some data related to system configuration and manufacturing system control and operation is also printed out, appendix 2, figure A2.2.

A number of FMS design and operating features may be investigated through a study of the changes in performance measures resulting from changes in the levels of input parameters, figure 9.7.1 .

9.7.2 Input Data

This section is intended to formalize the model input data, most of which has already been referred to in an informal way in sections 9.4, 9.5 and 9.6.

9.7.2.1 Workpiece Related Data

Physical and Organizational Data

- Number of part types

- Number of part operations or part-pallet set-ups per part type
- Machines which can process each part operation
- Tools required to process each part operation
- Processing time per part operation in each machine
- Palletising time per part-pallet set-up
- Depalletising time per part-pallet set-up
- Size of the assembly set (AS) or batch to which the part belongs to.
- Assembly set type
- Part types making up the assembly set.
- Number of parts of each type in the assembly
- Pallet type or types where each part, for each different operation can be palletised
- Positioning of each part on each pallet for each different part-operation.
- "Part operations" which can be palletised together in the same pallet.
- Production requirements mix: Part mix and assembly set mix of the system workload.

Scheduling-Sequencing Rules

The model has been structured to allow the easy definition of a large variety of priority dispatching and part loading rules. In many cases two simple statements are enough for defining a new rule. One of the statements is required to give the rule number and the other is necessary to specify the rule controlling variable called BFACTOR for dispatching rules and FACTOR for part loading priority rules.

Examples of rules which can be defined in this way are:

a) - Priority rules for dispatching the work into the system

- FCFS (section 9.5.1)

- Duedate or other user defined job priority factor.

- Total processing time per job

- Average part processing time per job

- Combination of any of the previous rules with balancing the product mix. In these rules a product mix is specified and job release is carried out in order to maintain at any time in the FMS that mix. A product is a combination of a number of different parts

A job is a batch or an assembly set, AS.

b) - Priority rules for part-loading and processing priority (section 9.5.3)

b1) - Part related rules:

- FCFS (section 10.4.1.3)

- Duedate of the part

- Remaining processing time of part

- Processing time of the next operation

- Part processed time

- Number of remaining unprocessed part operations

b2) - Assembly set or batch related rules

- MRPAS (section 10.4.2.2) Minimum Remaining Parts in the AS

- Maximum remaining parts in the AS or batch

- Remaining processing time of the unprocessed part operations belonging to the AS or batch

With these rules part priority is defined on the basis of dynamic variables dependent on the AS or batch dynamic characteristics to which the part belongs.

From the above rules the FCFS priority rule for dispatching and the FCFS and MRPAS priority rules for part loading, part priority at palletisation and part processing priority have been used for experimentation purposes.

9.7.2.2 Pallet Related Data

Physical and Organizational data

- Total number of pallets
- Types of pallets
- Number of available pallets per type
- Number of palletising positions per pallet
- Type of each palletising position
- Pallet central store size

Pallet selection/sequencing priority

A part may be palletised together on the same pallet with other parts. In this situation it is necessary to define a pallet sequencing priority factor. This is required for pallet loading into or unloading from buffers and/or machines, for pallet priority selection at unclamping and also at machining.

The priority is only dependent on the static or dynamic variables related to the parts palletised in the pallet.

Many rules can also be defined for pallet priority selection but this may require a slightly more complex procedure than that referred to for the previous rules. The principle is the same: a rule number has to be defined and the expression for the value of the rule controlling factor, now called FXFACTOR, must be established.

Examples of pallet selection priority rules which could be used are:

- Highest priority part rule.

  With this rule the pallet is selected on the basis of the highest priority part loaded on the pallet.

- Remaining processing time of the palletised parts

- Processed time of the palletised parts

- Number of unprocessed operations of all palletised parts

The highest priority part rule is used for experimental purposes. This simply means that priority is given to the highest priority part on the pallet for both machining and depalletising operations. In this work the emphasis is on producing complete assembly sets and individual parts priorities are set to achieve this. Hence in the experimental work the the highest priority part on pallet rule is used to ensure that high priority parts which are required for assembly sets are not held up in the system.

9.7.2.3 Machine Related Data

Physical and organizational data

- Number of machines in the system

- Types of machines in the system

- Number of machines of each machine type

- Type of tools which each machine may use for part processing.

- Machine local tool storage size - magazine size

- Number of machine buffers places - buffer positions for pallets. An 'n' position buffer has 'n-1' utilized buffer places for pallets. A spare place is necessary for pallet exchange.

- Machine assigned workload

This last variable is dependent on system state and is essentially used for machine pooling and part-loading as referred to in section 9.5.4.

Machining priority is determined by pallet priority as defined in section 9.7.2.2.

9.7.2.4 Tool Related Data

Sets of tools are defined for the processing of each different part operation, section 8.3. Tool groups are established having one or more such tool sets. The maximum number of tools in each tool group cannot be larger than the smallest tool magazine size into which the tool group is to be loaded.

The data which is necessary to define the tooling system configuration is:

- Number of tool sets
- Type of each tool set
- Number of available tool groups in the FMS
- Type of each tool group in the system.
- Tool sets which make-up each tool group
- Number of tools in each tool group.

In addition the times to replace tools at machines are given:

- On a tool by tool replacement basis
- On a magazine replacing basis

9.7.2.5 Handling Devices and Transport

The data input related to the transportation system are:

- Number of pallet transport/handling devices (HD);
- Number of pallets carried at a time or pallet carrying positions;
- Transport time to and from any defined area in the transport network, figure 9.5.2;
- Handling device function:
    - part-pallets carrying only
    - part-pallets and tools carrying

When the handling devices are also used for tool transport the transport time to the machines and tool group loading into and unloading from the HD must be given.

9.7.2.6 Operator Data

The operators' related data are:

- Number of operators
- Operator functions:
  - Palletising/Unpalletising only
  - Palletising/Unpalletising and tool replacement and/or tool transport.

Each of the operation functions applies to all operators during a specific simulation.

9.7.2.7 Other Input Data

It is also necessary to input a diversity of other parameters such as:

- Production period-Simulation duration
- Shift duration
- Number of shifts per day
- Day duration
- Part sequencing priority rule, section 9.7.2.1
- Pallet selection priority rule, section 9.7.2.2
- Job order releasing plan. This includes:
  - a list of all jobs (AS or batches) to be processed
  - the job releasing priority rule section 9.7.2.1. When this is not given jobs are released as they appear queued in the order plan, i.e. on a first come first served basis and

- the value of the priority factor, if any, for each job to be released.

9.7.3 Model Output

Model output includes a number of performance measures expressing the manufacturing simulation results, a number of system configuration and manufacturing control parameters as well as part spectrum related variables.

The main performance measures recorded by the model and which can be printed out, figure 9.7.1, are :

1 - Average utilization of a variety of classes of physical system entities which are involved direct or indirectly in the manufacturing of parts, namely machines, operators, tools, pallets and handling/transport devices, HD. In addition the utilization of each particular entity within each class is also obtained.

2 - Number of finished and in progress workpieces and assembly sets for each type as well as the corresponding totals for each of these two classes of entities.

3 - Average and frequency distribution of the work-in-progress, w.i.p., expressed as:

- number of w.i.p. parts and
- w.i.p. processed time

4 - Average and frequency distribution of the throughput times of both parts and assembly sets or batches.

5 - Average and frequency distribution of the throughput time index, TTI, of both parts and AS or batches.

$$TTI = \frac{\text{Throughput time}}{\text{Machining time}}$$

6 - Work-in-progress turnover of both parts, WIPTQ and processed time, WIPTT

$$\text{WIPTQ} = \frac{\text{Average number of parts produced in a year}}{\text{Average number of parts in progress}}$$

$$\text{WIPTT} = \frac{\text{Average total processed time in a year}}{\text{Average processed time in progress}}$$

7 - Production rate in workpieces per hour

8 - Production Synchronization Ratio, PSR, section 10.1.1.

Other variables are also printed out with the purpose of complementing information output and check on input data. These include:

<u>FMS configuration data</u>

- Number of operators in the system
- Number of machines in the system
- Number of pallet buffers in each machine
- Number of tool groups in the system
- Number of handling devices, HD, in the system
- Number of transport positions in each HD.
- Number of pallets of each type in the system.

<u>Manufacturing control data</u>

- Job releasing priority rule
- Part sequencing priority rule
- Pallet selection priority rule.

<u>Operational data</u>

- FMS running time/ Simulation time
- Number of loaded AS or batches per type

- Number of loaded parts per type

- Frequency distribution, mean and standard deviation of part-operation times of all loaded parts

- Frequency distribution, mean and standard deviation of machined operations. A machined operation may include the machining of one or more part operations, depending on how many parts are loaded together in a same pallet for processing at a given machine.

- Frequency distribution , mean and standard deviation of transport times of pallets

- Number of times each simulated activity succeeds during the simulation period.

9.8 MODEL VALIDATION

Ideally validation of a computer simulation model can be carried out by comparing model output with actual observed output. In many cases, particularly when investigating possible system configurations, as in this work, for high capital cost equipment, real systems output are not available.

Model validation in these circumstances can only be achieved by verifying that the program matches the conceptual model of the FMS's, that there is a correspondence between the model and the FMS's which it represents and that the simulation program behaves as intended.

In order to carry out this latter stage, during model development system dumps of variables were checked at every clock time to determine whether variables changed as expected. These expected changes were derived by hand for each FMS configuration tested, its elements, control rules and operational data.

In addition, output results of test runs were examined for consistency and, where appropriate, expected behaviour.

CHAPTER 10 - COMPUTER SIMULATION EXPERIMENTS

10.1 BOUNDARIES AND OBJECTIVES

For the reasons stated in chapter 4, set assembly manufacturing has been considered throughout the design and operation analysis of FMS's in this work.

The results and conclusions of this research work are based on computer experiments carried-out with a complex simulation model, chapter 9, which gives emphasis to tooling and palletising aspects which are central to this research work.

In particular the problem of finding tooling configurations for efficient FMS operation under minimum tooling requirements has been studied.

FMS design and operation are interrelated. Thus a specific design configuration is dependent on operating objectives and on the other hand the operation of an FMS, is significantly influenced by the design solution adopted. Due to this interrelationship the computer simulation experiments carried out can be seen as directed at evaluating both design and operation aspects of FMS.

The study considers tools to be a limited resource. This removes the usual simplification of assuming that tools are available and therefore scheduling decisions are not constrained by tooling. Such a simplification may be acceptable when modelling traditional manufacturing systems, in particular rigid transfer lines, but is unrealistic in FMS where it is necessary to avoid excessive tool duplication and tooling costs.

10.1.1 FMS Performance and Evaluation

Because this investigation is concerned with FMS's which produce sets of parts for subsequent processing, FMS performance will be considered as the combined view of both average utilization and assembly sets output during the FMS running period. A normalized representation of this measure is the production Synchronization Ratio, SR defined as:

$$SR = \frac{\text{Actual finished assembly sets in the period}}{\text{Theoretical maximum sets it is possible to finish in the period}}$$

In experiments concerned with varying the total load in the system, two other measures have been used. These are work in progress, w.i.p., expressed as the processed time of in progress parts, and job throughput time.

Job throughput time is considered as the average throughput time of assembly sets. As a normalized measure of throughput time the Assembly Set Throughput Time Index, ASTTI, will be used. This is given by:

$$ASTTI = \frac{\text{Average set throughput time}}{\text{Machining time per assembly set}}$$

10.1.1.1 Degree of Balance of an FMS

The maximum achievable machine utilization in a FMS is usually dependent on part mix processing requirements and alternatives for parts assignment to machines.

The assumption is made that it is possible to identify groups of machines, which may contain one machine or more, such that part operations can be performed anywhere within the machine group. The total work load is distributed among the groups and considered to be equally distributed within the machines of each group. As long as the machines in each group are fully utilized the theoretical maximum possible machine utilization for the FMS is 1. We can say that the FMS is in perfect balance. However, if due to the nature of processing mix requirements an unbalanced load assignment to the groups results, then that maximum is not achievable. Eventually the group with the largest load per machine may be fully utilized but the machines of the others are bound to remain idle for some time. In these circumstances the theoretical maximum machine utilization is no longer 1 (one) but a value less than that. In this case perfect FMS balance in not achieved and only a certain degree of balancing is achieved. The Degree of Balance of an FMS is defined as the theoretical maximum possible machine utilization of an FMS determined by the average of the total maximum possible utilization of the machine groups within the FMS. This theoretical machine utilization is given by:

$$UT = \frac{\sum_{i=1}^{g} m_i \cdot U_i}{\sum_{i=1}^{g} m_i}$$

Where:

UT - is the theoretical maximum FMS machine utilization or degree of balance of an FMS

m_i - is the number of machines in the machine group i

U_i - is the maximum possible utilization of machine group i, table 10.9.3 and

g - is the number of machine groups in the FMS

A practical application example of this concept is shown in table 10.9.3.

10.2 GENERALIZED SYSTEM SET-UP AND DATA

The FMS configurations and the data used in the set of experiments are mainly based on an existing FMS[139] for manufacturing of complex prismatic parts. Much of the data was obtained from direct observation. However, it is felt that the modelled configurations are sufficiently representative to allow some general conclusions to be made.

10.2.1 Production Planning Horizon and Shift Pattern

The experimental work is based on computer simulation runs for 3 eight hour shifts. This choice is based on the fact that, most frequently FMS's are run for planning horizons of one day[100]. The shift division of the daily production, which is a feature of the operation of many FMS's, offers flexibility in organization which is reflected in operational control. Thus scheduling and sequencing strategies may be changed over time and are frequently associated with particular shifts[53]. In this work, for instance, part urgency or priority scheduling is defined on a shift basis in some experiments, section 10.4.1.3.

10.2.2 Typical System Configuration

Variations in a basic FMS physical configuration, figure 10.2.1, may be adopted according the objectives of the analysis or evaluation study.

Four machining stations have been used for most of the experimental work and these may be limited or multipurpose machines. A tool central store is available where tool groups are kept to be exchanged in the tool storage area at the machines.

The number of tool groups held varies according to tooling configuration and is closely related to part mix processing requirements.

A single transport vehicle or handling device, HD, with a single pallet position, is used.

Two palletising operators are used for both palletising work and tool replacement at machines.

These two last types of system resources have been used in all experimental work and their utilization is low, namely around 0.55 for the handling device and 0.450 for operators. This fact combined with that of adopting these same resources for every experiment allows one to assume that the main variations in the performance measures are primarily due to the variation in the levels of the factors analysed in each particular simulation study.

A palletising and central store area with a capacity for 13 fixtured pallets is used in conjunction with a back-up store for the remaining available pallets. These pallets will be kept empty until they are transferred to the palletising and central store area where part clamping can take place.

10.2.3 Part Spectrum

The part spectrum used for the majority of the research is based upon a real set of parts associated with the NGL FMS a sample of which is shown in figure 10.2.2. Variations in this spectrum have been investigated.

A basic set of nine different complex prismatic parts is considered and relevant details are given in tables 10.2.1 and 10.2.2. Some of the parts have identical processing times but they are different parts and required for the assembly of a final product or set.

The part mix is required to form sets of parts. These sets of parts are called assembly sets (AS) and are seen as an organizational unit. The parts of such a unit can be identical or different.

The typical part requirements for each assembly set to be manufactured in the configured FMS is shown in table 10.2.1

10.2.4 Part Operations and Processing Times

A part operation consists of a number of elemental operations each requiring that a single tool or tool head be exchanged between tool magazine and machine spindle. These tools may well include touching and measuring probes.

The part operation processing times per each part operation type are given in table 10.2.2. A typical frequency distribution of the part mix operation times, is show in figure 10.2.3. The same figure 10.2.3 also includes a typical distribution of machine operation times which clearly shows that in the main the latter are larger than operation times because parts are palletised together and processed jointly. The distributions are dependent upon part mix, load requirements and interactions within the system.

These time distributions are related to the manufacturing of parts for a three eight hour shift period and are associated with the mix containing the ten parts required for each AS, section 10.2.3.

10.2.5 Part Release and Scheduling

Parts are released into the FMS in assembly sets, section 4.1.2. Thus when the set batch size is two, then two identical assembly sets are released into the system together. The release of work is an aspect which is not central to this research work. Thus it was decided to adopt a simple mechanism to release work. The work is released whenever the system load drops below a given value normally equivalent to a two shifts load namely 960 minutes for the typically configured FMS of figure 10.2.1. This time is equivalent to an average of 240 minutes per each of the four machines.

Work scheduling details and work scheduling flexibility has been discussed in both model description, chapter 9 and in chapter 7.

10.2.6 Initial Calculation of the Number of Pallets

The analytical work in chapter 5 can be used to obtain a first approximation of the number of pallets required to run the configured FMS for the part mix referred to above.

10.2.6.1 Number of Pallets for the Three Eight Hour Shift Planned Manufacturing Period.

If no reusage of pallets is considered than, as shown in section 6.3.1 the number of required pallets would be:

$$\bar{P}' = U^*(m \cdot T/p_p) \qquad (6.12')$$

where:

$\bar{P}'$ is the average number of required pallets

U is the average machine utilization

p_p is the average processing time per pallet set-up at a machine or workstation

T is the length of the manufacturing planned period

m is the number of available FMS workstations

If we consider that theoretically 100% machine utilization is possible then:

$$\bar{P}' = m \cdot T/p_p$$

In the FMS considered 4 machining centres are used, i.e. m is 4. Moreover the FMS planned manufacturing period is three eight hour shifts, i.e. T is 24 hours.

Based on figure 10.2.4 and table 10.2.2 it can be seen that there are eight different types of pallets to carry parts requiring a total processing time of 802 min which means that the average processing time per pallet set-up is:

$$p_p = \frac{802}{8}$$

$$p_p = 100 \text{ min}$$

Therefore:

$$\bar{P}' = \frac{4*24*60}{100}$$

$$\bar{P}' = 58 \text{ pallets}$$

Thus if no recirculation of pallets is allowed during the three shifts an average of 58 fixtured pallets is necessary to run the FMS.

10.2.6.2 Number of pallets required with pallet reusage

It was seen in section 6.3.2 that when pallet reusage is possible within the planned manufacturing period then the average number of pallets required can be considerably reduced and is given by:

$$\bar{P} = \bar{P}' / PR$$

which can be expressed as:

$$\bar{P} = \frac{m \cdot t_p}{p_p} \qquad (6.14)$$

Where t_p is the pallet cycle time, section 6.3.2

t_p can only be obtained from the study of a real system or through computer simulation of the FMS operation.

10.2.6.3 Minimum Number of pallets required

It was seen, section 6.3.4 equation 6.17 that:

$$\bar{P}_{min} = m + \frac{m(p_s + p_c)}{p_p} \qquad (6.17)$$

Where:

p_s - is the average time a pallet is used for part(s) palletisation /depalletisation per pallet cycle and

p_c - is the average pallet transport and handling times per pallet cycle

The p_s value can easily be determined from operation data. In the FMS as configured 4 min were required for part palletisation and 3 min for part depalletisation. Since a maximum of 26 parts must be clamped on 8 different fixtured pallets, the maximum time for palletising and depalletising per pallet is :

$$p_s = \frac{26*(4+3)}{8}$$

$$p_s = 22.75 \text{ min}$$

The time p_c is likely to be dependent on system configuration and also on the way work flows within the system. A value could easily be obtained through computer simulation. Nevertheless an approximation to p_c can be adopted based on handling and transport times between FMS stations.

In the configured FMS, pallet exchange times at palletising and work stations is 1 min and transport times between palletising and machining stations is 2 min. We can consider that pallets always return to the palletising area after processing before going to other machines. This is most probably the case when highly flexible machining centres are used as in the FMS configured. In this case p_c is the time to go from and return to palletising, namely 4 min plus the pallet exchange times at both machining and palletising areas, namely four times 1 min. Therefore p_c is 8 minutes.

Using equation (6.17) :

$$\bar{P}_{min} = 4 + \frac{4(22.75 + 8)}{100}$$

$$\bar{P}_{min} = 5.23$$

i.e. a minimum of 6 pallets would be required to operate the FMS. However account must be taken of the number of different pallets required, section 6.3.3 , which is 8. Therefore the real minimum has to be 8 pallets.

10.2 7 Number of Pallets and Palletising Approach

The previous calculation suggests that a single set of 8 different fixtured pallets may allow a good level of FMS utilization provided no other production resources, such as tools or transport vehicles, and production control impose delays on pallets. In reality a value larger than 8, i.e one set of fixtured pallets, but certainly smaller than 58, is likely to be required for high FMS performance.

Typically sixteen fixtured pallets, i.e.two each of eight different types, have been used in most of the simulation experiments. Any changes to this are dependent on the objectives of experimentation and will be referred to in appropriate sections.

All pallets carry a number of parts which are clamped to appropriate fixtures for joint processing, in groups of identical, different or mixed part types as shown in figure 10.2.4.

A fixtured pallet holds a minimum of two parts and a maximum of ten as shown. The figure shows which parts are clamped onto which fixtured pallets and the respective part operations to be carried-out.

Some parts may remain with the same pallet for all operations, but need reclamping between operations. Other parts may require a change of pallet/fixture combination between operations, see figure 10.2.4.

10.2.8 Tools Loading/Unloading

Tools are combined in sets which may be grouped together to constitute alternative magazine loads, based on part processing requirements.

Groups of tools required to process the work clamped onto pallets are loaded at the tool buffers of the machines. The choice of which group to load is determined by part processing requirements and part priority.

The decision to unload a given group of tools from the tool buffer at the machine is usually caused by the need to process a new part requiring a new group of tools.

Tool group replacement time in the model is taken to be 35 minutes. At the start of production only loading of a tool group takes place and slightly more than half of the load/unload time, namely 20 minutes, has been allowed. This is a simplification of what is likely to happen in practice. The simplification was necessary to avoid problems, in running the model, which were initially encountered due to the limitations of the simulation language referred to previously, sections 9.1 and 9.3. Verification showed that it would not affect noticeably the experimental results. Initial test runs showed that, for the 24 hour manufacturing period considered, tool loading at each machine takes place at most around four times, i.e. slightly more than once per shift, and at least once. This lower value occurs when tooling configurations with four tool groups are used in the four machine configured FMS. Hence the tool replacement time is a comparatively small fraction of the manufacturing period and therefore did not noticeably affect machine utilization and other performance measures.

10.3 OUTLINE OF COMPUTER SIMULATION EXPERIMENTS

Tooling Strategies and FMS Configurations

The scheme of experimental work using the computer simulation model has been designed to encompass the major combinations of machine tools and tooling availability as shown in table 10.3.1. Some extensions to this scheme have been included and these will be described in appropriate sections.

Thus two basic FMS configurations are considered. One uses identical highly flexible machining stations. These stations can process any part operations of the part mixes used in the experimental work. In the other FMS configuration, two different groups of limited purpose machining stations are used. These stations are only able to process a limited number of different part operations.

For each configuration, FMS performance is investigated for three general levels of tooling. One uses minimum tooling, i.e. no duplication of basic tool sets, section 8.3.1. Another level uses restricted tool duplication. Tools to be duplicated are chosen on the basis of a tool duplication heuristic rule, section 8.4.3.5. At the third level machining is not constrained by tooling but only by machine processing capabilities. This is referred to as the full tool replication case. In this case the machines within each machine group are identically tooled. Tool loading is performed only once at the beginning of the planned manufacturing period.

The planned set of experiments are set-up to study the impact of different tooling levels and tooling configurations on FMS performance measures. This is studied for different scheduling rules and different part mixes. The tooling configurations are designed using the heuristic rules for tool grouping, section 8.4.

Dynamic Analysis of Pallet and Tooling Configurations for Different Scheduling Rules and Batch Sizes.

A further important aspect of this research is the determination of the best number of fixtured pallets for efficiently running an FMS to manufacture a given part mix. A complex experiment was set-up, section 10.12, to study this in conjunction with a number of other factors. These include tooling levels for different tooling arrangements, different scheduling rules and 12 different levels of assembly set batch size, ASBS. An assembly set batch is a number of identical AS's which are released together into the system.

The interrelationships between these variables are studied in order to define the best combination of the levels of these factors to achieve high operating efficiency.

10.4 TOOLING CONFIGURATION DESIGN FOR MINIMUM TOOLING REQUIREMENTS WITH MULTIPURPOSE MACHINES FMS'S-EXPERIMENT 1

10.4.1 Phase 1

10.4.1.1 Objective

The objective of this study is to investigate the design of tooling configurations for the modelled FMS with multipurpose machining stations, and to evaluate the effectiveness of the heuristic tool combination rules developed in section 8.4, for generating those configurations.

10.4.1.2 Introduction

In this part of the research the minimum number of tools required to process a part mix is to be adopted to study the influence of different tooling configurations on FMS performance.

Tooling configurations are to be obtained from the available tools combined in groups which will be loaded into the machines. Under minimum tooling it is considered that no basic tool set will be duplicated.

The basis for evaluation will be the analysis of the FMS performance results for the tooling configurations generated and also their comparison with the FMS performance obtained for a set of randomly generated tooling configurations.

10.4.1.3 Experimental Set-up

<u>PHYSICAL FMS CONFIGURATION</u>

The FMS system, figure 10.2.1, consists of four machining stations (MC), a tool central store and a palletising and central storage area with a capacity for 13 fixtured pallets. A further back-up store holds the remain available pallets which will be kept empty unless they are transferred to the central store of palletised work. The total number of pallets is 16.

Machining Stations

In this experiment machines are considered to be similar and multipurpose in such a way that any of them can take any different tool group to carry out processing operations. Each machine is assumed to have a magazine capable of holding up to 100 tools.

In front of each machine is a buffer consisting of a two position shuttle. A single position pallet carrier transfers pallets between the part store and each of the machine shuttles.

Tools

A maximum of twenty one basic tool sets corresponding to the twenty one different part operations to be carried out on the part mix are initially combined into eight basic tool groups, table 10.4.1, appropriate to the part operations accommodated on each of the eight different fixtured pallets. This resulting tooling configuration is referred to as the basic tooling configuration, section 8.3.2.

Machine set-up

The machine set-up involving tool replacement, is carried out by the two available palletisation operators.

Part mix, fixtured pallets, pallet stores, clamping and loading areas, operators and other physical data have been described in section 10.2. Processing data for the 21 part operations is shown in table 10.2.2.

ORGANIZATIONAL AND OPERATING CONSIDERATIONS

Parts and tools routing flexibility

The multipurpose nature of the FMS machining centres allows any different pre-defined tool group to go to any machining station to carry out appropriate processing operations on the part mix. However, since minimum tooling is to be investigated in this experiment an operation can only be carried out in a unique machine at a given instant. Such a machine has either to have tools, for processing the part, already loaded in it, or have tools available to be loaded into it. In the first case no alternative part routing is provided; in the second however, before tools are loaded, the maximum routing flexibility is available.

The choice of a machine is dependent on system state conditions, in particular on machine state, and also on the manufacturing control strategy adopted.

Manufacturing Control Strategy

a) Job Release

A job releasing switch based on a minimum system work load is used to release work into the system, section 10.2.5. The work is released on an individual assembly set basis, i.e. ASBS, section 10.3, of one is used. Thus work load includes parts which are actually being worked on and is equivalent to four working hours per machining station. This value of the workload is shown, section 10.6, to be a reasonable workload.

The job to be released is chosen on a FCFS basis, section 9.5.1.

b) Operational Control

b.1) Priority Rules

From the range of static and dynamic priority rules referred to in section 9.7.2 a rule based on the timing of job entry in the system is used. The rule used gives identical priority to the parts for assembly sets or batches which are released in the same shift. Parts for assembly sets or batches loaded in later shifts have lower priority.

For identical priority at a work station, the rule selects the part or pallet which is first in the queue. This rule will be referred as FCFS scheduling rule.

b.2) Pallet Priority

Due to the variety of parts which can go on a pallet the pallet priority is made equal to the highest of the part priorities, section 9.7.2.2.

TOOLING CONFIGURATIONS

Complete enumeration has already been shown, section 8.2. to be an inadequate method of generating practical tooling configurations. There remains therefore two basic approaches:

1 -Random combination of tool groups and

2 -Use of heuristic rules

1 - Random Combination

Tooling configurations based on random combination of the available tool groups in an existing configuration are successively obtained by randomly choosing two such tool groups which will be combined into one. It is assumed that tool combination is unconstrained by magazine size.

This tool combination approach starts from an initial tooling configuration. This is the basic tooling configuration, BTC, as defined in table 10.4.1.

The random combination cycle ends when a configuration is obtained with as many combined tool groups as there are machining stations to accept them. Since there are four identical multipurpose machining stations and an initial tooling configuration with eight tool groups, four additional tooling configurations are obtained for each random generation cycle. A typical set of tooling configurations, generated in this way is shown in table 10.4.2.

2 - The use of heuristic rules

Four heuristic rules described in section 8.4 are compared with each other and also compared with the random generation rule.

To recap, the heuristic rules are:

Rule A - Least utilized tool groups rule.

Rule B - Lowest to highest parts ratio (WPR) rule,

Rule C - Highest to highest WPR rule.

Rule D - Ungrouping-regrouping rule.

Due to their nature, rules A B and C only generate, n, tooling configurations each with:

$$n = NTG_i - m$$

NTG_i - Number of tool groups in an initial solution

m - Number of machining centers in the configured FMS.

The initial basic tooling configuration used in this experiment has eight tool groups and since four machining centres are available then n will be four. Therefore each of these rules will generate four tooling configurations.

Rules D may generate any possible number of tooling configurations limited however to the maximum given by the mathematical recurrence formula (8.5) developed in section 8.2.

10.4.1.4 Results and discussion

Each generated tooling configuration was evaluated by running the simulation model as configured.

The simulation time required for a simulation run is on average 3 minutes of CPU time on a Prime 700 mini computer for each three eight hour shift simulated manufacturing periods.

A sample of 6 sets of four tooling configurations each was randomly generated. This is a total on average 6 times more than the configurations needed to be generated by each of the A B or C heuristic rules.

The randomly generated configurations and the FMS performance measures under each one are shown in table 10.4.2 together with the BTC for the part mix. An overall average for each measure as well as their ranges are also shown. These results can be compared with those obtained under the heuristic tooling configuration design rules shown in table 10.4.3.

Figure 10.4.1 illustrates the differences in the two main performance measures considered.

The application process of heuristic tool combination rules and resulting tooling configurations are shown in appendix 3.

DISCUSSION

As would be expected in general the heuristic rules are better than the random rule in finding tooling configurations which perform well.

In average terms heuristic rules give utilizations considerably above that obtained for the random rule. The same pattern is also noticed for the number of finished assembly sets (AS) during the three eight hour shift running period. This number was on average 4.69 for the heuristic rules and only 3.2 for the random rule, tables 10.4.2 and 10.4.3. Average machine utilization was 0.857 for the heuristics and 0.703 for the random strategy.

Rule D shows, in the case studied, a better behaviour than any other. With its use it is possible to design tooling configurations which, even under no tool set duplication, are capable of yielding a relatively high number of assembly sets and good machine utilization.

In addition, performance variations between the tooling configurations generated by the tooling combination rules for both utilization and finished sets are considerably smaller than those of the random rule, table 10.4.2. In this sense rule D also has the best performance.

Utilization variation is around 0.53 for the random tool combination strategy, and only 0.14 for the heuristics, table 10.4.3. On the other hand finished sets vary between 4 and 6 for the heuristics and zero and 5 for the random strategy. Thus it is possible to conclude that the heuristics are undoubtedly better than the random strategy. However tooling configurations obtained under some of the heuristics do present considerable variations in performance. Therefore it is necessary that tooling configurations are well designed to guarantee the achievement of production performance objectives.

In this respect, under the environment of this experiment the heuristic rules discussed, and in particular rule D, have shown to be good useful aids for that design. It must be pointed out that rule D is normally applied to a TC obtained from application of other rules and usually with the aim of finding new configurations under which FMS performance can improve. In this case rule D was applied to TC9 improving utilization from 0.872 to 0.93 and AS from 4 to 6.

10.4.1.5. Main Findings

From the results and discussion of this experiment a few major findings can be stated:

1 - Under fixed minimum tooling resources tooling configuration greatly affects FMS performance. As a consequence there is a need to correctly identify those tooling configurations which can achieve best FMS performance objectives.

2 - This identification can be carried out effectively through the application of heuristic tool group combination rules.

3 - It has been shown for the FMS configuration studied that the heuristics developed perform better overall then a random strategy in achieving both high FMS utilization and high assembly set throughput per manufacturing period.

4 - In the environment of the experiment it was shown that without tooling duplication good system performance can be obtained.

However, this is obviously dependent on a number of factors, one of which is part mix processing requirements. Thus, if a single type of part is to be processed within the FMS it is natural that tool duplication will be required. As part variety increases such requirements will be reduced.

5 - We can also conclude that pooling machines to provide simultaneous part routing alternatives may not be necessary to achieve high levels of system performance. In the case studied no machine pooling is possible and nevertheless good levels of FMS performance are obtained table 10.4.3 and figure 10.4.1.

10.4.2 Phase 2

10.4.2.1 Objective

The objectives of this second phase of the experiment are to investigate whether or not the findings obtained in the first phase under the FCFS rule related to the tool combination heuristic rules can be applied to the situation when the MRPAS scheduling rule, see below, is used and additionally to evaluate the effectiveness of this new scheduling rule in achieving the performance objectives. In particular its potential ability for providing high output of sets and high utilization under different tooling configurations will be investigated.

In later experiments, e.g. section 10.12, the performance of the MRPAS rule will be compared with that of the FCFS rule under different FMS operating set-up configurations.

10.4.2.2 Introduction

In the first phase, tooling configurations were developed and evaluated by operating the modelled FMS under the FCFS scheduling rule, section 10.4.1.3.

It is pertinent to examine the possibility of designing a control strategy which provides better system performance under varying tooling configurations and operating conditions. It is important to obtain high utilization of FMS due to the high cost of such systems.

The scheduling rule devised is related to the requirement for achieving high output of sets whilst retaining high machine utilization. The rule has been named MRPAS - Minimum Remaining Parts of the Assembly Set. As the name suggests, under the MRPAS rule parts which belong to sets nearest to completion will be given priority. This is done not only for part assignment to machines and transport but also for part palletising operations.

10.4.2.3 Experimental Set-up

The experimental set-up is the same as the one used in the first phase of the experiment except that the FMS system will be operated under the new scheduling MRPAS rule, instead of the FCFS.

10.4.2.4 Results and discussion

Tooling configurations under no tool set duplication were designed by means of the four heuristic tool group combination rules A, B, C and D, section 8.4, and the iterative use of the simulation model just as was done in phase 1, section 10.4.1

The tool set composition of each tooling configuration is shown in table 10.4.4, which also includes the values of average machine utilization and output of assembly sets for the running period.

A comparison of performance results under the MRPAS rule, table 10.4.4, and the results previously obtained for the FCFS rule, table 10.4.3, is shown in figure 10.4.2 .

It can be seen that, in general under MRPAS scheduling the heuristic tool group combination rules considered in this phase perform consistently better than under FCFS. This is particularly so for sets output although machine utilization is also, on average, better under MRPAS for the heuristics rules taken overall. Among rules A, B and C rule B is the one which performs the best with a maximum of 6 sets output for every tooling configuration generated and average utilization of 0.896. But again rule D performs best as has already happened when running the FMS under the FCFS scheduling rule.

At this stage it is not immediately clear why utilization is better under the MRPAS rule. Further experimentation carried out later, mainly in section 10.12, will to some extent clarify this.

Under no tool set duplication there are tooling configurations, e.g. TC9, TC13 and TC14, table 10.4.4 for which the FMS performance is high, which, because of having as many tool groups as there are machines, once loaded into the machines no part routing alternatives are provided, i.e. a given operation can only be carried out in the single machine which has the right tools.

10.4.2.5 Main Findings

1 - The conclusions reached in the first phase under the FCFS scheduling rule are valid for an identically configured FMS operated under the MRPAS scheduling rule.

2 - For the multipurpose machining station FMS operated under minimum tooling, in general the MRPAS rule performs better than the FCFS rule. The MRPAS rule is consistent in leading to high FMS utilization and particularly to high output of assembly sets.

3 - Heuristic tool combination rule D performs better than the other tool combination rules for both FCFS and MRPAS scheduling rules.

10.5 RANDOMIZATION OF PART TYPES WITHIN ASSEMBLY SETS-EXPERIMENT 2

10.5.1 Objective

The objective of this experiment is to test wether the deterministic ordered release of the assembly set parts has introduced a bias in the FMS results.

10.5.2 Introduction

In the previous experiment, section 10.4, the parts of any AS are released into the system in an identical and systematic order as they appear listed in the AS. Therefore the AS parts are always released in a deterministic part type sequence.

It may be argued that this fixed ordering of AS parts release may introduce a bias in FMS performance results and therefore make conclusions based on the previous experiments questionable.

To investigate this possibility, a non-ordered AS part type release strategy i.e., part release in random order, has been used in this experiment.

10.5.3 Experimental set-up

To meet the objective of this experiment, the FMS set-up and part-mix must be identical to that of the previous experiment with a basic difference concerning only the order of release of parts making up each assembly set.

Thus the release of parts in this experiment is randomized in such a way that any of the parts, within an assembly set still to be released, can be released next with identical probability. This means that any time a set is released, a new random order by which the parts of the assembly set are released is generated.

<u>Tooling</u>

In this experiment no new tooling configurations are obviously required to be generated. Instead the tooling configurations generated in the previous experiment can and must be used.

10.5.4 Results and discussion

In order to reduce the amount of computer runs and simplify experimentation it was decided to make a selective choice of only some of the 28 tooling configurations generated in the previous experiments and shown in tables 10.4.3 and 10.4.4.

Twelve of these tooling configurations were selected. The criteria for selection was to choose complete sets of tooling configurations associated with particular heuristic tool combination rules which performed well in the previous experiment.

Thus tooling configurations TC6 to TC13 from table 10.4.4 corresponding to rules B and C were selected and are identical to TC1 to TC8 in table 10.5.1. The other configurations selected were TC10 to TC13 from table 10.4.3 corresponding to rule C and are identical to TC9 to TC12 in table 10.5.1.

The 12 tooling configurations were run for both FCFS and MRPAS scheduling rules but now under randomization of the AS part release. The results were compared with those obtained for the part ordered release case. Thus, a total of 48 simulation runs were necessary.

The zero hypothesis in this experiment is to postulate that part type ordered release does not affect significantly the performance results and therefore tooling configurations for which FMS performance was high/low should lead under part release randomization to high/low FMS performance as well. In other words, the mean difference between a performance measure under deterministic part release and randomized part release must be zero, i.e., $H_0 : \mu = 0$.

Table 10.5.2 shows the differences in performance results between the two order release strategies.

There is a very close similarity in the results obtained under the ordered pattern of part types within an AS and the random one as tables 10.5.1 and 10.5.2 and figures 10.5.1 to 10.5.5 show.

Moreover the trend observed under randomization of part release, for each of the three groups of four tooling configurations, fig. 10.5.5, is identical to that seen under the conditions of the previous experiment for the same tooling configurations. This is so not only under FCFS scheduling rule but also under the MRPAS rule.

Additionally under the FCFS rule, the AS output varies little for each of the two part release strategies considered. Thus for 50% of the runs, AS output is the same under each of the strategies. From the remain pairs 11 show a variation of only one AS and for one pair there is a variation of two AS.

The results were tested at 5% significance level, using a two sided t-test for each of the four differences corresponding to the four columns of table 10.5.2.

Two sided t-test of significance of the results

In general, since the mean of the difference between the values of the performance measures should be zero, the null hypothesis is:

$$H_0 : \mu = \mu_0$$

$$\text{with } \mu_0 = 0$$

And for a 5% significance level $t_{a,n-1}$ is $t_{0.025,11} = 2.201$

CASE 1: Machine utilization difference under MRPAS

$$x_1 = \sum_{i=1}^{n} x_{1i} / n$$

$x_1 = - 0.087/12$ $\qquad x_1 = - 7.25 * 10^{-3}$

$\Sigma x_{1i}^2 = 4.739 * 10^{-3}$

$s_1 = \sqrt{((\Sigma x_{1i}^2) - x_1^2) / (n-1)}$ $\qquad s_1 = 0.0193256$

$|t_{01}| = |(x_1-0)/(s_1/\sqrt{n})|$ $\qquad |t_{01}| = 1.3 < 2.201 = t_{0.025,11}$

Since $|t_{01}| < t_{0.025,11}$ there is not enough evidence to reject the null hypothesis and it is therefore possible to conclude that utilization under the MRPAS rule does not vary significantly when deterministic release of AS parts is compared with randomized part release.

CASE 2: Machine utilization difference under FCFS

$$x_2 = \sum_{i=1}^{n} x_{2i} / n$$

$x_2 = -0.145/12$ $\qquad\qquad\qquad\qquad$ $x_2 = -1.2 * 10^{-2}$

$\Sigma x_{2i}^2 = 5.77 * 10^{-3}$

$s_2 = \sqrt{((\Sigma x_{2i}^2) - x_2^2)/(n-1)}$ $\qquad\qquad$ $s_2 = 0.0191$

$|t_{02}| = |(x_2-0)/(s_2/\sqrt{n})|$ $\qquad\qquad$ $|t_{02}| = 2.19 < 2.201 = t_{0.025,11}$

Since $|t_{02}| < t_{0.025,11}$ there is not enough evidence to reject the null hypothesis and it is therefore possible to conclude that utilization under the FCFS rule does not vary significantly when deterministic release of AS parts is compared with randomized parts release.

CASE 3: AS output difference under MRPAS

$$x_3 = \sum_{i=1}^{n} x_{3i} / n$$

$x_3 = -2/12$ $\qquad\qquad\qquad\qquad$ $x_3 = -1/6$

$\Sigma x_{3i}^2 = 6$

$s_3 = \sqrt{((\Sigma x_{3i}^2) - x_3^2)/(n-1)}$ $\qquad\qquad$ $s_3 = 0.75878$

$|t_{03}| = |(x_3-0)/(s_3/\sqrt{n})|$ $\qquad\qquad$ $|t_{03}| = 0.761 < 2.201 = t_{0.025,11}$

Since $|t_{03}| < t_{0.025,11}$ there is not enough evidence to reject the null hypothesis and it is therefore possible to conclude that assembly sets output under the MRPAS rule does not vary significantly when deterministic release of AS parts is compared with randomized parts release.

CASE 4 : AS output difference under FCFS

$$x_4 = \sum_{i=1}^{n} x_{4i} / n$$

$x_4 = 5/12$ $\qquad$ $x_4 = 0.41666$

$\Sigma x_{4i}^2 = 9$

$s_4 = \sqrt{((\Sigma x_{4i}^2) - x_4^2) / (n-1)}$ $\qquad$ $s_4 = 0.79296$

$|t_{04}| = |(x_4-0)/(s_4/\sqrt{n})|$ $\qquad$ $|t_{04}| = 1.820 < 2.201 = t_{0.025,11}$

Since $|t_{04}| < t_{0.025,11}$ there is not enough evidence to reject the null hypothesis and it is therefore possible to conclude that AS output under the FCFS rule does not vary significantly when deterministic release of AS parts is compared with randomized parts release.

10.5.5 Main conclusion

The deterministic release of the parts of an AS, adopted in the previous experiment does not introduce any significant difference in the FMS performance results when compared with the randomization of AS part release into the system.

10.6 FMS PERFORMANCE SENSITIVITY TO SYSTEM WORKLOAD UNDER DIFFERENT TOOLING CONFIGURATIONS

10.6.1 Objective

To study the interrelated influence on FMS performance of different work loads and tooling strategies.

10.6.2 Introduction

Typical management aims in operating FMS's are to achieve high system utilization and low job throughput time. These are usually seen as two objectives which pull in opposite directions .

Two factors which might affect the two performance measures are the amount of work released into the system and tooling strategies under which the FMS is operated.

10.6.3 Experimental Set-up

The system work load was studied for a number of levels, figure 10.6.1 under two different tooling configurations chosen from among the set of configurations under minimum tooling requirements shown in table 10.4.3.

The basic tooling configuration, TC1, was chosen together with the best performing configuration under experiment 1, phase 1, namely configuration TC14.

The FMS was set-up as in the first phase of experiment 1 and operated under the FCFS rule.

10.6.4 Results and Discussion

The results of the simulation experiment are summarized in figures 10.6.1 to 10.6.3.

It is clear that different work loading levels within the FMS do affect differently machine utilization and assembly set throughput time.

Generally machine utilization increases with system work load and tends to stabilize at a level dependent upon the tooling configuration. However the assembly set throughput time index, ASTTI section 10.1.1, keeps increasing as the load level increases. This pattern is the same for both tooling configurations although one of them, viz TC14, consistently exhibits considerably better average machine utilization, figure 10.6.1, throughout the whole range of the system work load. Up to the load used in the previous experiment corresponding to a level of 960 min, there is little difference in assembly set throughput time, figure 10.6.2, and also in work in progress, w.i.p., figure 10.6.3, for the two tooling configurations. At higher load levels the differences in each of the two measures for the two tooling configurations become greater. The difference in utilization under the two tooling configurations, is large and almost constant over the load range.

The results also show that with a load level of 960 min two highly different levels of utilization directly linked to the tooling strategy adopted, are obtained without noticeable differences in job throughput time and work in progress, figures 10.6.2 and 10.6.3.

The results suggest that before a given part mix is manufactured in an FMS operated under conditions similar to those of this experiment, the following steps should be taken:

1 -Determine the system loading level after which utilization does not increase significantly

2 -For that load level, check that the average job throughput time is acceptable according to manufacturing objectives.

3 -Choose the "best" performing tooling strategy.

4 -Run the FMS under the "best" tooling strategy at the system loading level determined in step 1.

5 -If condition 2 is not met, change the loading level to that which gives the desired throughput time. This results in a trade-off with utilization which, as a result of a reduction in loading level, tend to decrease.

10.6.5 Main Findings

1 -The loading level of 960 min, two shifts of work load, which has been adopted in the previous experiments is shown to be a reasonable value for the following reasons:

a)-The average system utilization tends to stabilize near this value,

b)-Assembly set throughput time and particularly w.i.p. start showing large differences for different tooling configurations after that loading level, and

c)-System utilization difference is almost constant over the load range. This allows the conclusion that the previous findings from the experimentation on tooling configurations are likely to be valid for a large range of workloads.

2 -A "good" tooling strategy gives better utilization over the whole range of system loading than does a "poor" strategy.

3 -Increase in machine utilization can be achieved in three ways:

a)-by increasing the loading level. However as machine utilization increases work in process and job throughput time also increases;

b)-by adopting better performing tooling strategies. In this case machine utilization can increase without increasing w.i.p. or job throughput time for a specific load level.;

c)-by adopting both steps a) and b).

4 -It is possible to identify a work load level, for each tooling configuration after which machine utilization is likely to be constant.

In addition any increase in workload beyond such a level tends to increase considerably both assembly set throughput time and work in process without having any noticeable benefits on machine utilization.

10.7 FULL TOOL REPLICATION IN MULTIPURPOSE MACHINES FMS'S-EXPERIMENT 4

10.7.1 Objective

The objective of this is to study system performance behaviour under maximum machine pooling, chapter 7, using the FCFS scheduling rule.

10.7.2 Introduction

When full tool replication is provided in every machine of an FMS then a Single Stage System results. This creates the simplest work flow system possible namely the single stage FMS[83]. Moreover not only is the maximum degree of machine pooling achieved but also, consequently, real-time maximum simultaneous alternative part routing is available.

In the previous experiments it was seen that it is possible to achieve good system efficiency with the minimum number of tools, without tool set duplication.

Other investigations[108] have suggested that pooling machines together increases FMS performance. This can be explained in part by the provision of a larger number of alternatives for assigning parts to machines.

10.7.3 Experimental Set-up

In this experiment maximum machine pooling is achieved by providing the identical machining centres of the FMS with identical tool groups. Each of these contains the tools to perform all of the manufacturing operations in the part-mix.

Apart from the tooling arrangements the FMS configuration, figure 10.7.1, is the same as the first experiment,phase 1, section 10.4.1.3.

Once tools are loaded at the initial stages of the FMS running period, no more tool loading/unloading is necessary. The assumption is made that tool life has been accounted for to achieve such an objective. In this situation, the tooling strategy is fixed i.e. the system contains a maximum number of tools.

10.7.4 Results and Discussion

Performance results under full tool replication can be compared with those under no tool set duplication which are summarized in table 10.4.3. In particular a comparison can be made with the performance under the best performing configuration, TC14 in table 10.4.3 for minimum tooling, figure 10.7.2.

Output of assembly sets for the planned period is the same for both cases. But full tool replication provides slightly better overall utilization. Synchronization of work flow is also slightly better for full tool replication. In fact although the same 6 AS output is obtained under both tooling configurations, for the 3 eight hour shifts running period, under the full replication case only one part type, namely part type 1, is preventing the AS output from reaching 7 AS while under TC14 the completion of 3 part types would be required to achieve the same objective.

This synchronization can be explained by the highest routing flexibility, provided under full tool replication, and also by the FCFS sequencing priority mechanism. This gives priority to parts of the assembly sets which are released first into the FMS. This priority determines the part flow which is not constrained by tooling under full tool replication. This is not the case under minimum tooling because tooling restrictions, in this case, tend to direct parts to certain machines, without alternative part routing. This is likely to delay parts which have high priority, i.e. from first assembly sets loaded, because alternative machines are not available.

For the configured FMS it is also noticed that the w.i.p., measured as the number of AS in process and the number of parts in process, figure 10.7.2 b) and c), is higher for full tool replication than for minimum tooling.

However the results show such small differences in performance between the two tooling configurations that it is difficult to state that, in this configured FMS and for the part mix considered, the full tool replication performs overall better than the minimum tooling strategy. It is however clear that only for very well performing tooling configurations, for the minimum tooling case, can the FMS performance approximate that obtained under full tool replication. Moreover, if high FMS performance is to be achieved under minimum tooling then a diversity of parts with different processing routes are required when running the FMS.

10.7.5 Main Finding

With full tool set replication and for the part mix and machine configuration used, there was little difference in machine utilization compared with the use of minimum tooling under the best tooling strategy. Also, output of assembly sets was identical. Moreover there is a larger average of w.i.p under full tool replication as figure 10.7.2 b) and c) suggests, than under minimum tooling.

Hence, operating FMS under complete machine pooling by providing every machine with all the tools for the running part mix does not necessarily guarantee better overall system performance than that which could be obtained operating the FMS under a tooling strategy which minimizes tool set duplication.

10.8 RESTRICTED TOOL DUPLICATION IN FMS WITH MULTIPURPOSE MACHINES CONSIDERING ALTERNATIVE PART MIXES-EXPERIMENT 5

10.8.1 Objective

The objective of this simulation study is to examine tool duplication strategies with alternative part mixes.

10.8.2 Introduction

One of the difficulties that usually arises in FMS is the determination of the minimum level of tool duplication for efficient system operation. Another is establishing tooling strategies using available tools which achieve high system performance. This experiment is concerned with these two aspects.

Four heuristic rules have been shown to perform well in defining tooling strategies for efficient FMS operation under minimum tooling i.e. with no duplication of tool sets, section 10.4.

A tool duplication heuristic rule, rule E, section 8.4.3.5, was also defined with the objective of minimizing tool duplication within FMS. This rule essentially proposes stepwise duplication of those tool groups which are highly utilized and are used to process parts which are restricting the output of completed assembly sets.

10.8.3 Experimental Set-up

The FMS physical configuration is identical to the one used in experiment 1 section 10.4.1.

Since the FCFS scheduling rule was shown in section 10.4.2 to perform worse overall than the MRPAS rule in meeting the FMS multiple performance objectives then the MRPAS rule is adopted in this experimental work.

10.8.3.1 Part Mixes

The experiment will be carried out for two part mixes:

-Part mix A and

-Part mix B

The structure of part mix A is shown in tables 10.8.1 and 10.8.2, which give quantities required per assembly set and part-operation processing times.

The parts of part mix A, which are also considered to be prismatic, are clamped onto six fixtured pallets in the configuration shown in figure 10.8.1.

For mix A six basic tool groups are defined, table 10.8.3, which correspond to the part-operations grouped for processing on each of the six pallets.

Part mix B is the one used in experiment 1, and data related to this mix is shown in tables 10.2.1 and 10.2.2 and figures 10.2.2 and 10.2.3 .

10.8.4 Results and Discussion

10.8.4.1 Part Mix A

<u>FMS performance under no tool set duplication.</u>

From figure 10.8.2 it can be seen that average machine utilization is low and that output of assembly sets is restricted due to low workpiece parts ratio, WPR, of part type 1.

Analysis of the results in conjunction with the tool duplication heuristic rule E indicates that the first basic tool group should be duplicated, because it is very highly utilized and required to process part type 1 with the lowest WPR.

FMS Performance Under Tool Duplication

The results show a considerable improvement in system performance by simply duplicating the 1st basic tool group. The resulting tooling configuration TC2 shown in both table 10.8.4 and figure 10.8.3 includes a new, 7th tool group, identical to the 1st.

It can be seen that machine utilization increased from 0.672 to 0.800, i.e. improved by an absolute value of 0.128 corresponding to a relative increase of 19.05%. The increase of assembly sets output during the three eight hour shift running period was even larger, namely from 3 to 5 AS's corresponding to a relative increase of 66.7%.

Additional searching for new configurations, without altering the level of tool duplication, by applying tool group combination rule A, shows it to be possible to improve still further the FMS performance. Thus average machine utilization could have an additional increase of 0.073 corresponding to an increase of 9.13% in relation to the initial tooling configuration under tool duplication, namely configuration TC2 of table 10.8.4.

Output of assembly sets is shown to be less sensitive to tool configuration. It actually did not change in spite of improved utilization.

By extending still further the search for new tooling configurations using now the ungroup-regroup rule D, utilization was taken to 0.929 for a 5 assembly set output. This means that there was an increase in processed work but not enough to complete further assembly sets within the running period. This was only achieved for tooling configuration TC9, obtained through further application of rule D, which produced the highest assembly sets output, namely six, and practically the highest machine utilization possible , namely 0.924.

Relative to the basic tooling configuration twice the number of assembly sets are produced and the average machine utilization also increased from 0.672 to 0.924 i.e. an increase of 37.5%.

Such improvements were achieved in two ways:

1 - by restricted and controlled tool duplication,

2 - by searching for good tooling configuration through the application of heuristic rules.

The rules behaved well in establishing tooling strategies for efficient FMS operation. In particular the ungroup-regroup rule once again has shown consistency in developing efficient tooling strategies.

10.8.4.2. Part Mix B

A considerable number of tooling configurations were developed in experiment 1, section 10.4.1.4, for part mix B.

It was possible to show that a high level of FMS performance could be obtained without tool set duplication table 10.4.3. Therefore the scope for improving tooling strategy through tool duplication, is small in this case. Nevertheless, it is important to know if under such circumstances tool duplication has some impact.

By using the tool duplication rule an attempt was made to improve FMS performance beyond that obtained under the most efficient tooling configuration namely configuration TC14 of table 10.4.3, section 10.4.1.4. Since the lowest WPR is that of part type 1 and the most utilized basic tool group for this part is BTG No.1 than this tool group is duplicated. The resulting tooling configuration is TC14 plus BTG No.1 which contains tool sets 1 and 2.

The results, figure 10.8.4, show that overall performance under tool duplication has not improved.

This lack of improvement in performance can be explained by the fact that under no tool duplication, tooling operational configurations were found which practically achieved maximum FMS performance.

10.8.5. Main Findings

1 -Tool set duplication, within FMS's, for efficient operation is primarily dictated by part mix processing requirements.

2 -Under some part mixes there is no significant advantage in duplicating tools in different machines although they are able to process identical operations. It is therefore necessary to identify which tools should be duplicated, if any, to guarantee high system performance.

3 -The methodology presented for identifying the minimum quantity of tools and their type as well as to design good tooling configurations, based on the simultaneous use of both a set of heuristic rules and the simulation model developed, has been proved to achieve good results. Thus it is possible to identify the tools which must be duplicated as well as to define tooling configurations to run FMS's which guarantee high system performance.

4 -It was shown that the "tool ungrouping-regrouping" heuristic rule D helps to generate high performing tooling configurations even when applied to the best tooling configurations formed by other heuristics.

10.9 MINIMUM TOOLING REQUIREMENTS FOR FMS WITH LIMITED PURPOSE MACHINES-EXPERIMENT 6

10.9.2 Objective

For the sake of clarity this experiment will be divided in two phases. In the first one this work investigates whether the conclusions from the study on tooling strategies for FMS with multipurpose machines can or cannot be extended to FMS's with more specialized machining stations and therefore to potentially less flexible systems.

In particular, at this stage, the case of efficient system operation without tool set duplication will be analysed.

Thus tooling configurations will be developed based on the same heuristics developed in section 8.4.

In the second phase the problem of FMS balancing is raised and the ungrouping-regrouping heuristic rule will be applied to seek improvement of the results from the first phase.

10.9.2 Introduction

The set of experiments previously carried out have considered that the machining stations within the configured FMS's were identical or at least similar enough, provided tools were available, to perform any processing operation in a scheduled part mix. The findings may be only applicable to very versatile FMS's. Therefore it is pertinent to investigate whether or not the methodology to generate tooling configurations for system operation under different control strategies can successfully be extended to less versatile FMS's and whether the general conclusions of previous experiments can also be applied to these systems.

10.9.3 Phase 1-Use of Heuristic Sequential Rules Only

10.9.3.1 Experimental Set-up

FMS Physical Configuration

A model of a four machining station FMS will be configured comprising two groups of machines each with limited purpose machining capabilities. Each machine in the group is only able to process a restricted number of operations on the part mix.

Each of the two different groups have two identical machines, i.e. machines which can process the same restricted range of operations. A schematic representation of the configured FMS is shown in figure 10.9.1.

Tools

The same eight basic tool groups without duplication, adopted in experiment 1, section 10.4, will also be used. There is however an essential difference. Tool groups are restricted to particular machine groups as figure 10.9.1 illustrates.

Because there are no duplicated tool sets, no two machines can simultaneously provide a processing destination for a given part operation, i.e. simultaneous alternative part routing is not available.

Part mix

The nine part types described in section 10.4 are adopted in this experiment. As before, parts must be manufactured so as to provided a steady outflow of finished assembly sets.

Other Aspects

All other aspects of the model, i.e. palletisation structure, system configuration and system operation are as in experiment 1, section 10.4.

Two heuristic tool group combination rules were used, namely the "lowest to highest output parts ratio", rule B and the "highest to highest output parts ratio, WPR", rule C.

These have been shown to perform well in establishing tooling strategies which lead to high system performance.

Some of the tooling configurations were obtained by successive iterations using the scheduling rule MRPAS, (Minimum Remaining Parts in Assembly Set), and others the FCFS rule, section 10.4.1.3 .

10.9.3.2 Results and Discussion

A total of thirteen tooling configurations, table 10.9.1, were defined with the help of the heuristics and simulation model. Thus TC2 to TC9 were developed using tool heuristics B and C and FMS operation under the FCFS rule. The TC10 to TC13 configurations were obtained by applying tool heuristic B and operating the FMS under the MRPAS rule.

All of the tooling configurations obtained were then tested using the two scheduling rules, i.e. under MRPAS and FCFS. The tooling configurations and all associated performance results under the two scheduling rules are shown in table 10.9.1.

Figure 10.9.2 and 10.9.3 are graphical representations of the two FMS performance measures. The results show that both heuristic tool group combination rules perform well. They lead to tooling configurations which can provide not only good levels of system utilization but also a high number of finished assembly sets for the running period.

However, some of the configurations developed under the FCFS scheduling rule, figure 10.9.2 do not perform well in terms of assembly sets output, for it is seen that with some tooling configurations a very low number of assembly sets is finished during the running period. We can therefore conclude that the FCFS rule in conjunction with the two heuristics does not show consistency in generating tooling configurations which can provide for good overall FMS performance.

A similar analysis under the MRPAS rule, figure 10.9.3, shows that this rule is more consistent in helping to generate tooling configurations which in general perform well. These also perform well when the system is operated under the FCFS rule.

Conversely, it is seen that tooling strategies that give poor assembly sets output under the FCFS rule perform well under MRPAS giving good levels of assembly sets output.

It appears that FMS performance is firstly restricted by the tooling configurations adopted but, in this case, is also very sensitive to the scheduling rule used.

10.9.3.3 Main Findings

1 -The findings obtained under experiment 1, section 10.4.2.4 can in general be extended to less versatile FMS.

2 -For this case FCFS and MRPAS scheduling rules can have markedly different influences on system performance. With limited purpose machines it appears that the scheduling rules show larger performance differences than with highly versatile FMS systems, section 10.4.1.4.

3 -Although tooling strategies can be seen as a major limiting factor to the level of performance which an FMS can achieve, it was shown, in this case, that it is under the MRPAS scheduling rule that the best potential performance under most of the tooling strategies can be realized.

10.9.4 Phase 2 - Seeking Maximum Performance Through the "Ungrouping-Regrouping" Tool Combination Heuristic Rule

10.9.4.1. Objective

The objective of this phase of the study is to investigate the extent to which new tooling configurations, without tool set duplication, can be generated through the use of the ungrouping-regrouping tool combination heuristic rule D, section 8.4, which can perform better than the configurations already developed, table 10.9.1, in phase 1 of this simulation experiment.

It is also intended to evaluate the effectiveness of the heuristic in leading to high performing tooling configurations, under no tool set duplication, for FMS with limited purpose machines.

10.9.4.2. Experimental Set-up

The results of the first phase of the study have indicated that generally the MRPAS scheduling rule is better than the FCFS rule in meeting the two FMS performance objectives, namely high FMS system utilization and high output of assembly sets for the FMS running period. For this reason only the MRPAS will be used.

In all other aspects of FMS operation and physical configuration the experimental set-up is identical to that used in the first phase.

10.9.4.3. Results and Discussion

Table 10.9.2 shows the results under tooling configurations TC14 and TC15 developed as a result of applying the Ungrouping-Regrouping heuristic tool combination rule, rule D, to tooling configuration TC13. The sequential tool group combination process that led to the generation of the tooling configurations TC10 to TC13 of table 10.9.1, is represented in figure 10.9.4. The figure also shows configurations TC14 and TC15.

Application of rule D led to tooling configurations which offer considerably better machine utilization than any previously generated configuration. Moreover the assembly sets output remain reasonably high at four finished assembly sets.

Influence of FMS Work Load Balancing on System Utilization

It can be argued that although better performing tooling configurations were obtained through the application of rule D, the 0.835 utilization value for the best performing configuration, TC15, figure 10.9.4, can be considered low when compared with the maximum of 0.957 which was obtained under full tool replication for the multipurpose machines FMS, section 10.7 . However there is a constraint which limits the maximum utilization which can be obtained. This limitation is imposed by the work imbalance within the FMS as explained below.

Normalized Machine Utilization

Figure 10.9.5 is a similar representation of the results shown on figure 10.9.4, with the difference that a normalized utilization measure has been used.

The normalized utilization is a relative value determined on the basis of the degree of balance, section 10.1.1, or maximum theoretically possible machine utilization, UT, for a given scheduled part mix or assembly sets mix.

To achieve a balanced output of sets, one machine or in this model, one group of machines will be fully utilized whilst, due to the scheduling of assembly sets, the other group will not be fully loaded. This situation will always arise when the workload balance between parts is not perfect.

In the case of the configured FMS in this study, set-up to manufacture assembly sets with nine different parts and a total of 21 different processing operations, the degree of balance is 0.876 as shown, table 10.9.3.

The normalized utilization values associated with each configuration in figure 10.9.5, were obtained as the relationship between the absolute machine utilization and the degree of balance as illustrated in table 10.9.4.

It is now clear that almost maximum possible machine utilization was obtained for at least one of the two tooling configurations generated through the use of the "ungrouping-regrouping" tool group combination heuristic rule. The greatest improvement in utilization relative to the initial configuration, TC1 , figure 10.9.5, is:

$$100 * (0.953 - 0.837)/0.953 = 12.2 \%$$

On the other hand the utilization improvement relative to the best configuration obtained by applying the "Least to Highest Parts Ratio" rule, TC13, is:

$$100 * (0.953 - 0.90)/0.953 = 5.6\%$$

10.9.4.4. Main Findings

1 - The ungrouping-regrouping tool group combination rule has been shown to perform better than any other rule. This has also been verified for two differently configured FMS's. It seems highly likely that the rule is

consistent in generating tooling configurations which lead to high FMS performance.

2 - Very high FMS machine utilization was obtained under no tool set duplication. It is concluded that the scope for improvement through either full tool replication in every machine within the machine group or restricted tool duplication is small.

In these circumstances it would be reasonable to recommend FMS operation under minimum tooling because good system performance could be obtained under particular tooling strategies.

3 - Another important conclusion from this experimentation is that the degree of balance of an FMS, section 10.9.4.3, can be a limiting factor on the level of machine utilization that can be expected from an FMS.

A method was devised, table 10.9.3, to determine that degree of balance which is essentially dependent on part mix processing requirements in relation to the alternatives for work assignment to machines.

4 - If high FMS utilization is desired it is essential that a part mix is found for which the degree of balance of the FMS, is high. At best it should be 1.

This fact however must be combined with the use of good tooling configurations otherwise the potential utilization is not realized.

10.10 MAXIMUM TOOL REPLICATION IN FMS WITH LIMITED PURPOSE MACHINES-EXPERIMENT 7

10.10.1 Objective

The objective of this experiment is to evaluate the performance resulting from full tool replication in each of the machines within a group as compared to the minimum tooling situation.

10.10.2 Experimental set-up

The physical and organizational FMS set-up is identical to that of the previous experiment, section 10.9. Differences concern only the amount of tools which can be provided simultaneously in every machine.

In the previous experiment, section 10.9, an FMS was set-up with two different groups of limited purpose machines. Moreover the system was run under minimum tooling. That FMS configuration contained the most restrictive part routing situation considered in this work. Increased part routing flexibility of the FMS can be provided through the tooling system.

Since there are two different groups of identical machines then tools may be provided at each machine in a group in such a way that simultaneous alternative part routing is available. This means that any part-operation which is required to be performed in the machine group may be processed in either of the machines of the group.

In this experiment the tools for processing the part-operations mix which can be assigned to a machine group are all available in any of the machines of the group, i.e. full tool replication in each of the machines is provided.

10.10.3 Results and Discussion

The results, figure 10.10.1, show that total machine utilization under full tool replication is only slightly better than that obtained for tooling configuration TC15 under minimum tooling.

Individual machine utilization within each group is almost identical in the full tool replication case. This is not the case for the other tooling configurations. Thus a more balanced use of machine resources is achieved as a result of using full tool replication in the machines of each group. This is because for the full replication case the maximum possible alternative part routing is provided. Under these circumstances there is a high likelihood of a similar amount of work to be assigned to each machine in the group during the running period.

The imbalance in workload between the two groups is again evident. Utilization values, figure 10.9.4, shows that, when compared with the values in table 10.9.4, virtually maximum utilization is achieved in both machine groups for TC15 under minimum tooling and with full tool replication. Based on utilization alone tool replication cannot be justified.

However, if throughput of finished sets is considered then full tool replication does allow rapid throughput of sets of parts, in this case 5 sets compared to 4 without replication.

Therefore under the experimental set-up adopted, for the limited purpose machining stations case, full tool replication leads to an overall better performance.

Examination of the detailed parts output, based on parts ratio,WPR, shows that in the case of full tool replication only part 1 is preventing 6 assembly sets being completed while for the other tooling configurations there are a larger number of parts contributing to that situation, figure 10.10.1 .

Thus, under minimum tooling there is a worse balance of parts output towards finishing assembly sets and slightly worse FMS machine utilization than under full tool replication. This can be explained by the restrictions that minimum tooling and tooling configuration design are likely to impose on the way that the work flows within the FMS. If a machine becomes free, it may not be able to load work contributing to completion of a set because the tools are already in use in another machine. This limitation will never happen under full tool replication.

10.10.5 Main Findings

1 - Full tool replication within machine groups has been shown to perform well in a limited purpose machines FMS.

2 - Full tool replication provides the best opportunity for the best performance of such a system. However, this performance can be approached with limited tooling.

3 - Under full tool replication a more balanced use of machine stations can be achieved.

10.11 TOOL DUPLICATION WITH LIMITED PURPOSE MACHINES FMS'S-EXPERIMENT 8

10.11.1 Objective

This experiment is set-up to study the performance of an FMS with limited purpose machines operated under restricted tool duplication for processing different part mixes.

10.11.2 Experimental Set-up

This experiment is equivalent to experiment 5, section. 10.8, but considers that machining centres are limited purpose. Thus the FMS physical configuration is identical to the one used in experiment 6, section 10.9.3, figure 10.9.1.

Tool duplication is controlled by applying the tool duplication heuristic rule, rule E, section 8.4.3.5. As previously mentioned, this rule duplicates highly utilized tool groups used to process parts which are restricting output of finished assembly sets.

Other aspects of experimental set-up are identical to those of experiment 5.

The MRPAS scheduling rule used in experiment 5 also used here.

Part Mixes

The experiment will be carried out for the two part mixes:

- -Part mix A and
- -Part mix B

as described in section 10.8.3.1.

10.11.3 Results and Discussion

10.11.3.1 Part Mix A

FMS performance under no tool set duplication.

The performance of the configured FMS operated under no tool duplication is shown in figure 10.11.1.

It can be seen that average machine utilization is low and that output of assembly sets is constrained by the low workpiece ratio of part type 1.

Analysis of the results in conjunction with the tool duplication heuristic rule E indicates that the first basic tool group should be duplicated.

FMS Performance Under Tool Duplication

The performance of the configured FMS operated with the 1st. tool group duplicated, is compared for a number of different tooling configurations, table 10.11.1.

The results show a considerable improvement in system performance by simply duplicating the 1st basic tool group. This originates tooling configuration TC2 which includes a new, the 7th tool group, identical to the 1st.

With TC2 it can be seen that machine utilization improved by an absolute value of 0.056 corresponding to a relative increase of 8.3%. AS output did not increase. This can be explained in two ways. First because with the basic tooling configuration TC1, table 10.11.1, a good level of output of sets was already obtained, namely 4 sets. This together with the fact that three parts of type 1, requiring a total processing time of 390 min, i.e. 6.5 hours, are necessary for each new AS indicates that the scope for improving AS output is small. Second, to manufacture such parts the machines cannot be producing other parts and therefore the output of parts of other types, required to assemble a set, is likely to decrease.

Additional searching for new configurations, without altering the level of tool duplication, bu by applying tool group combination heuristic rule B, has shown that it is possible to further improve the FMS performance. Thus the average machine utilization had an additional increase of 0.052 corresponding to a relative increase of 7.14% in relation to the performance of configuration TC2. Output of assembly sets was also improved from 4 to 5. It appears we can say that a good balance of the use of manufacturing equipment towards finished AS was obtained.

If a comparison with the maximum possible utilization is made, it can be concluded that practically maximum utilization was achieved under tooling configurations TC4 and TC5, table 10.11.1. The maximum theoretical utilization, imposed by both part mix and machine grouping structure, is 0.81, table 10.11.2. Therefore the normalized utilization under TC4 is

$$\frac{0.78}{0.81} = 0.96 .$$

Thus there is little scope for further improvement.

Again it is seen that a better use of FMS capacity could be obtained if there was a more balanced part mix, i.e. a part mix which created a better balanced work load among the machine groups of the FMS.

Compared with the performance of the basic tooling configuration the greatest improvement in the average performance values of the configured FMS is 25% for assembly sets output, i.e an extra set relative to the initial 4, and 16% for average machine utilization, i.e

$$\frac{0.78-0.672}{0.672} * 100 = 16\%$$

These improvements were achieved in two ways:

1 -by restricted and controlled tool duplication,

2 -by searching for good tooling configuration through the application of heuristic tool combination rule B.

The two rules behaved well in establishing tooling strategies for efficient FMS operation.

10.11.3.2. Part Mix B

For this part mix it was shown that even under limited purposed machines high level of FMS performance could be obtained without tool set duplication, tables 10.9.3 and 10.9.4. Therefore the scope for improving tooling strategy through tool duplication is small. Nevertheless, it is important to know if under such circumstances tool duplication has some impact.

By using the tool duplication rule, section 8.4.3.5, an attempt was made to improve FMS performance beyond that obtained under the two most efficient tooling configurations namely configuration TC14 and TC15 of table 10.9.2 section 10.9.4.

Thus since for TC14 the lowest WPR is that of part types 7, 8 and 9 then only the basic tool group, BTG, for these parts , namely BTG No.8, is duplicated. The resulting tooling configuration is TC16, table 10.11.3. The application of the sequential tool combination process, through heuristic rule B, leads to TC17 for which FMS performance is close to that under full tool replication.

If the basis for tool duplication is TC15, the same BTG No.8 should be duplicated leading to TC18 for which FMS performance is literally identical to that obtained under TC15, i.e. the duplicated tool group was not used. The application of the sequential tool combination heuristic rule B suggests that the combination of the duplicated TG with the BTG No.1 leading to TC19. Part ratios Table A3.7 of the previous lowest WPR parts did in fact improve but WPR of part type 1 was considerably lowered. This was to some extent expected because one of the two machines of the MGI , which was dedicated to manufacture part type 1, would have now to share processing with parts 5 to 9. Additionally, output of parts of types 6 and 7 was increased although this did not contribute to improved AS output.

Application of the tool duplication rule to TC15 also suggests that only the tool sets for parts in highest demand, i.e. lowest WPR parts may need to be duplicated. This originates TC20, table 10.11.3, for which FMS performance is practically identical to that obtained under full tool replication.

This clearly shows that when maximum FMS performance is not obtained under minimum tooling, it is possible to closely approximate performance to that obtained under full tool replication through controlled and restricted tool duplication of basic tool groups or only some of their basic tool sets.

The results show that for less flexible FMS, by duplicating particular tools performance can be improved. This was not so clear, under part mix B when the highly flexible FMS was used at experiment 5. It appears that compensation for reduced flexibility of FMS machines may to some extent be achieved through some restricted tool duplication, provided the FMS configuration allows pooling of machines, section 6.1.3.

This may be explained by the fact that some of the flexibility in part routing lost due to limited purposeness of the machines can be gained through pooling machines within each machine group provided by duplication of some tool sets.

10.11.4. Main Findings

1 - The strategy of controlled tool duplication produces similar results when applied to both highly flexible FMS, which use multipurpose machines, and less flexible FMS configured with limited purpose machines. However tool duplication is likely to be more advantageous as routing flexibility of FMS's decreases provided machine pooling is still possible.

2 - The amount of tool duplication is primarily dictated by part mix processing requirements and it is necessary to identify which tools should be duplicated, if any, to guarantee high FMS system performance.

3 -Tools which should be duplicated to achieve high FMS performance can be identified through the methodology used.

4 - It was also shown, that the particular heuristic choice of the tools to duplicate, together with heuristic tool grouping can provide a better balanced output and improved machine utilization relative to the best performing tooling configurations under minimum tooling, viz TC14 and

TC15. In particular there may not be a need to duplicate all tool sets of a particular basic tool group, but only some of its basic tool sets corresponding to the parts with the lowest WPR, as TC20, first tool group, table 10.11.1 illustrates.

5 - Due to the part mix and machine grouping structure a limit may be imposed on FMS performance. It was found that the maximum possible average machine utilization was 0.810, table 10.11.2, and that on average MGII could not be utilized beyond 0.62.

6 - It can also be concluded that the restriction in FMS performance referred to above can only be overcome by changing the part mix for the FMS running period in such a way that a better balancing of work load among the groups of machines can be achieved. This conclusion points to the possibility of increasing machining capacity in the most utilized machine group which may have the effect of pulling up utilization of under utilized machines of other groups increasing therefore average machine utilization and also AS output. Such a proposal would need to be tested by experimentation.

10.12 RELATIONSHIP BETWEEN ASSEMBLY SET BATCH SIZE, TOOLS AND PALLETS-EXPERIMENT 9

10.12.2 Objective

To investigate the effect of assembly set batch size and numbers of pallets on system performance in a multipurpose machine FMS, operated under different tooling configurations and different scheduling rules.

10.12.2 Introduction

FMS systems in general, and those for prismatic parts manufacture in particular, are suitable for assembly set production, ASP, section 4.1, and it is pertinent to ask what should be the adequate Assembly Set Batch Size, ASBS, to adopt. ASBS is defined as the number of identical assembly sets which would be released together, with the same priority, into the FMS. This simulation study is set-up to investigate the influence of ASBS on FMS performance measures.

Pallet availability will also affect FMS performance. This part of the work also includes an investigation aimed at assessing their effects.

Since there are likely to be variations in performance related to the scheduling rule adopted, this experiment incorporates both the FCFS and the MRPAS rules.

10.12.3 Experimental Set-up

The FMS system configuration is identical to the one used in the experiment 1, i.e. multipurpose machines. The experimentation here carried out will however consider three different tooling configurations, table 10.12.1, namely the basic tooling configuration TC1, full tool replication TC3, and a tooling configuration TC2, under no set tool duplication which previously had been shown to perform well, i.e. number fourteen of table 10.4.3.

In this experiment the ASBS was varied between 1 and 12 in steps of 1 and the number of identical sets of fixtured pallets between 1 and 4 in steps of 1.

The FCFS rule is used at the first stage and the MRPAS rule at the second stage of the study.

Since 12 ASBS levels will be considered for 3 tooling configurations under 4 different sets of fixtured pallets a total of 12 x 3 x 4, namely 144 computer simulation runs will be carried out for the first phase analysis of the experiment under the FCFS rule.

At the second phase, based on the previous runs only a further half of this total will be run under the MRPAS rule.

10.12.4 Results and Discussion-1st Phase-Use of FCFS Scheduling Rule Only

Maximum Tooling Restrictions - No Tool Set Duplication

Figure 10.12.1. shows that under the basic tooling configuration, TC1, there is an upwards trend in machine utilization for all pallet levels used. For tooling configuration TC2 the behaviour of machine utilization is somewhat different. Although with a single set of pallets utilization increases slightly with ASBS, it is practically constant for two and three set of pallets and exhibits the opposite behaviour for the maximum number of sets of pallets considered.

A possible explanation for this behaviour is the small size of the central store for palletised work, namely thirteen pallet places, section 10.2.2, combined with the control strategies at the palletising stations, chapter 9. Thus a situation is likely to occur in which, for a considerable part of the manufacturing period, many identical parts become available for processing, which may require tools only available on particular machines. These become bottlenecks, while other machines may be waiting for work which, although available cannot be loaded into the central store area from where it can be fed into the system due to storage space limitations.

This is also likely to happen due to the simultaneous influence of high ASBS and high number of identical pallets available contributing to an excessive number of identical parts in the system requiring the service of tools available on certain machines only. The situation does not occur with the basic tooling configuration, TC1 because higher flexibility of part routing to machines is provided due to the availability of a much larger number of tool groups, namely eight, as compared to only four tool groups for the tooling configuration TC2, for the same total number of tools available. Thus, under the basic tooling configuration, for each four tool groups loaded into the four machining centres a further four tool groups are available under the basic tooling configuration while none is available under tooling configuration TC2, which is made up of only as many tool groups as there are available machining centres.

Unrestricted Tooling Conditions - Full Tool Replication in Every Machining Centre

The results, figure 10.12.2, show that if maximum tooling facilities are available, namely full tool replication at machines, than machine utilization increases for the single set of pallets case. However, for two or more pallet sets the utilization is high and practically constant at 0.96.

Moreover, as ASBS increases throughput time also increases, figure 10.12.4. Thus best operating conditions would be obtained under low batch size.

The influence of the number of pallets

For the tooling configurations studied there is a considerably lower utilization with the single set of fixtured pallets than with the other pallet levels figures 10.12.1. and 10.12.2. However, increasing the number of sets of pallets beyond two does not cause any significant change in machine utilization except for large ASBS and four sets of fixtured pallets with tooling configuration TC2.

For full tool replication and to a lesser extent for tool configuration TC2, figures 10.12.3 and 10.12.4, the number of pallets has little effect on throughput time for low assembly set batch sizes, ASBS. As ASBS increases the assembly set throughput time index, ASTTI, tends to increase. This tendency is also observed as the number of pallet sets increase. For some of the highest ASBS's, no assembly sets are finished within the manufacturing period, i.e. ASTTI becomes very large. In these cases ASTTI could not be calculated and this corresponds to the missing points in the figures.

For the case of the basic tooling configuration, figure 10.12.3, the ASTTI behaviour is different. It is almost identical for the whole ASBS range when two or more sets of fixtured pallets are used but it is considerably higher for the single set of pallets case. Moreover for an ASBS of four, there is a tendency for a lower value of ASTTI than for an ASBS of three which is particularly apparent for the one set of pallets case. This behaviour is likely to be related to the fact that four multipurpose machining stations are used in conjunction with numbers of pallets available which are multiples of four. This result although apparently logical was not envisaged. This shows that in FMS it is difficult to predict and fully understand the many important dynamic and complex interrelationships between the parameters involved.

Work in progress is plotted in figures 10.12.5 and 10.12.6 and, as it could be expected its behaviour is similar to the behaviour of the ASSTI.

The results further reinforce the previous conclusion of best operating conditions for low batch sizes.

The effect of Tooling Configuration Design and Tool Restrictions

Analysed in relation to ASBS and pallet levels it can be seen, figures 10.12.7, that under the basic tooling configuration machine utilization is generally low when compared to that which can be obtained with the same tooling resources under tooling configuration TC2. The differences are large for the whole ASBS range where a single set of fixtured pallets is used, figure 10.12.7 a). Above this number of pallets the differences are larger for lower batch sizes, figure 10.12.7 b), c), and d). For the 4 pallets case, TC2 behaves differently at the upper range of ASBS with average machine utilization decreasing as ASBS increases. The reasons given earlier relative to figure 10.12.1 explain this behaviour.

With exception of the 4 pallets case machine utilization values obtained under tooling configuration TC2 closely compare with those obtained under no tool restrictions, TC3, for most of the range of ASBS and pallet levels, figure 10.12.7. Thus it can be said that as long as good tooling configurations are designed under minimum number of tools then tool restrictions may not be a significant constraint to FMS performance. However if bad tooling configurations are used than considerable FMS efficiency can be lost.

10.12.4.1. Main Findings - 1st Phase (General Analysis)

1 - No particular optimum ASBS was found for machine utilization. However ASBS of one can provide both good utilization and the lowest assembly set flow time. In this sense it can be considered optimum.

2 - The influence of the number of sets of fixtured pallets available in the system is only visible up to a particular level after which no clear improvement in FMS utilization can be expected.

3 - This level can be determined through the use of the simulation model. For the configured FMS two sets of pallets, accounting for a total of sixteen pallets are sufficient for achieving practically the best performance under all of the varying tooling strategies investigated. Therefore this could be considered the optimum number of pallet sets.

4 - Although machine utilization is in general best for the situation under full tool replication, good utilization is also obtained under the other two tested configurations which do not include tool duplication, figures 10.12.1 and 10.12.2

10.12.4.2. Analysis of Production Synchronization Ratio

Production Synchronization Ratio (SR) is the relationship between the number of assembly sets which are actually finished during the FMS running period and the number which could theoretically be obtained on the basis of the level of machine utilization and the machining requirements per assembly set, section 10.1. A graphical representation of the SR for each of the pallet levels, is shown in figure 10.12.8.

By comparing the four graphs, a) to d), i.e. from 1 set to 4 sets of fixtured pallets it can be seen that in general the value of the SR ratio increases at high ASBS values for tooling configuration TC1. With the other tooling configurations, in particular TC3, the converse is true, i.e. at high ASBS the SR decreases as the number of pallets increases. This shows that in general with the basic tooling configuration, TC1, increasing the number of pallets causes the SR to improve as ASBS increases. The opposite tends to happen with the other tooling configurations, i.e. increasing the number of pallets causes the SR to worsen as ASBS increases.

In general a single set of fixtured pallets would be sufficient to operate the FMS under all tooling configurations tested dependent upon the ASBS value. Under TC1 ASBS's of 5 and below should be used. For these ASBS levels the other tooling configurations also perform well.

However to achieve both good SR and machine utilization, figure 10.12.7, for reduced investment on pallets and fixtures then two sets of fixtured pallets would be recommended for all tooling configurations within that low ASBS range.

There is also what may be seen as a cut-off ASBS for most of the situations, figure 10.12.8, associated with the fact that the SR ratio become zero at that ASBS and above. This means that during the FMS running period of three eight hours shifts no assembly set was completely finished. In other words, the assembly set throughput time is becoming particularly long. This situation is a consequence of the likely routing of too many identical parts in sequence instead of the routing of a good part type diversity as required for high SR.

Under the basic tooling configuration this behaviour is likely to be reinforced by the controlling mechanism to save tooling set-ups at the machines. In the other cases this is more likely to happen only because too many identical pallets are available. This is particularly evident for the full tool replication case, which allows simultaneous processing of identical parts in different machines, figures 10.12.8 c) and d).

10.12.4.3. Main Conclusions

1 - Good SR and machine utilization can be obtained at low ASBS values, say between 1 and 5, for all the tooling configurations simulated. This performance can be achieved for a low number of pallets, in this case two identical sets of pallets, i.e. a total of sixteen pallets.

2 - There is a number of pallet sets above which, for the same tooling configuration, utilization does not improve significantly. Under minimum tooling it can worsen as it is shown for TC2, figure 12.1. In this series of experiments this number of pallet sets is two. For the full tool replication

case, utilization is practically constant not only for a number of pallet sets larger than one, figure 10.12.2, but also for most of the range of ASBS.

3 - To keep machine utilization high a single set of pallets is not enough. Under this condition utilization is low when compared with the cases of moderate or high number of available pallets, figures 10.12.1 and 10.12.2.

4 - In general low ASBS provides both reasonably high SR, low ASTTI, low WIP and high FMS utilization, figures 10.12.4 to 10.12.8. This is particularly so when the non basic tooling configurations are used.

10.12.5 Results and Discussion - 2nd Phase - Relative Behaviour of the FCFS and MRPAS Scheduling Rules

From figure 10.12.9 it can be seen that the MRPAS scheduling rule does give a high production synchronization ratio under the basic tooling configuration and for a single set of fixtured pallets at practically all levels of ASBS. Under identical conditions, the FCFS rule has a cut-off assembly set batch size of 8 at which the SR falls to zero.

The results show that the MRPAS rule behaves as was intended, i.e. it achieves high output of completed assembly sets.

However, when three sets of fixtured pallets are available, the advantages of the rule as compared to FCFS are only apparent in the region of relatively small ASBS, figure 10.12.10. At higher values of ASBS the performance of the two rules are identical. Thus the number of sets of identically fixtured pallets does greatly affect the flow of work through the system.

These results highlight the complex nature of the design and operation of FMS's, in particular the interactions between resources and operating rules. Work flow is determined by the available options of assigning pallets to machines and these options are related to the number of pallets available and the assembly set batch size. For instance, when a low number of fixtured pallets is used, the parts belonging to highest priority assembly sets based on the MRPAS rule are clamped first and processed on the machines. Only when processing finishes can parts of other sets of the same type be palletised because only then do the pallets become available. At this stage the MRPAS rule once again chooses the parts belonging to the highest priority sets which will mean that it is necessary to refixture the semifinished part which has just been unclamped either in the same fixtured pallet but in a different location or in a another available fixtured pallet, if this is required, and reroute it to a machine before any other part, even of an assembly set with the same initial priority.

However, when a larger number of identically fixtured pallets is available they will be routed, with parts clamped on them, in succession to the machines. When a pallet with semifinished parts is unloaded from a machine these parts do not take priority over parts already loaded onto the machine buffer, even though they belong to the highest priority set and have reached the state of processing second operations. This manufacturing control procedure is not designed to do that, i.e., to unload pallets already loaded at machines or on machine buffers or make the machine wait for part reclamping before the parts on the next, and most possibly identical pallet, already loaded onto the machine or buffer, are machined. Therefore with the larger number of identically fixtured pallets, it is very unlikely that a semifinished part is reassigned and reloaded to a machine before any other part.

This mechanism tends to increase the flow time of assembly sets and therefore the number of sets which can be completely finished within the planned manufacturing period of three eight hour shifts is affected. This seems to explain why under a single set of fixtured pallets the MRPAS rule produces a high synchronization ratio and with more sets, for instance three, it does not.

The fact that for three sets of fixtured pallets the MRPAS rule does show an improved production synchronization ratio relative to the FCFS rule but only at very low ASBS can be similarly explained. Thus, when ASBS is small, particularly of size one, there will not be many parts of different assembly sets clamped ready to be loaded in succession to machines and hence the MRPAS rule plays again a stronger role in determining the work flow within the system.

Although the tendency for improved SR by using the MRPAS, rule rather then the FCFS, is also noticeable under other tooling configurations, figures 10.12.12 to 10.12.14, the differences are less striking than under the basic tooling configuration. For the case of tooling configuration TC2 and a single set of fixtures, the SR under the two rules are identical, figure 10.12.11. This may because only one tool group is available for each machine and no alternative part routing is possible. Since tool set duplication is not available then the tooling configuration TC2 constraints the flow of work through the system and therefore scheduling rules play a less important role.

These results show that the impact of the MRPAS rule is highly dependent on the tooling configuration adopted and the available pallets. Tooling configuration and pallet levels constrain the scheduling of work, affecting this the scope of action of the scheduling rules.

Interaction between resources and scheduling rules is very marked which again emphasizes the complex nature of FMS system operation and shows the difficulty of predicting system performance for different operational set-ups of FMS's without experimentation.

10.12.5.1 Main Findings - Behaviour of FCFS and MRPAS Scheduling Rules

1 - Scheduling rule MRPAS exhibits an overall better behaviour in achieving good output of finished assembly sets during the FMS running period than does the FCFS rule. This is particularly noticeable with a low number of fixtured pallets and the basic tooling configuration.

2 - The design of the tooling configuration used considerably constraints the influence of those scheduling rules on system output by determining to a great extent, the work flow pattern within the system.

3 - For a low number of pallets the flow is predominantly controlled by the scheduling rules and tooling configuration but for a high number of pallets the influence of scheduling rules is smaller.

4 - The behaviour of the production synchronization ratio indicates the complex nature of the design of a FMS and its operating rules

CHAPTER 11 - CONCLUSIONS

11.1 GENERAL ASPECTS

The work reported in this thesis provides a system for aiding FMS design and operation in the form of an FMS detailed simulation model, chapter 9, used in conjunction with a set of heuristic rules for tooling configuration design, chapter 7. The study has explored the influence of the level of tool replication, the influence of different tooling configurations and the number of fixtured pallets on the performance of FMS.

One major finding of the study was that tooling configuration greatly influences FMS performance.

Two situations can be distinguished:

i) - that in which a minimum number of tools is available to process the part mix and

ii) - that in which tool replication is allowed.

In both cases a need exists for finding the best way of combining tools to load into the machines, i.e. to establish a tooling configuration to manufacture a part mix.

In the first case the main aim is to combine the tools which are required to process the part operations in a way which permits high FMS performance.

The second case creates a need for weighting the production benefits of using replication of tools against the costs of such a measure.

In the work, for differently configured FMS, it was found that tooling configurations could be developed without replication of tools for which high levels of system performance could be obtained.

The method devised to solve the tooling problem in FMS's can provide good solutions for minimizing tooling. The method also allows the pin pointing of particular sets of tools which should be duplicated and indicates alternatives of combination of the tools to constitute tool magazine loads.

In many cases duplicated tooling is only necessary in a given FMS manufacturing planned period due to the imbalance of processing requirements. Good part mixes are those which provide a high diversity of part routing, i.e. high diversity of processing requirements. A corollary of this is that split part batch sizes should be avoided because this is likely to create the need for simultaneous processing of identical parts in different machines and therefore tool duplication would be necessary. An additional consequence would be the unnecessarily high number of identically fixtured pallets.

To initially estimate the required number of tools and pallets to operate an FMS an analytical method was developed. Although this method provides a good starting point, the number of tools required is dependent on the dynamic behaviour of FMS operation which is not taken in account in the analytical model. For this reason computer simulation needs to be used to accurately determine the quantity of each type of these resources.

11.2 DETAILED CONCLUSIONS

The main conclusions from the work can be summarized as:

1 - The simulation model and strategies for FMS operation and design presented in this work were used to determine levels of fixtured pallets and tools, for which the performance of the modelled FMS configurations was good.

2 - The Ungrouping-Regrouping tool combination heuristic rule was shown to produce tooling configurations with which performance was the highest in all the situations studied. Therefore this heuristic rule should be adopted in designing tooling configurations under which FMS should be operated. The rule sould be applied to good tooling configurations developed initially by applying the tool grouping heuristics B, i.e. the lowest to highest parts ratio rule, to the basic tooling configuration.

This procedure is recommended not only when the work flow flexibility within an FMS is high due to the multipurposeness of machines but also when this flexibility is reduced due to the limited purposeness of the machines in the FMS, sections 10.4.2.5 and 10.9.4.4.

3 - The possibility cannot be ruled out of there existing tooling configurations under minimum tooling which may provide FMS performance as good as with the full tool replication case.

This was particularly true for a tooling efficiency analysis under a highly flexible FMS, section 10.7.5, although for a less flexible FMS very high performance was also obtained for the same part mix referred to in section 10.2.

4 - High routing diversity provided through systematic tool duplication in various machines of an FMS can be efficient for achieving high FMS performance but may be unnecessary.

This conclusion is based on the fact that high system performance was obtained, for different FMS configurations and different part mixes with none and only some limited and controlled tool duplication.

5 - An analytical method, section 6.2, was developed for determining the number of tools to operate an FMS.

This analysis can be used to establish the minimum number of tools referred to in 3 above

6 - The results of applying the analytical method, section 6.3, suggested that a single set of pallets could be used to operate the FMS. However, FMS simulation showed that although good throughput time was obtained under such circumstances, it was generally better to use two instead of only one set of fixtured pallets.

7 - FMS's can efficiently manufacture Assembly Sets, AS. It was shown, section 10.12.4.1, that an Assembly Set Batch Size, ASBS, of one can lead to high system performance. In general good synchronization of production towards part needs for assembly and good machine utilization were obtained provided ASBS was not high, i. e., larger than 5. But as ASBS increases there is the disadvantage of having larger

quantities of work in progress and the likelihood of higher throughput time of AS.

8 - A scheduling rule called MRPAS was designed and shown to perform well in achieving the objective of low assembly set throughput time and high FMS utilization. The FMS performance under MRPAS was in general considerably better than that under the FCFS scheduling rule.

9 - In general the best Production Synchronization Ratio, SR, section 10.1, was obtained using the MRPAS scheduling rule. However the influence of this rule decreases as the number of identically fixtured pallets increases.

10 - It was also shown that the tooling configuration greatly influences the work flow pattern through the system and that it can considerably restrict the influence of scheduling rules on system output.

11 - For a low number of pallets the work flow is predominantly controlled by scheduling rules and tooling configuration but for a high number of identically fixtured pallets, the influence of scheduling rules is smaller.

12 - Increasing the number of pallets beyond two sets does not improve FMS performance significantly. In some cases, i.e. for ASBS, larger than 5, it may worsen performance. Also increases in job throughput time and w.i.p. occur.

These conclusions clearly show that there are many interrelationships between FMS configuration elements and operating strategies which can influence the performance of the system. In particular large performance variations were observed by varying the number and type of manufacturing aids such as tools and fixtured pallets. As might be expected, some of the results obtained were not intuitive. In particular, operating an FMS under minimum tooling can be efficient.

This performance behaviour complexity of FMS suggests that aids such as those developed in this work should be used to evaluate the operating efficiency of FMS under varying manufacturing situations. This is essential to prepare a good system set-up and also for establishing good control strategies for efficient FMS operation.

11.3 GENERAL GUIDELINES

Within the experimental framework of the FMS configurations used in this work and production of AS's, general rules for operating these systems are:

1 - Operate the FMS with minimum tooling.

2 - Operate the FMS with the minimum number of pallets

3 - Use the minimum Assembly Set Batch Size, i.e. 1.

When operating the FMS under these conditions high system performance was achieved from the model. These conditions also have the additional advantage of minimum capital cost of investment in tools, fixtures and pallets.

However this requires both good system control and the use of good tooling configurations. Thus:

4 - A scheduling rule such as MRPAS should be used,

5 - Tool groups should be defined on the basis of applying the "Lowest to Highest Parts Ratio" tool heuristic combination rule B and then the "Ungrouping Regrouping" rule D.

6 - The heuristic Tool Duplication rule E should be used for controlled and restricted duplication of some tools when this is required due to the imbalance of processing requirements of the part mix to be manufactured.

11. 4 FURTHER WORK

Package for Automatic Generation of Good Operational FMS Set-ups.

The process adopted in this work for establishing good tooling configurations for FMS operation requires the evaluation of the results at each successive simulation run. However, this evaluation is performed through human interaction which at each successive simulation run applies a heuristic rule for obtaining the tooling configuration.

This cycle, user-simulation-user, can be avoided by integrating the simulation model with a software package which can deal automatically with the generation of good tooling configurations to manufacture a part mix. Artificial Intelligence techniques offer the possibility of producing such a package.

The package could also include automatic procedures for investigating other factors such as work load level, pallets and fixtures, scheduling rules and FMS physical configurations

General Aspects

This research work studied the FMS performance of two FMS configurations and two different part mixes with a maximum of nine different parts. To assess the generality of the conclusions and particularly the system operation and design guidelines, further work is required using alternative operating set-ups with different part spectrums, different part mixes and larger variety of FMS structures.

In this work a number of different parts usually are palletised together in the same pallet. Under this approach, for the scheduling rules studied and particularly for the MRPAS rule, high FMS performance was obtained. Situations need to be investigated with alternative palletising approaches, e.g. one part per pallet and many identical parts per pallet.

In any future research, advantage should be taken of the newer simulation languages and systems which are available and which to a great extent overcome the limitations inherent in the simulation language used in this research.

Effects of limited tool life have not been considered in this work. Whilst this is not expected to invalidate the overall conclusions, in order to determine the total amount of tooling within FMS, tool life aspects need to be introduced. Tool refurbishment and replacement are also important aspects which will affect the total tooling requirements and also the operating strategies of such systems. Interactions between these aspects and the system design and operating parameters already investigated need to be examined.

BIBLIOGRAPHY -

- MAIN TEXT

1. Autorenkollektiv, "Automatisierte Fertigungsuberwachung", Industrie Anzeiger, Vol.106, No. 7.56, 12.7.1984

2. Baguley, R. J., "Creation of an FMS using Standard Modules, Available Now", 3rd. Int. FMS Conf., 1984, IFS Pubs. Ltd.

3. Bauer et al, "Rechnerunterstützeten Entwurf und Maßnamhmen zur Ausfürung flexibler Fertigungssysteme", Ind.Anzeiger Nr.74 (1974)

4. Bell, R. and Souza, R.B.R., "The Management of Tool Flows in Highly Automated Flexible Machining Installations", Int. Conf. on Computer Aided Production Engineering, Edinburgh, April87

5. Bevans, J.P., "First Choose an FMS Simulator", American Machinist, May 1982 pp.143-145

6. Bilalis, N. G. and Mamalis, A.G., "The Flexible Manufacturing Systems (FMS) in Metal Removal Processing: An Overview", J. Applied Metalworking, Vol.3 No.4 January 1985.

7. Bilalis, N. G., "The Design and Control of FMS for Rotational Parts", Ph.D. Thesis. Loughborough University, GB, 1983

8. Boolinger. J.G., Crookall, R., "The Role of Simulation in Designing/Teaching of Manufacturing Systems", Annals of the CIRP vol. 30/2/1981

9. Bosh Catalogue, "Automatic Assembly of a Complex Unit", 1982

10. Brodbeck, B., "Computer controlled Flexible Production for Precision Parts at MBB, Dynamics Division", 3rd. Int Conf on FMS, 1984, IFS (Publications) Ltd

11. Buzacott, J.A. and Shanthikumar, J.G., "Models for Understanding Flexible Manufacturing Systems", AIIE Transactions, Dec. 1980, pp. 339-349.

12. Buzacott, J.A. and Yao, D.D., "Flexible Manufacturing Systems: A Review of Analytical Models", Man. Sc. Vol 32 No.7, July 1986

13. Buzacott, J.A. and Yao, D.D., "Flexible Manufacturing Systems: A Review of Analytical Models", Man. Sc. Vol 32 No.7, 1986

14. Carrie., A.S. and Perera, D.S.T., "Work Scheduling in FMS", 1985 Conf. of the O.R. Soc. Durham, Sept. 1985

15. Carvalho. S. and Crooks, J.S., "Celular Simulation", ORQ, Vol27 (1976), No.1, pp. 31-40

16. Cavaille, J.B., Forestier. J.P. and Bel G., "A simulation Program for Analysis and Design of Flexible Manufacturing Systems", 1981 Int. Conf. on Cybernetics and Society: Alternative Futures, Atlanta, G.A. Oct.1981

17. Charles Stark Draper Laboratory "Flexible Manufacturing Systems Handbook", National Technical Inf. Services, U.S.A., Dep of Commerce, 1983

18. Chatfield , C., "Statistics for Technology", Penguin Books, 1970

19. Chemielnicki, S. and Stute G., "Modell Kontrolle bei dem Simulationsprogrammsystem SIKTAS", Ind.Anzeiger No.10, 1982

20. Clementson A.T., "The simulation of Flexible Manufacturing Systems", 1985 Conf of the Operational Research Society, Durham, Sept 1985.

21. Clementson, A.T., "Computer Aided Programming of Simulations", Users' Manual, University of Birmingham, 1972

22. Clementson, A.T., "Extended Control Simulation Language", User's Manual Cle. Com Ltd, 1982.

23. Conte, G., "Alsthom Unlec FMS-A Case Study", 2nd. Int. Conf. on FMS, 1983, pp. 317-338, IFS(Publications) Ltd

24. Cook, N.H., "Computer Managed Parts Manufacture", Scientific American, Feb.75 pp 22-29.

25. Crite, G.D., Mills, R.I. and Talavage, J.J., "PATHSIM:, A Simulator for Automatic Tool Handling System Evaluation in FMS", Journal of Manufacturing Systems, Vol 4 No.1

26. Darrow, W. P., "An International Comparison of Flexible Manufacturing Systems Technology", Interfaces 17:6 Nov.-Dec.86-91, 1987

27. Dreyfack, K.,"Minicomputer is FMS traffic cop", American Machinist, July, 1982

28. ElMaraghy, H.A., "Automated Tool Management Flexible Manufacturing", Journal of Manufacturing Systems, Vol.4 No.1

29. Enghill, J.S. and Davies A., "Flexible Manufacturing Systems-The Mith and Reality", Int. Journal of Advanced Manufacturing Technology, 1985

30. Engineering News, "NC complex combines high output with low capital cost", No. 337 February 1, 1968.

31. Eversheim, W., "Simulation-Voraussetzung für rationelle Anlagenplanung", Ind. Anzeiger No. 56/57, 18.7.86, Vol. 108

32. Eversheim,W and Herrmann, P., "Technical and Economical Planning of Automated Manufacturing Systems", Proc. 4th Int. Conf. on Production Research, Tokyo 1980

33. "Flexible Manufacturing Systems - Notes to supplement the video cassette", Numerical Engineering Society /Inst.Production Engineers, 1985

34. FMS Magazine, "FMC cells and ancillaries dominate Tokyo Show", FMS Magazine Jan.1985

35. FMS Magazine, "British Aerospace Aims Sky High", FMS Magazine, April 1985

36. FMS Magazine, "Free range AGV uses laser guidance", FMS Magazine July 1983

37. FMS Magazine, "KTM confirms UK leadership", April 1985

38. Gatelmand, C. D., "Machine Tools Evaluation for FMS", Renault Machine Outils, France,

39. Gatelmand, C.D., "A Survey of Analytical and Simulation Models for Design and Control of Flexible Manufacturing", CIRP Seminar on Manufacturing Systems, 1982

40. Gatelmand, C.D., "A Survey of Flexible Manufacturing Systems", J. of Manuf. Systems Vol.1 NO. 1, 1983

41. Genschow, H. and Hammer, H., "New Flexible Duplex Cell for the Automatic Boring and Milling Machine Operation", Werksttatt und Betriebe 116 (1983)

42. Groover, M.P. "Automation, Production Systems and Computer Aided Manufacturing", Prentice-Hall, Inc, N.J. ,1980.

43. Haddock J., "A Simulation Generator for Flexible Manufacturing Systems Design and Control", IIE Transactions, March 1988

44. Hammer,H., "Improving Economic Efficiency Through Flexible Automation in Milling and Boring", ZwF-Zeitschrift Bd 78 (1983) Nr.2

45. Hankins, S.L. and Rovito, V.P. (1984), "The Impact of Tooling in Flexible Manufacturing Systems", 2nd. Biennial Int. Machine Tool Technical Conf., Sept. 84, National Machine Tool Builders' Association

46. Hannam, "Alternatives in the design of F.M.S. for prismatic parts", Proc. Instn. Mech. Engrs., Vol.199, No.b2 1985

47. Hartley, J., "FMS at work", IFS Publications Ltd, 1984.

48. Hatavany, J., Merchant, M.E.,Rathmil, K. and Yoshikawa, H., "World Survey of CAM", Hatavany, J (Ed.), Butterwords

49. Hermann, G., "Process Intermittent Measurement of Tools and Workpieces", Journal of Manufacturing Systems, Vol. 4, NO.1 (1986)

50. Hesse, S., "Problem der werkstuckspeicherung beim Einsatz von Industrierrobotern", Machinenbautechnik,31 (1982) 11

51. Ho, Y.C., "Performance Evaluation and Perturbation Analysis of Discrete Event Dynamic Systems", IIIE Transactions on Automatic Control, Vol. AC-32 No.7 July 1987.

52. Hoop, P., "Einsatz von kombinationswerkzeugen in FFS", tz. für Metalbearbeitung, 76 1982 no.7

53. Hormann, D., "Betrieb rechnersteuerter Fertigungssyteme", Diss. T.H. Aachen, 1973

54. Huang, P.Y. and Chen, C.S., "Flexible Manufacturing Systems:An Overview", Production and Inventory Management Third Quarter 1986

55. Hutchinson, G.K., "Flexible Manufacturing Systems in Japan", Wisconsin Univ. Milwaukee, Man. Res. Center, Nov. 1977

56. Hutchinson, G.K., "Prismatic and Rotary Flexible Manufacturing Systems in the German Democratic Republic", Wisconsin Univ. Milwaukee, Man. Res. Center, Nov. 1977

57. Iwata, K., "FMS in Japan", Bull. Japan Soc. of Prec. Engg., Vol.18, N0.2 (Jun84)

58. Jackson R.J., "Jobshop-like queueing systems", Man.Sc. Oct.1963

59. Jackson, R.J , "Network of waiting lines", O.R. Vol. 5 No.4 (Aug.1957)

60. Jain, S., "Basis for Development a Generic FMS simulator", Proc. of the second ORSA/TIMS conf. on Flexible Manufacturing Systems, K.E. Stecke and R.Suri (Eds), Elsevier SAcience Publishers, Amsterdam, 1986

61. Kankunte, M.V, Sarin, S.C. and Wilhelm, "Flexible Manufacturing Systems", A Review of Modelling Approaches for Design, Justification and Operation"Flexible Manufacturing Systems: Methods and Studies, A.Kuziak (Ed.), Elsevier Sc.Pubers., 1986

62. Kleindorfer, P.R. (ed.), "The Management of Productivity and Technology in Manufacturing", Plenun Press, N.Y. , London 1985.

63. Kochan, A., "French Interest Centres on Flexible Cells at Paris", The FMS Magazine Jul.86

64. Kochan, A., "FMS - An International Overview of Applications", 1st Machine Tool Conference, 1984

65. Kochan, D. and Jacobs, H.J., "Integrated Manufacturing- First Steps to the Partly Unmanned Factory for Batch Production", Proc. of the 4th Int. Conf. on Production Engineering, Tokyo 1980

66. Lebrecht, H.M., "The Machining Centre Concept", Proc. of the 8th. MTDR Conf. - Advances in Machine Tool Design and Research, Manchester, 1967 (Sept.)

67. Lehmann, W., "Flexible Drehzellen", VDI-Z 125 (1983) Nr.18-Sept.

68. Lenz, J., "MAST: A Simulation as Advanced as the FMS it studies", Proc. of the 1st. Int. Conf. On Simulation in Manufacturing Systems, March 85, IFS Pubs. Ltd.

69. Lewendon, B. N., "The Use of Touch and Trigger Probes on Machine Tools - Potential Benefits and Pitfalls", Development of Flexible Automation Systems, 10-12 July, 84 pp 103-108

70. Lewis, G., "Modular Fixturing Systems", 2nd. Int FMS Conf., 1983, IFS Pubs. Ltd

71. Lord, L.K., "Machine Tools for Use in FMS", The FMS Magazine, Oct. 1984

72. Luca, A., "Software for FMS Preliminar Design: A complete Industrial Case", Proc. of the 1st. Int. Machine Tool Conf., Birmingham, NEC 26-28/6/84

73. Machinery and Production Engineering, "High Stakes in the Batch Production Race", 15 Nov 1978

74. Mamalis, A.G., Bilalis, N.G. and Konstantinidis M.J., "On Simulation modelling for FMS", Simulation, Vol.48 No.1 pp.19-23, 1987

75. Marsh, P., "Britain advances in computerized factories", New Scientist, Vol.89 No.1245 Match 1981

76. Mathewson, S.C., "The Application of Program Generator Software and its Extension to Discrete Event Simulation Modelling", IIE Transations March 84 pp3-18

77. Mellicamp. J.M. and Wahab, A.F.A., "An Expert System for FMS design". Simulation, Vol.48 No.5 pp.201-208, 1987

78. Mertins, K., "Entwicklungsstand flexibler Fertigungssyteme in den USA", ZwF, (1981) 76, No.2

79. Meyer, P., "Probabilidade-Aplicações `a Estatística", Livros Técnicos e Científicos, Brasil, 1987

80. Miner, R.J. and Rolston, L.J., "A Modelling and Analysis Program for Batch Manufacture", Proc. of the 1983 Annual Industrial Engineering Conference

81. Nof, S.Y. Deisenroth, M.P. and Meier, W.L., "Using Physical Simulators to study Manufacturing Systems Design and Control", 1979 Spring Annual Conf. on M.S. and Productivity, AIIE, 1979, USA.

82. O'Grady, P.J., Bao, H. and Lee, K.H., "Issues in Intelligent Control for FMS", Computers in Industry., 9, (1987) 25-36

83. Opitz, H. and Hormann, D., "Planning and Utilization of FMS", Annals of the CIRP 21/1/72, pp. 29- 30

84. Peithmann, L., "Entwicklungschwerpunkte und Probleme in automatisierten Materialfluß"

85. Perry, C.B., "Variable Mission Manufacturing System", 1st Int. Conf. on Product Development and Manufacturing Technology", McDonald, London, 1970 pp 314-333.

86. Popplewell, F. and Smool, P., "FM - the proven Approach", 5th. Int Conf on FMS, 1986, IFS (Conferences) Ltd

87. Preni, S.K. and Besant C.B. "A review of various vehicle guidance techniques that can be used by mobile robots or AGV", 2nd Int. Conf. of AGV Systems 1983

88. Ranky, P. "The Design and Operation of FMS", IFS Ltd, UK 1983.

89. Reiser, M. and Lavenberg, S.S., "Mean Value Analysis of Multichain Queueing Networks", Journal of The Assoc. for Computing Machinery, Vol. 27 No.2, April 1980 pp. 313-322

90. Rinn, J. "Automatish drehen, messen, laden in flexiblen Fertigungszellen"

91. Sackett, P.J. and Rathmil, K., "Manufacturing Plant for 1985-Developments and Justification", Proc. of the Instn. of Mech. Engrs., Vol196 (1982) pp. 265-280

92. Scamp Systems Ltd, "Scamp - FMS catalogue", 1983

93. Schlaugh, R., "production Scheduling in a Flexible Manufacturing System (FMS)", 1st Int. FMS Conf. Oct. 1982, Brighton.

94. Schmoll, P."Flexible Automation made to measure", 2nd. Int. Conf. on Flexible Manufacturing Systems, Sept.1984, IFS(Publishers) Ltd

95. Schraft, R.D. "Recent Developments in Materials Handling", IFAC 1979 conf. on Information Control Problems in Manufacturing Technology

96. Schulte, H.J. "Flexible Fertigungssyteme- zum Stand der Arbeiten bei Sonderforshungsbereich 155 in Stuttgart", VDI-Z (1980) NO. 15/16

97. Schutz, W. "Installed flexible manufacturing cells, flexible manufacturing islands and flexible manufacturing systems,(FMS), built in modular construction, 3rd Int. FMS conference, 1984, IFS Pubs. Ltd.

98. Seidmann, A., Oren, S.S. and Schweittzer, P.J., "An Analytical Review of Several Computerized Closed Queueing Network Models of FMS", Proc. of the 2nd. ORSA/TIMS Conf. on Flexible Manufacturing Systems, 1986 Stecke, K.E. and Suri, R. (Eds), Elsevier Sc. Pubers.Amsterdam.

99. Shannon, R.E., "Knowledge Based Simulation Techniques", I.J.P.R. Vol. 26 No.5, 1988, pp953-973

100. Smith, M.L., Ramesh, R., Dudeck R.A. and Blair, E.L. (1986) "Characteristics of the US Flexible Manufacturing Systems-A

Survey)", Proc of the 2nd. ORSA/TIMS Conf. on Flexible Manufacturing Systems, 1986, Eds. Stecke, K.E. and Suri, R., Elsevier

101. Solberg, J. J., "Computer Models for Design and Control of FMS"16th. Numerical Control Society Annual Meeting, March 79

102. Solberg, J.J., "A Mathematical Model of Computerized Manufacturing Systems", Proc.of The 4th. Int.Conf. on Production Research, Tokyo, Japan, Aug.1977

103. Solsberg, J.J., "Mathematical Design Tools for Integrated Production", Proc.of The MTDR Conf. No.23 , Sept.1982

104. Spur, G. und Mertins, K., "Flexible Fertigungssysteme, Productionsanlagen der flexiblen Automatisierung", ZwF (1981), 9, pp. 441-448

105. Spur, G., and Weisser, W., "Verkettung von Werkzeugmaschinen durch Industrieroboter", 1976 Girardet-Essen

106. Spur, G., "Realisierung eines modulares Flexiblen Fertigungssytems mit automatischer Informationsverarbeitung, KfK-PDV 195 Berichte, Kernforschungszentrum, Karlsruhe, Aug.1980

107. Stecke, K. and Solberg, J.J., "Loading and Control Policies for FMS", IJPR, Vol.19, No.5, 1981 pp. 481-490

108. Stecke, K., "Production Planning Problems for FMS", Ph.D Thesis, 1981, Purdue University, USA

109. Steinmuller, P.H., "Flexible Fertigungssyteme und ihr kunftiger Ensatz in der Industrier", Ind. Anz. Vol 103, no.104 30.122.1981

110. Storr, A., "Plannung und realisierung flexibler Fertigungssysteme", Wt Zeitschrift für industriell Fertigung Vol.60 nr.11 1979

111. Stradhagen, J.O., "Expert Knowldege in Object Oriented Simulation of Manufacturing Systems", Proc.of the 3rd Int. Conf. on Simulation in Manufacturing Nov. 1987, IFS (Conferences) Ltd

112. Stute G., Bauer E. and Wilhelm, R., "Workflow Layout of a Flexible Manufacturing System", Advances in Computer Aided Manufacture, North-Holand, 1977

113. Stute, G. "Some Aspects of Tool Flow in FMS", Proc. of the FMS Workshop Conf., Sept.88, pp. 73-82, Milawkee, USA

114. Stute, G., "Flexible Fertigungssysteme", wt-Z. ind. Fertigung, Vol. 64 No.3, 1974.

115. Stute, G., "Organizational Control in an FMS", FMS Workshop conference, Milwaukee, USA Sept. 78

116. Stute, G., Stoor A. and Chmielnicki, "Simulation and Motion Display an a Graphic CRT", Manufacturing Systems Vol.12 N0.2, pp.130-136, 1982

117. Suri, R. and Cao, X "Optimization of Flexible Manufacturing Systems Using New Techniques in Discrete Event Systems", Proc. of the 1982 Allerton Conf. on Communication Control and Computing

118. The FMS Magazine, "British Aerospace Aims Sky High", The FMS Magazine, April 1985, pp 77-80

119. The FMS Magazine, "Flexible Cell for Track Links", The FMS. Magazine, July 1983

120. Treywin, E.T. "Integration of Inspection into a Flexible Machining Line", Proc. of the 5th. Int. Conf. on Automated Inspection and Production Control Stuttgart, Jun 1980 pp. 253-265

121. Tuffentsammer et al, "Automatic Loading and Machining Systems and Automatic Clamping of Workpieces", Annals of The CIRP, vol.30/2/1981

122. Vettin, G. "Analysis der Konzeption flexibler Fertigungssysteme", VDI-Z 121 Nr 1/2 Jan.1979

123. Vettin, G., "Analyse von Grundtypen flexibles Fertigungssyteme und ihrer Varianten", ZwF 72 (1977) 9 pp-476-482

124. Vuzelov, V., "A Modular Approach to Flexible Automation", 2nd. Int. FMS Conf. 1983, IFS Pubs. Ltd.

125. Warnecke, H.J. and Steinhilper R., "New International Developments for Flexible Automation in FMS", 2nd Int. FMS Conf., 1983, IFS Pubs. Ltd

126. Warnecke, H.J. and Vettin G., "Strategies for the Organization and Control of Discontinous conveyors in FMS", CIRP Journal of Manufacturing Systems. 1977 Vol6 No.3, pp. 197-209

127. Warnecke, H.J. and Vettin G., "Technical Investment Planning of Flexible Manufacturing Systems", Journal of Manufacturing Systems, Vol 1 no.1 1982

128. Warnecke, H.J. and Zeh, K.P., "Simulation and Compuyer-Aided Planning of FMS", 3rd Int. Conf. on FMS, Out. 1984

129. Warnecke, H.J., Roth H.P. and Schulel, J., "FMS Applications in Germany-Objectives and Constraints", Proc. of the 3rd. Int. Conf. on FMS, Sept.1984, Warnecke (Ed.), IFS (Publications) Ltd and North Holland

130. Warnecke, H.J., Steinhilper, R. and Zeh, K.P., "Conclusions from Simulation of Small and Large FMS Projects", 4th Int Conf. on FMS, Oct 1985

131. Weck, M. and Schuring, "What Aids are available for design and development of Computer Controlled Manufacturing Systems", 15th NAMRC Conf. on Metalworking and Research, 1975.

132. Weck, M. et al, "New Developments of Data Processing in Computer Controlled Manufacturing Systems", Fourth IFIC/IFAC Conf 1979, North Holand Pub.

133. Westkaemper E., "Automatisierung in der Einzel-und Serienfertigung-Ein Beitrag sur Plannung, Entwicklung und Realisierung neuer Fertigungskonzept", Diss. T.H. Aachen, WG, 1977

134. Wild, R., "Mass Production Management", Wiley, N.Y., 1972

135. Wilhelm, R., "Analyse des Materialflusses flexibler Fertigungssyteme", wt-Z. Ind. Fertig. 66 (1976) no.9 pp.529-536

136. Wilhelm, W.E., "Models for Design of Flexible Manufacturing Systems", Proc. of the 1983 Industrial Engineering Conference

137. Williamson, D.T.N. "Molins System 24 - A New Concept of Manufacture", Machinery and Production Engineering, October 25, 1967 pp. 852-863

138. Williamson, D.T.N. "System 24 - A New Concept of Manufacture", 8th MTDR conf. 1967 pp 327-376.

139. Wills, K.F. "Advanced Computer Aided Engineering and Manufacturing", Proc. of Instn. of Mechanical Engrs. Vol. 197B pp. 81-87, 1982

140. Wynne, B.E. and Hutchinson, G.K., "Simulation of Advanced Manufacturing Systems", Proc. of the Winter Simulation conf. Washington, D.C. Jan74

141. Yingchao, X., "Prospects for FMS in China's Aviation - A Personal View", 2nd Int. FMS Conf. IFS. Pubs. Ltd pp.31-38

142. Yong, R.E. and Rossi, M.A., "Towards Knowledge-Based control of Flexible Manufacturing Systems", IIE Trans. Mars. 1988 pp. 36-43

143. Yoshida, Y., "Present Status of Machining Centres in Japan, "Bull. Japan Soc. of Prec. Eng. Vol.18, N0.2, Jun84

144. Zeleny, J., "Manufacturing Cells with Automatic Tool Flow for Unmanned Machining of Box-like Workpieces", Manufacturing Systems, Vol.11 No.4 1982

145. Zick,M., "Plannungs und Ausfürungsbeispiel eines stufenweise ausbaufähigen flexiblen Fertigungssysteme", VDI-Berichte NR.440, 1982

146 Inaba, S., "Factory Automation- Das Konzept eines aitomatisierten Fertigung und seine Verwirklichung", VDI-Z 125(1983) N0.20 October

BIBLIOGRAPHY -

- SIMULATION MODELS LISTED IN TABLE 3.1

1. Acree, E.S.," Simulation of Flexible Manufacturing Systems-Application of Computer Operating System Techniques" Annual Simulation Symposium, Oct 1985, Florida, USA

2. Athans, M. et al "Complex Materials Handling and Assembly.Systems", Sept. 1977, MIT- ELS, USA

3. Bevans, J.P., "First Choose an FMS Simulator", American Machinist, May 1982 pp.143-145

4. Bilalis, N. G., "The Design and Control of FMS for Rotational Parts", Ph.D. Thesis. Loughborough University, GB, 1983

5. Boolinger. J.G., Crookall, R., "The Role of Simulation in Designing/Teaching of Manufacturing Systems", Annals of the CIRP vol. 30/2/1981

6. Chemielnicki, S. and Stute G., "Modell Kontrolle bei dem Simulationsprogrammsystem SIKTAS", Ind.Anzeiger No.10, 1982

7. Cook, N.H., "Design and Analysis of Computerized Manufacturing Systems (CMS)", Annals of the CIRP Vol. 28/1/1979

8. Crite, G.D., Mills, R.I. and Talavage J.J., "PATHSIM, A Modular Simulator for Automatic Tool Handling System Evaluation in FMS", J. of Manufacturing Systems Vol.4 (1985), N0.1

9. ElMaraghy, H.A, "Simulation and Graphical Animation of Advanced Manufacturing Systems" J.of Manuf.Systems Vol.1 (1982) No.1, pp.53-63

10. ElMaraghy, H.A., "Automated Tool Management in Flexible Manufacturing" J.of Manuf.Systems Vol.4 (1985) No.1

11. Eversheim, W and Pfermenges, R., "Plannung der Fertigung mit hilfe der Simulation", Ind. Anzeiger, 100 No.37 10.5.78 pp. 67-70

12. Eversheim, W., "Simulation-Voraussetzung für rationelle Anlagenplanung", Ind. Anzeiger No. 56/57, 18.7.86, Vol. 108

13. Feuer,Z. Mendelson, Z. and Kohen, A., "Evaluation of Advanced Manufacturing Systems using Simulation", 3rd Int. Conf. on Simulation in Manufacturing,Nov, 1987. IFS Conferences, Ltd

14. Gatelmand, C. D., " A Survey of Analytical and Simulation Models for the Design of FMS" 1982 CIRP Seminar on Manufacturing Systems

15. Gatelmand, C. D., and Tartarian, D."Computer Aids for the Design of Flexible Manufacturing Systems", Proc. of the 3rd. Int Conf. On Flexible Manufacturing Systems, 1984

16. Grant, H., " Production Scheduling using Simulation Technology". Proc. of the 2nd. Int. Conf. on Simulation in Manufacturing, 1986, IFS Pub. Ltd.

17. Haddock, J., " A Simulation Generator for Flexible Manufacturing Systems Design and Control", IIE Transactions, March 88

18. Hutchinson, G.K. and Wynne, B.E., " A Flexible Manufacturing System" Ind. Eng. Dec. 1973

19. Iwata, K., "Simulation for Design and Operation of FMS", Annals of the CIRP Vol 33/1/1984

20. Lenz, J., et al, "The optimal Planning of Computerized Manufacturing Systems" Rep. No.7, Aug.77. NSF Grant No.April 74-15256

21. Lenz, J., "General Computerized Manufacturing Systems Simulator", Master Thesis, Purdue University, 1977

22. Lenz, J., "MAST: A Simulation as Advanced as the FMS it studies", Proc. of the 1st. Int. Conf. On Simulation in Manufacturing Systems, March 85 IFS Pub. Ltd.

23. Mamalis, A.G., Bilalis, N.G. and Konstantinidis, M. J, "On Simulation Modelling for FMS", Simulation No. 1987

24. Manuelli, R. and Guiducci, G., "FASTSIM: A Simulation Tool for Flexible Manufacturing Systems", Proc. of the 1st Int. Conf. On Simulation in Manufacturing, March 1985, IFS Pub. Ltd,

25. Metalworking Engineering and Marketing, " FMS Operation ratio over 90%", Metalworking Engineering and Marketing, Sept. 85

26. Miller, R. K.,"Manufacturing Simulation-A New Tool for Robotics FMS and Industrial Process Design", SAI Technical Publications and Technical Insights Inc.

27. Mills, R.I., "Simulation Programs for FMS Design", Proc. of the 1st. Int. Conf. On Simulation in Manufacturing Systems, March 85 IFS Pub. Ltd

28. Miner, R.J. and Rolston, L.J., "A Modelling Analysis Program for Batch Manufacturing" Proc. of the 1982 Annual Industrial Engineering Conference

29. Prini, G., Cannizo, G. Valcada, A. and Boero, M., "Simulation for Design and Operation of a Turbine Blades Production FMS", Proc. of the Int. Conf. on Simulation in Manufacturing, Nov. 1987. IFS Conferences, Ltd

30. Solberg, J.J., "Computer Models for Design and Control of FMS", 16th National Control Soc. Annual Meeting, 1979

31. Talavage, J.J., " Models for The Automatic Factory", Simulation March. 1978

32. Talavage,J.J. and Barash, M.M., "Information Control in Computerized Manufacturing Systems", IFAC/IFIP Conf., 1977

33. Valcada, A. and Mastretta, M., "Comparison of Different Computerized Design Tools for Flexible Manufacturing", Proc. of the 3rd. Int.Conf. On Simulation in Manufacturing, 1984,

34. Wakai, H., Kado, S., Sakamoto, C. and Sata, T., " KOSMO- A Simulator for Flexible Manufacturing Systems", Annals of the CIRP vol 35/1/1986

35. Warnecke, H.J. and Steinhilper, R., "Conclusions from Simulation of Small and Large FMS Projects", 4th. Int. Conference on FMS, Oct85, IFS(Pub) Ltd

36. Westkämper, E., "Automatisierung in der Einzel und Serienfertigung" Diss. T.H. Aachen, WG, 1977

37. Wichmann, K. E., "An Intelligent Simulation Environment for the Design and Operation of FMS", Proc. of the 2nd.Int.Conf. on Simulation in Manufacturing,1986 IFS Pub. Ltd.

38. Wynne, B.E. and Hutchinson, G.K., " Simulation of Advanced Manufacturing Systems", Proc. of the Winter Simulation Conf., Jan1974, Washington D.C., USA.

GLOSSARY

Assembly Set, AS - is a set of parts to completely assemble one or more product units.

Assembly Set Batch Size, ASBS - is the number of Assembly Sets released together into the FMS.

Assembly Set Production, ASP -is a form of manufacturing where production in carried out in Assembly Sets.

Assembly Set Throughput Time Index, ASTTI - is a normalized measure of throughput time given by:

$$\text{ASTTI} = \frac{\text{Average set throughput time}}{\text{Machining time per AS}}$$

Assembly Sets Output, ASO - is the number of Assembly Sets manufactured during the FMS running period.

Basic Tool Group, BTG - are the tools required to process all of the operations of parts loaded onto a pallet in a single set-up.

Basic Tool Set, BTS - is a set of tools required to process a particular part operation

Basic Tooling Configuration, BTC - is the minimum number of basic tool groups necessary for processing a given part mix.

Degree of Balance of an FMS, UT - is defined as the average theoretical maximum possible machine utilization of an FMS determined by (see Table 10.9.3):

$$UT = \frac{\sum_{i=1}^{g} mi \cdot Ui}{\sum_{i=1}^{g} mi}$$

Where:

Ui - is the maximum possible utilization of machine group

mi - is the number of machines in the machine group i

g - is the number of machine groups in the FMS

Fixtured pallet - is a pallet provided with fixtures for part clamping.

Job throughput time - is the average throughput time of Assembly Sets.

Limited purpose machine - is a machine tool or machining centre capable of performing only some of the operations in a part mix.

Machine Group, MG - is defined as a group of machines similar enough to process the same set of operations provided they are loaded with appropriate tools.

MRPAS -is a scheduling rule which schedules work on the basis of the number of parts still unfinished belonging to an Assembly Set, Assembly Sets.

Multipurpose machine - is a very versatile machine, e.g. a machining centre, capable of performing any part operation in a part mix.

Part operation - is an operation to be carried out on a part or workpiece, in a single set up of a pallet at a machine and consists of a number of elemental machining operations each of which requires a single tool to be performed.

Parts Ratio, WPR - is defined as:

$$WPRi = \frac{\text{Number of finished parts of type i}}{\text{Number of required parts of type i per Assembly Set}}$$

Pool of machines, PM - is a group of machines such that any machine within the group can actually be a real time part-routing alternative to a number of identical part operations which need to be processed simultaneously.

Subtooling Configuration, STC - is a partition of the available tool groups which are used to process the part operations associated with a specific machine group. The tools in a STC can only be allocated to the machines of a specific machine group.

Synchronization Ratio, SR - is a normalized measure of Assembly Sets Output given by

$$SR = \frac{\text{Actual ASO in a manufacturing period}}{\text{Theoretical maximum ASO possible to finish in the period}}$$

Tooling Configuration, TC -is the total set of tool groups which are to be loaded into the machines

FIGURES

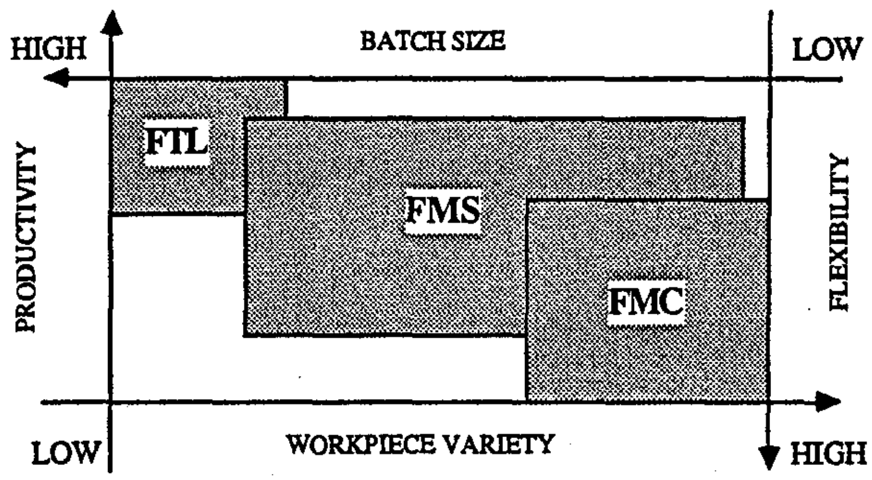
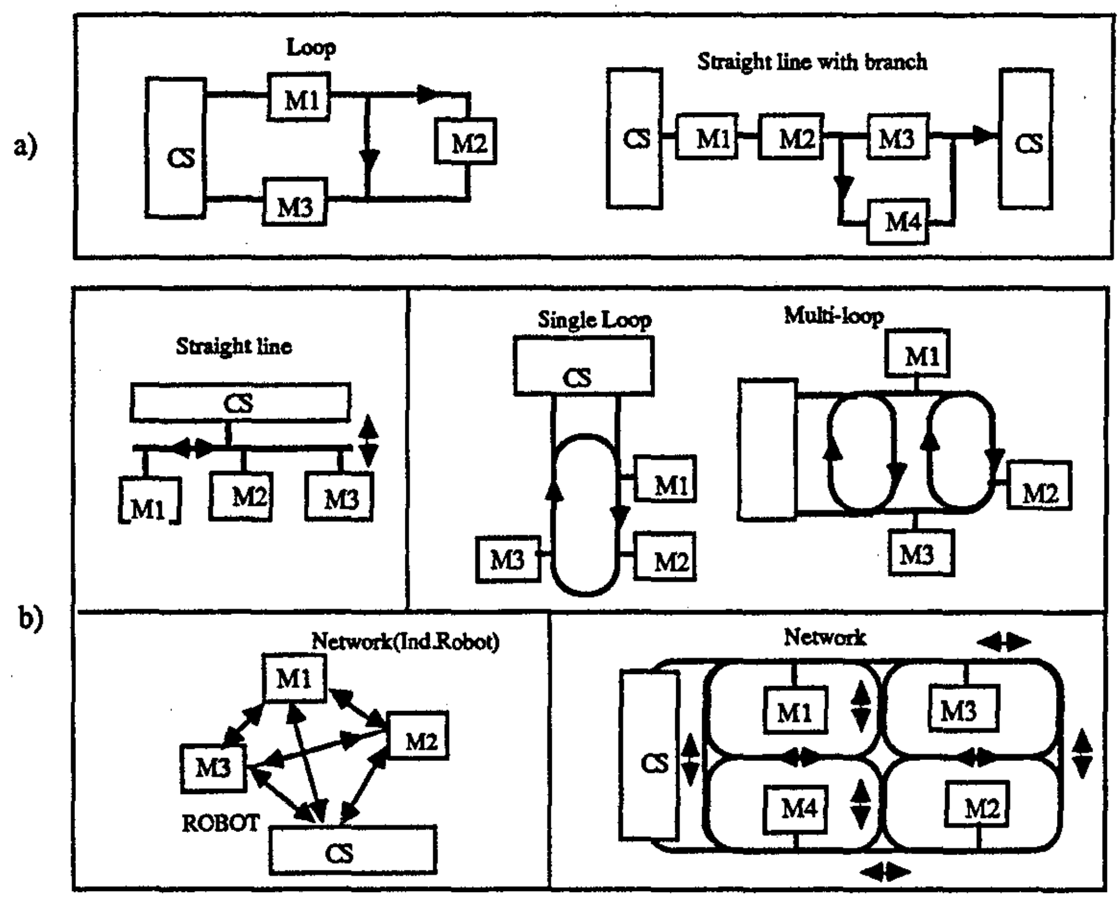
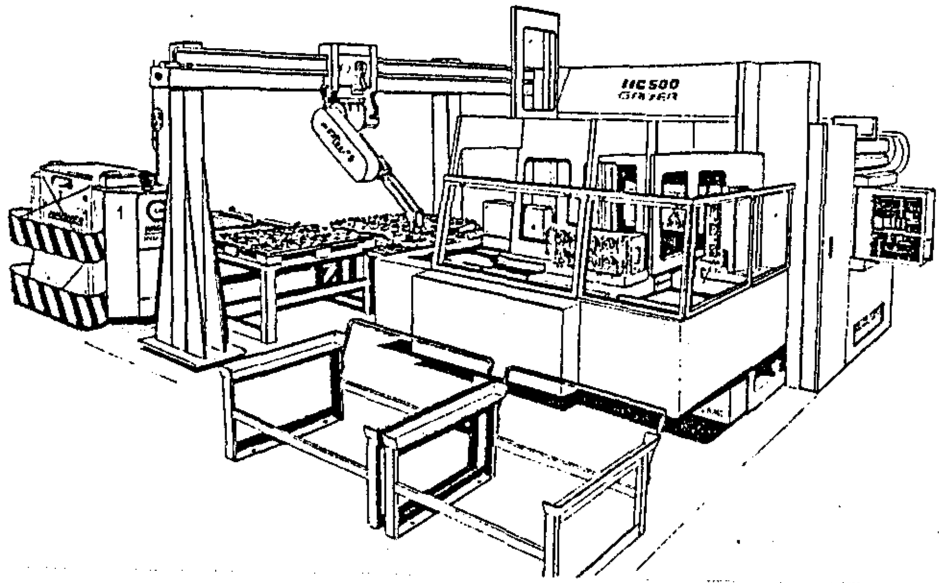


Fig. 2.1	Suitability of the three classes of FMS



Legend: CS - Central Store for blank and/or finished parts

Fig. 2.2	Schematic representation of the typicalwork flow patterns in systems for flexible manufacture: a) Flexible Tranefer Lines ; b) Flexible Manufacturing Systems



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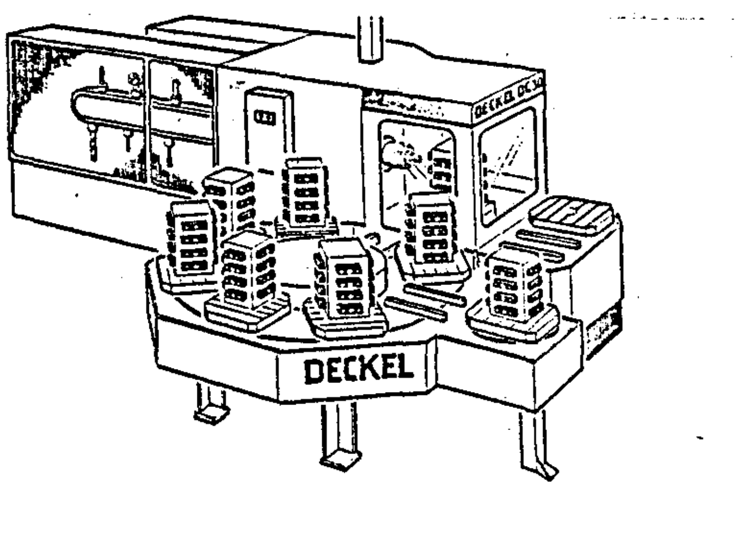
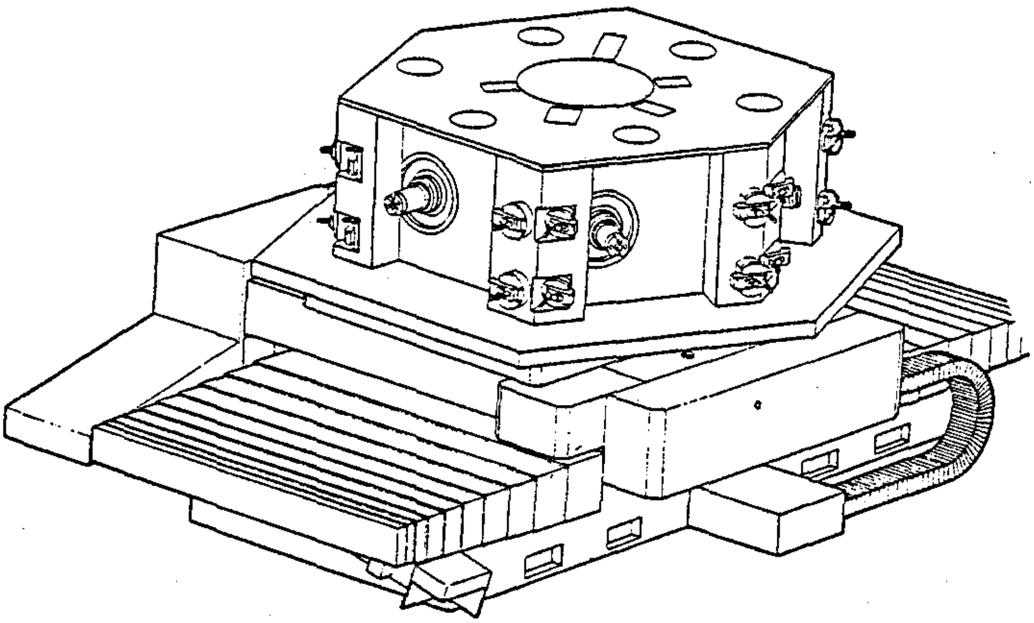
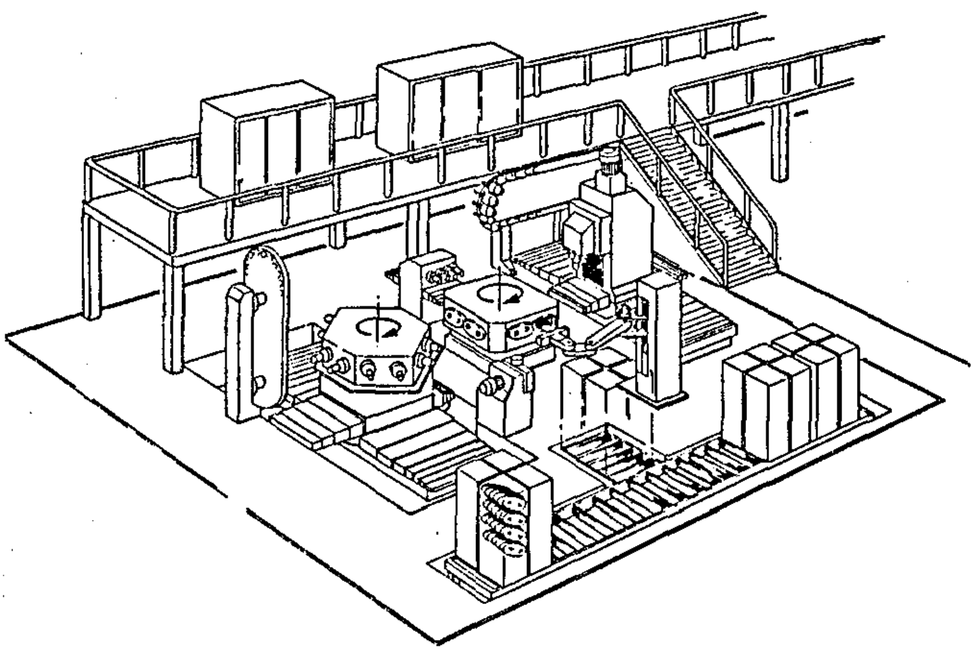


Bibl. source (86)

Fig. 2.3	Examples of Flexible Manufacturing Cells for Prismatic parts

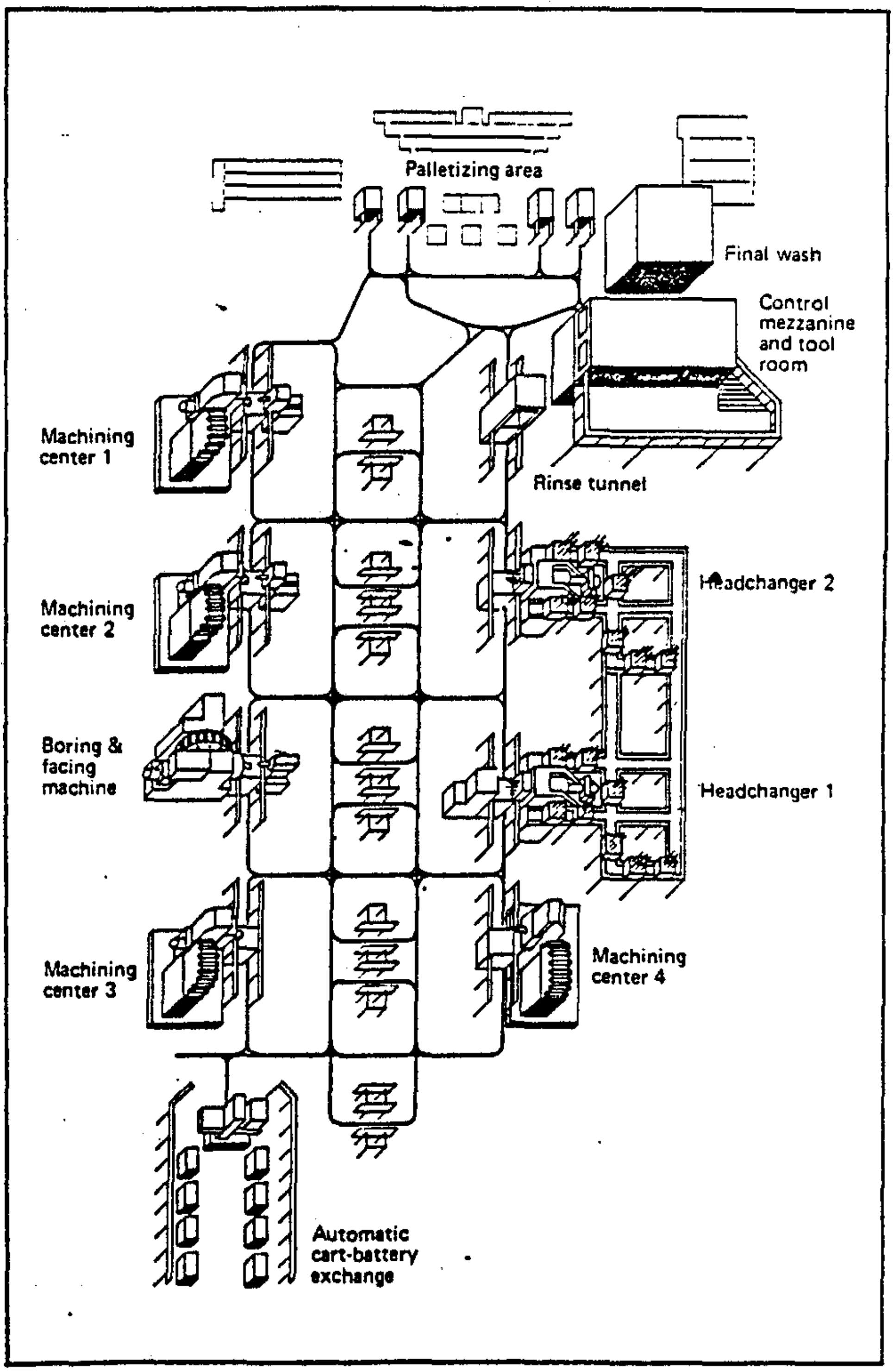


Bibl. source: (24) a)



Bibl. source: (119) b)

Fig.2.4	Application examples of tool head indexers and tool head changers: a) Head Indexer; b) Application of a Head indexer; c) Use of Tool head changers in a FMS.



Four machining centers, two headchangers, and a boring/facing machine compose this minicomputer-directed system, where normally only six workers are needed

Fig.2.4 (cont.)	c) Use of Tool head changers in a FMS. Bibl. source: (27)

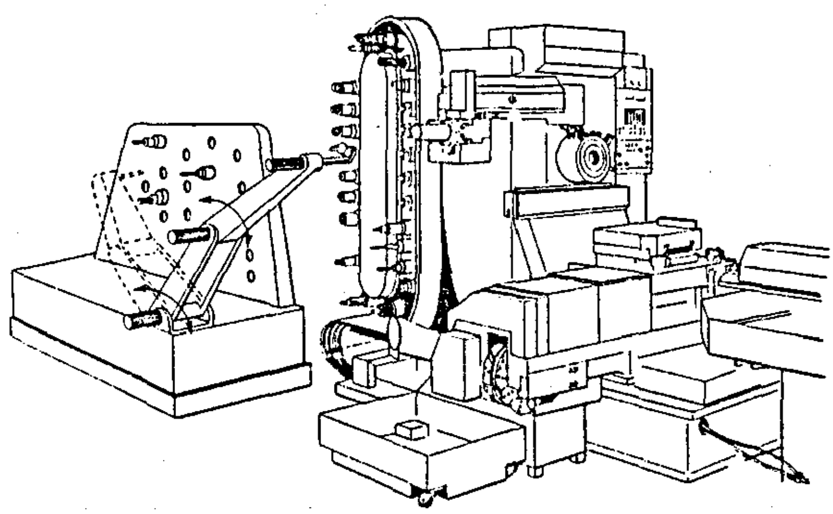


Fig. 2.5

Automatic replacement at the tool magazine of a machine of tool kits taken to the machine by an automated transport vehicle.

Bilbl. source: Hartley (47)

LEVELS OF DECISION MAKING FOR FMS'S				
TIME HORIZON	MANAGEMENT LEVEL	TYPICAL TASKS	TYPICAL DSS SW USED	HARWARE USED
Long term	Upper	-Part mix changes -System modification/expansion	-Part selection SW -Queueing models -Simulation	-Main frame or DSS computer
Medium term	FMS line supervisor	-Divide production into batches -Maximize Machine Utilization -Respond to disturbances in production planning/material available.	-Batch and balancing programs -Simulation	-D.S.S. computer or FMS computer
Short term	Supervisor (exceptions only)	-Work order scheduling and dispatching -Tool management -Monitoring and Diagnostics -Reaction to system failures	-Work order dispatching programs -Operation and tool realocation programs -Simulation	-FMS computer

Legend: DSS - Decision Support Systems
FMS's - Flexible Manufacturing Systems

Fig. 2.6 Production Control tasks and tools for FMS's

Bilble. source: (17)

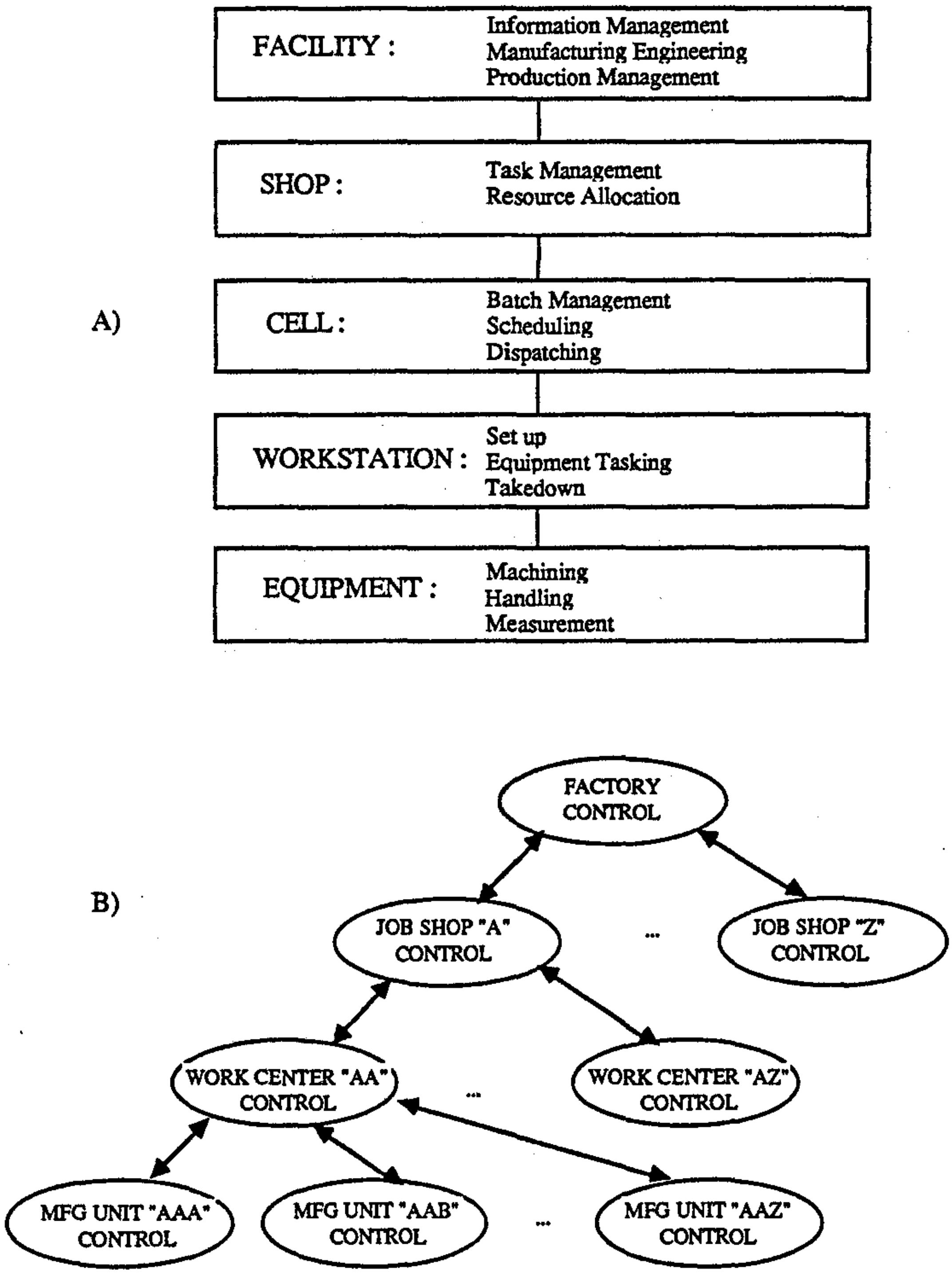


Fig. 2.7

Control Hierarchy in the
A) - Automated Manufacturing Research Facility, AMRF and
B) - Advanced Factory Management System, AFMS

Bibl. source: (82)

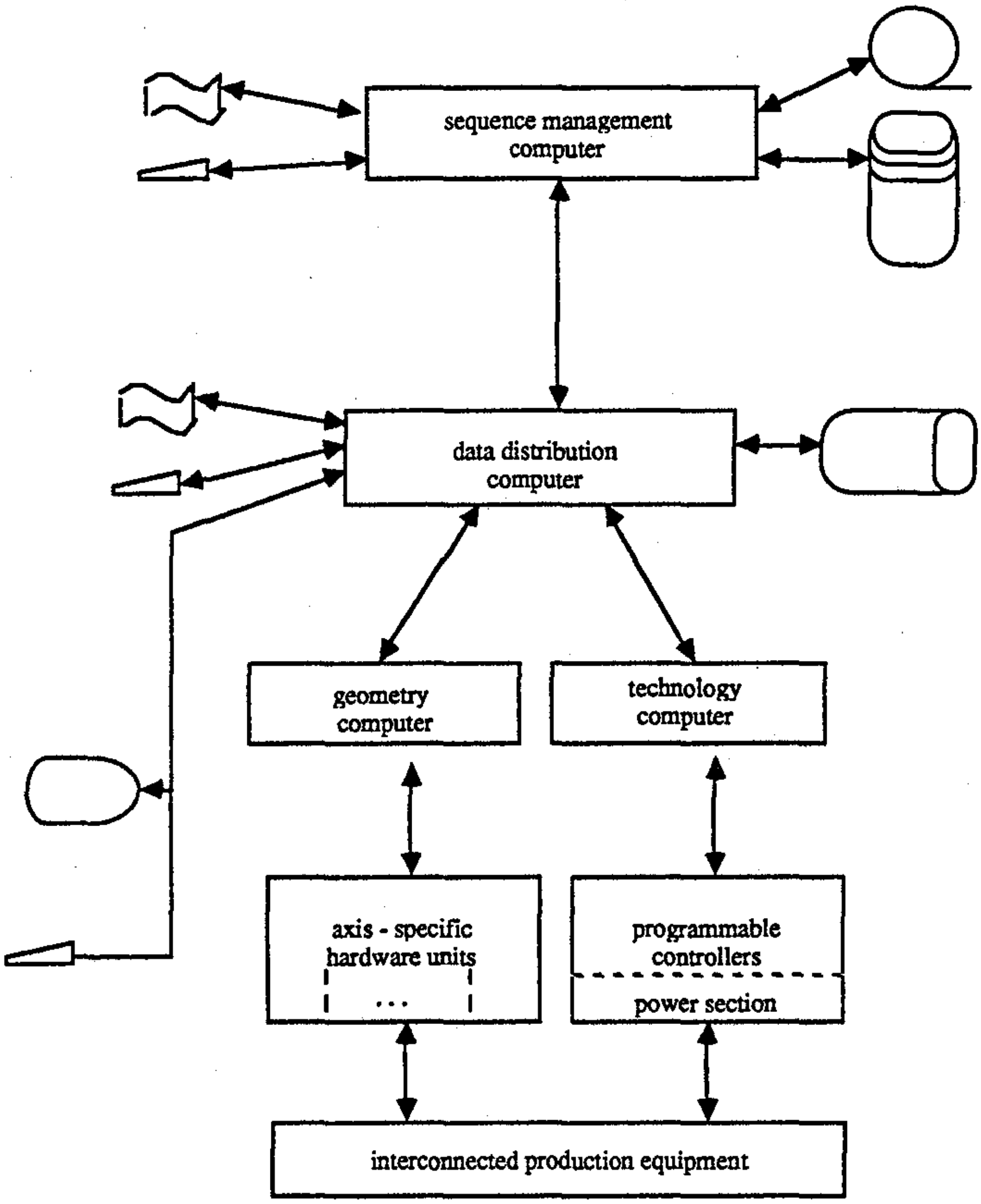


Fig. 2.8

Schematic representation of a hierarchical function based control system for Flexible Manufacturing Systems

Bibl. source : (115)

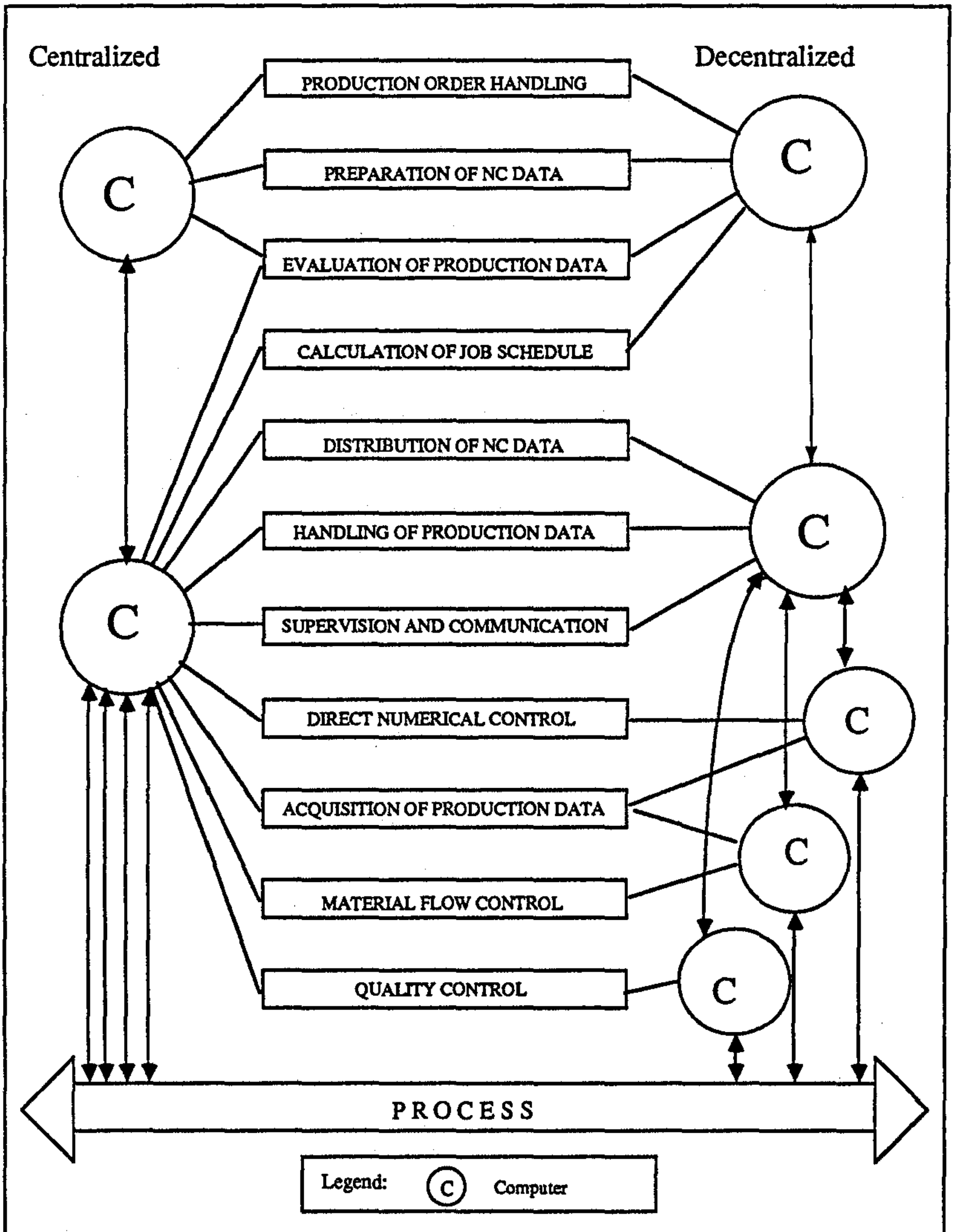


Fig. 2.9 Main control tasks in centralized and decentralized control systems for FMS's

Bibl. source: (132)

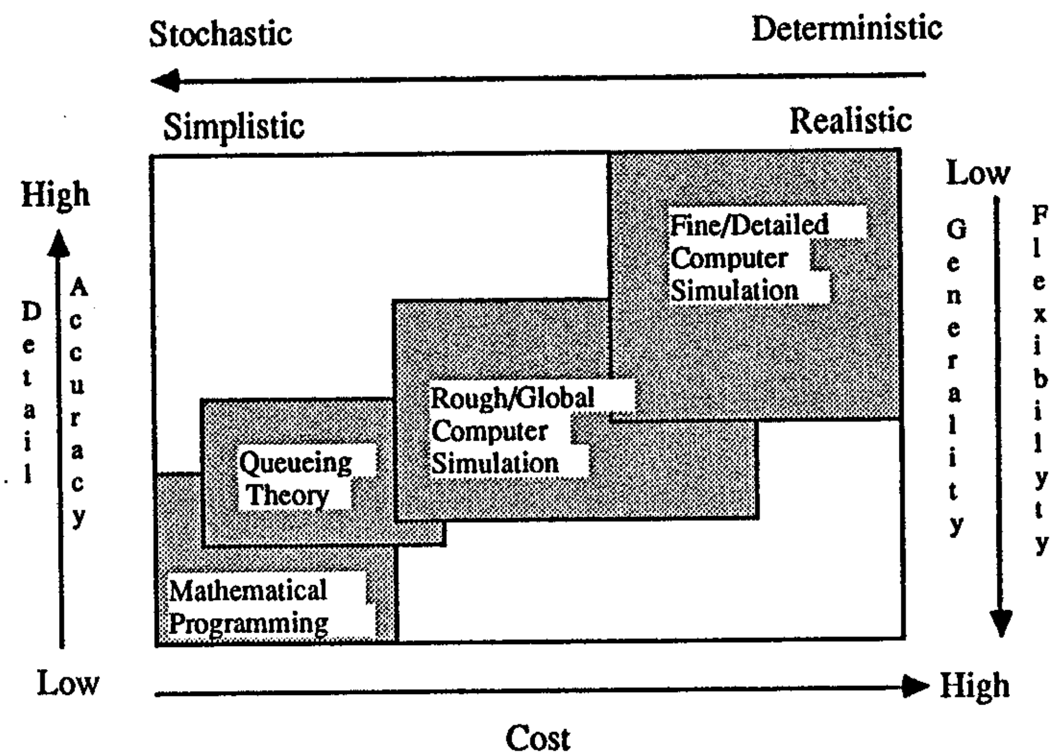


Fig. 2.10 Relationship between different Modelling Techniques for the study of FMS

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1 *View from above of part of a model of the System 24 installation now being laid down at the Deptford works of the Molins Machine Co., Ltd. In the foreground are the work-setting stations, with the storage rack for pallets, and the associated Molacs, beyond. At the rear may be seen some of the multi-axis n.c. machine tools and loading units for pallets and tool magazines*

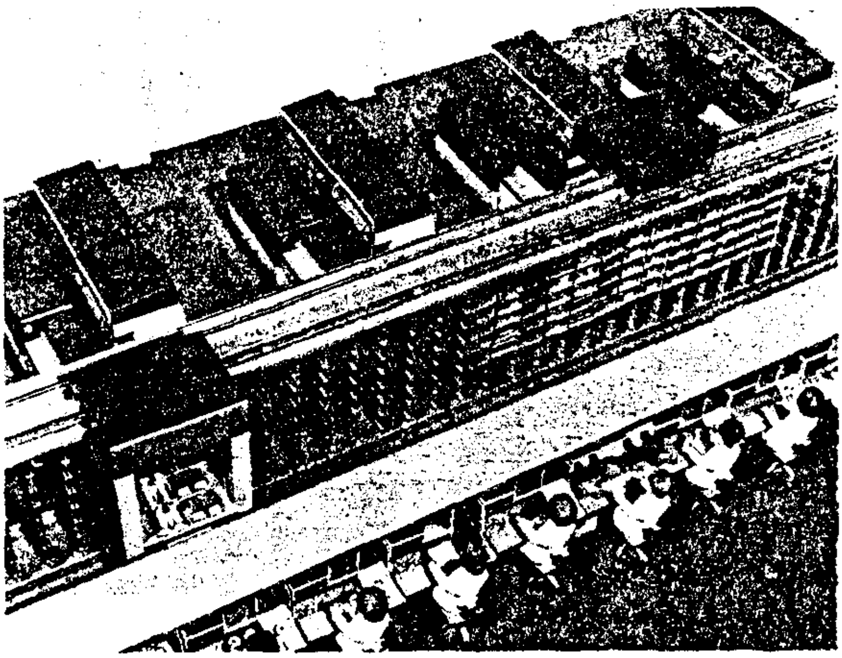


Fig. 3.1	The Molins 24 FMS system Bilbl. Source (137)

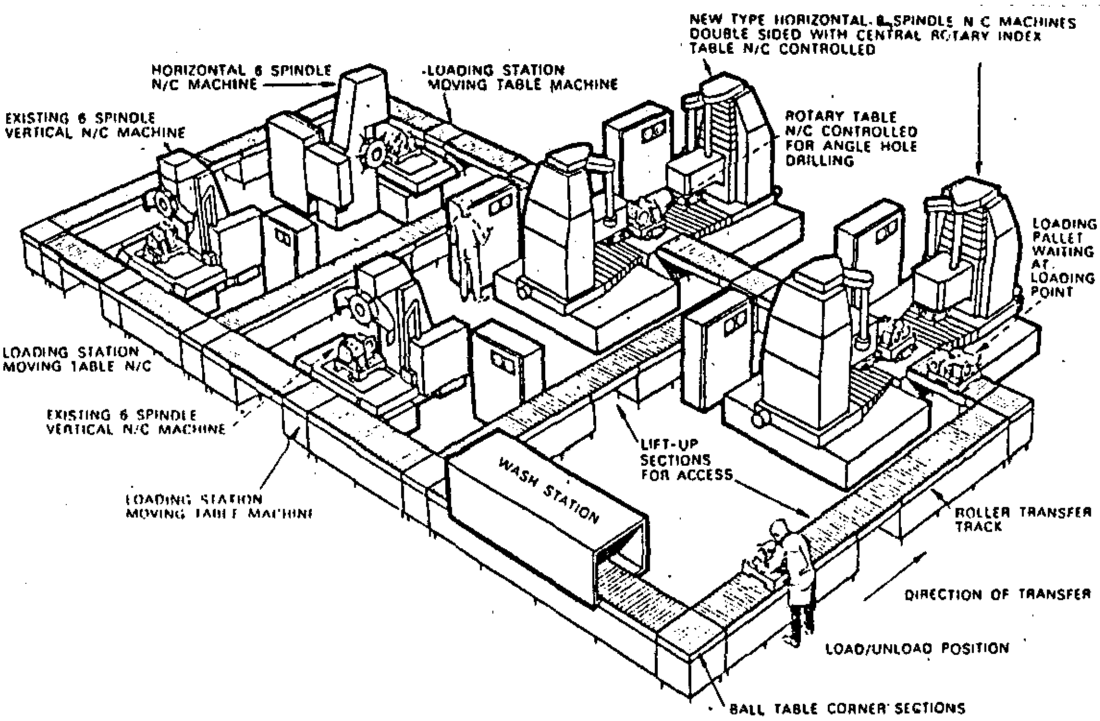


Fig. 3.2	The Variable Mission Manufacturing system(VMM) Bilbl. Source (30)

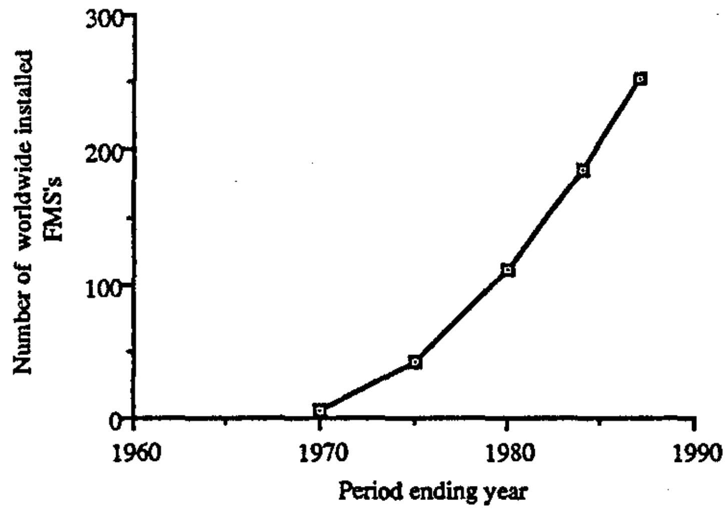


Fig.3.3	Growth of the number of FMS plants installed throughout the world After Bilalis (6) and Darrow (26)

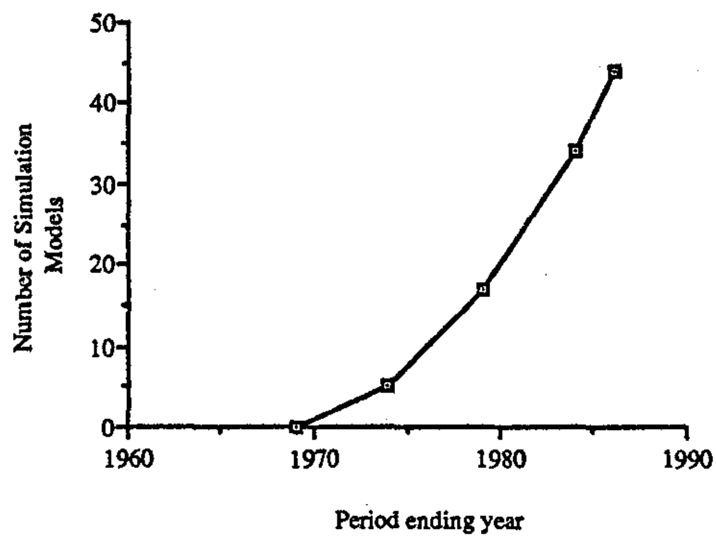


Fig.3.4	Growth of the number of FMS simulation models developed (See table 3.1)

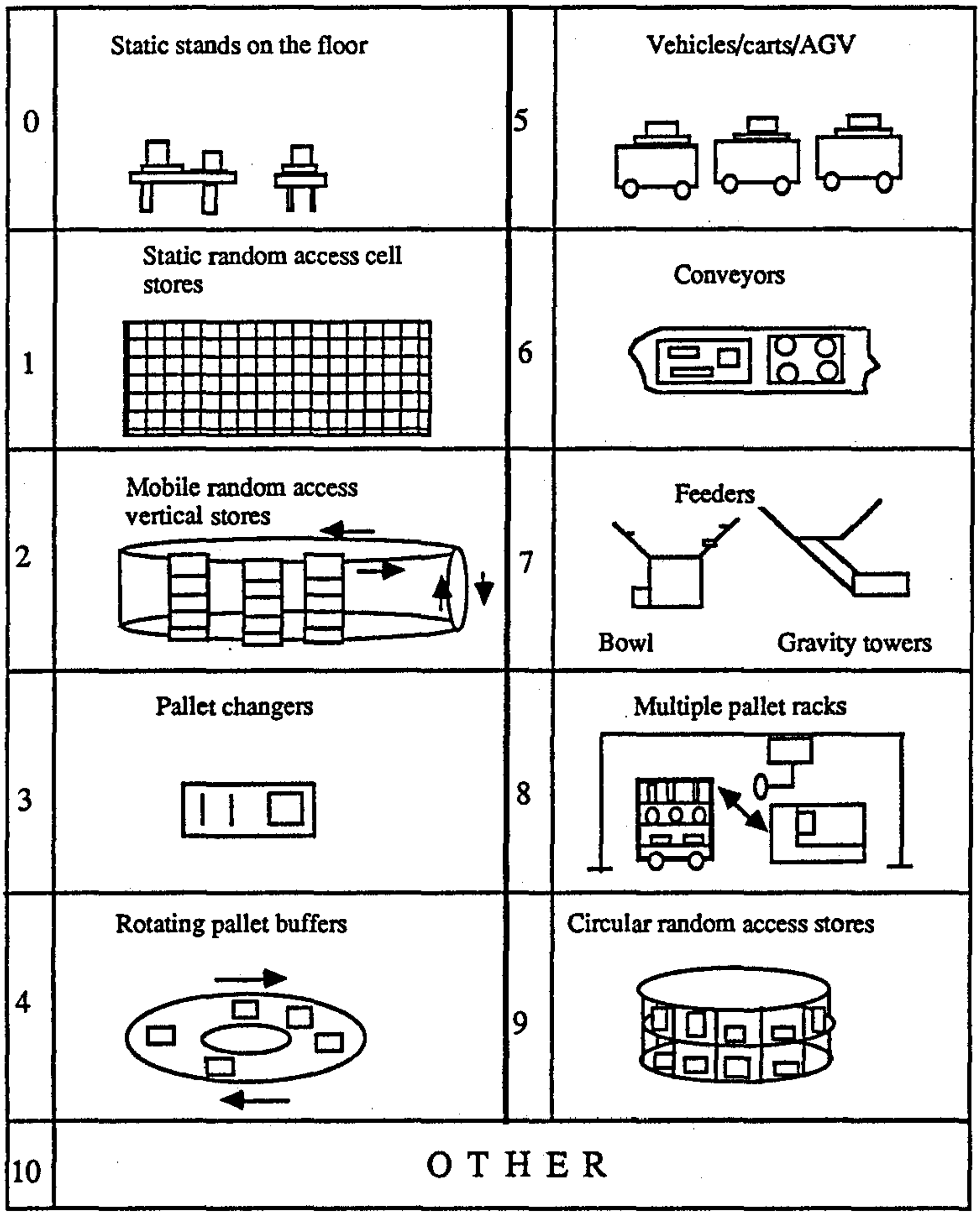
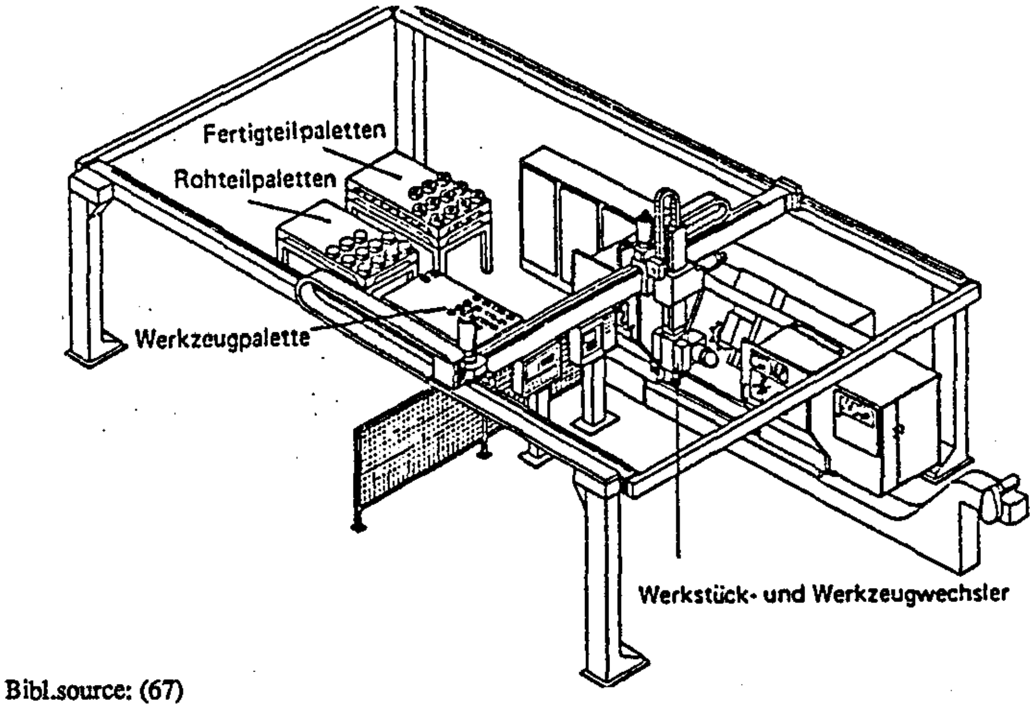


Fig. 5.1	Basic work storage and buffer elements



Bibl.source: (67)

Fig. 5.2	Flexible Manufacturing Turning Cell with local storage on static stands for keeping pallets of parts and tools which are accessible by an overhead IR moving in an horizontal plan

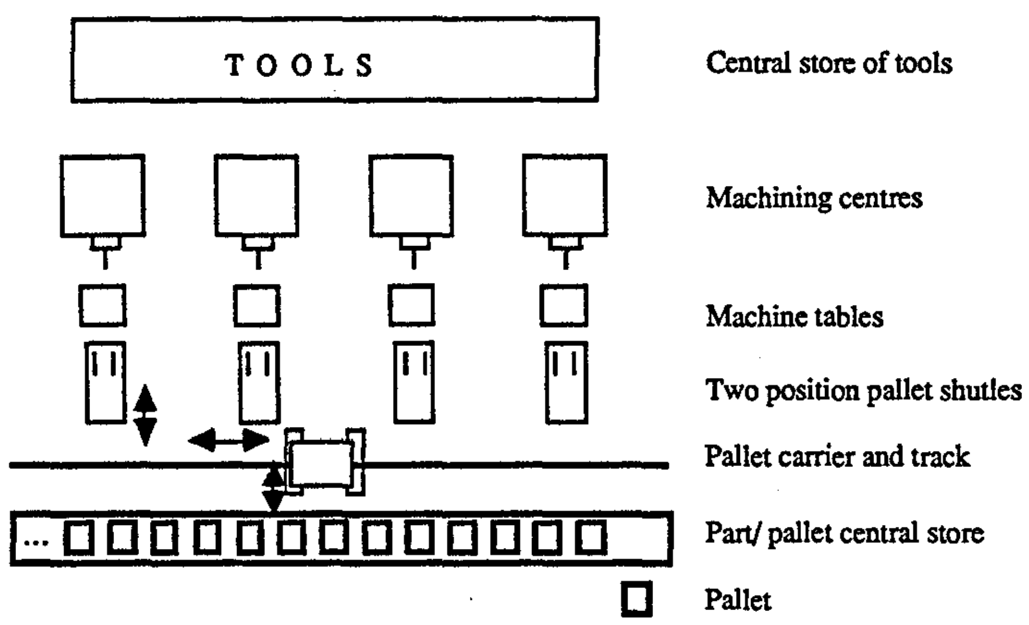
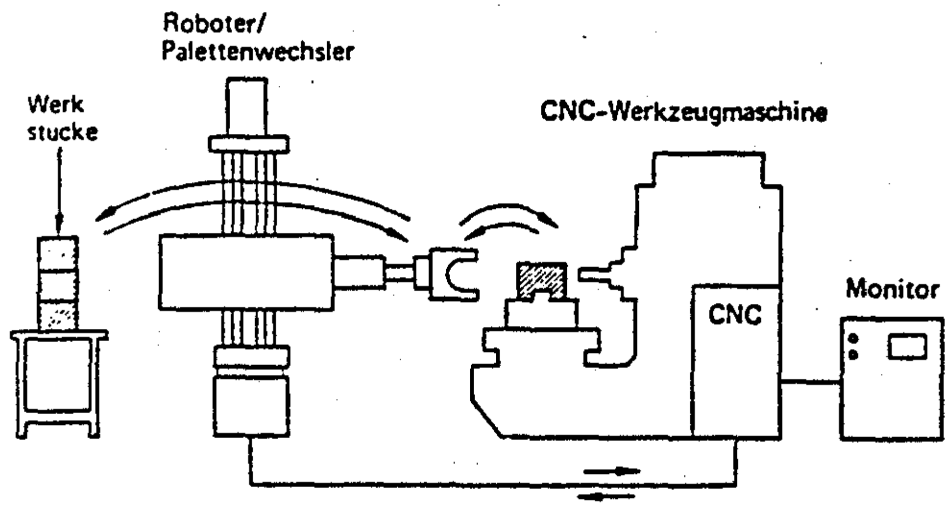


Fig. 5.3	Schematic representation of a typical FMS configured with part/pallet storage on static stands

a)



b)

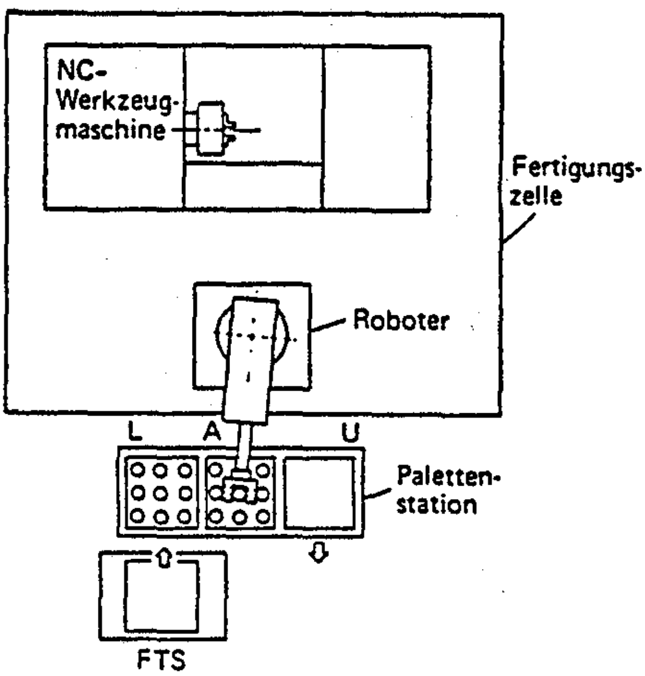
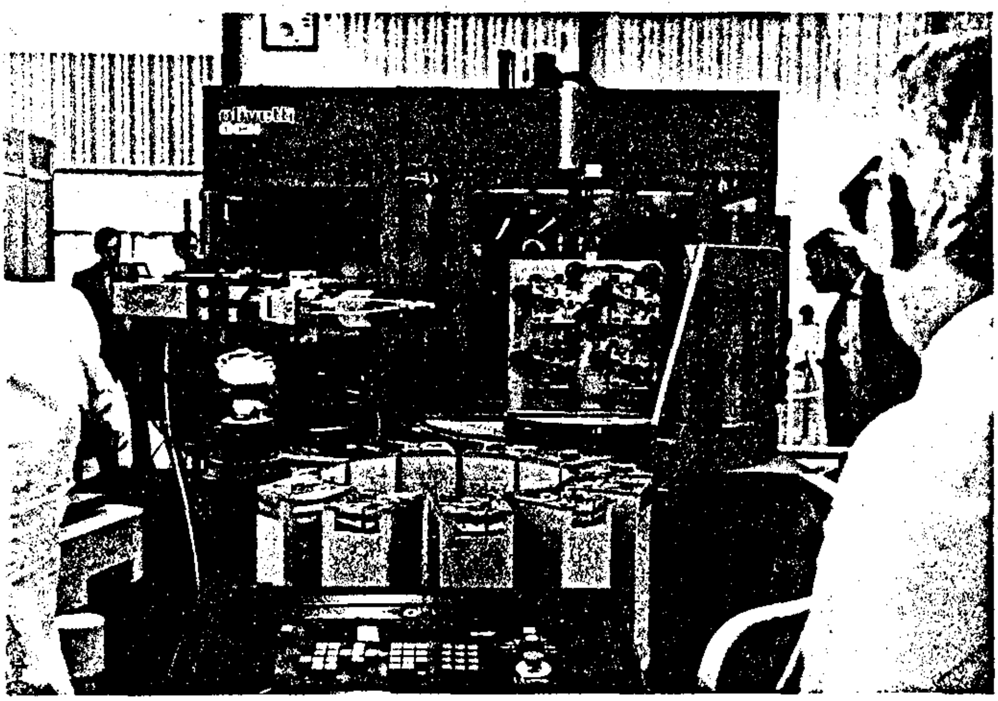
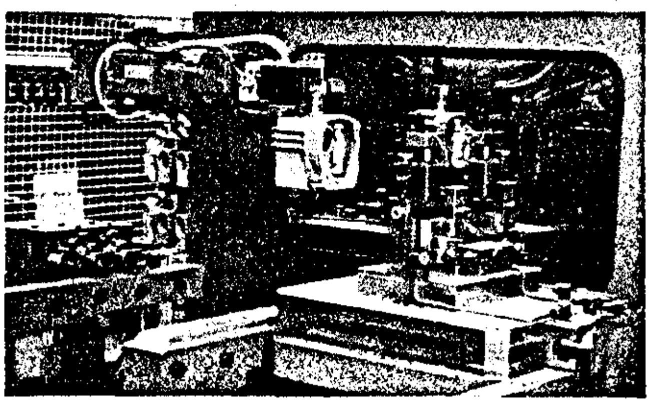


Fig. 5.4	Automatic part loading and clamping on holding devices: a) Prismatic parts b) Rotational Parts Bibl. source: (146)





Source: Werntze
(Ind.&Prod.Eng.4.82)

Fig. 5.5	Non-rotational parts automatically clamped into fixtured pallets at the machining area with the aid of indudtrial robots.

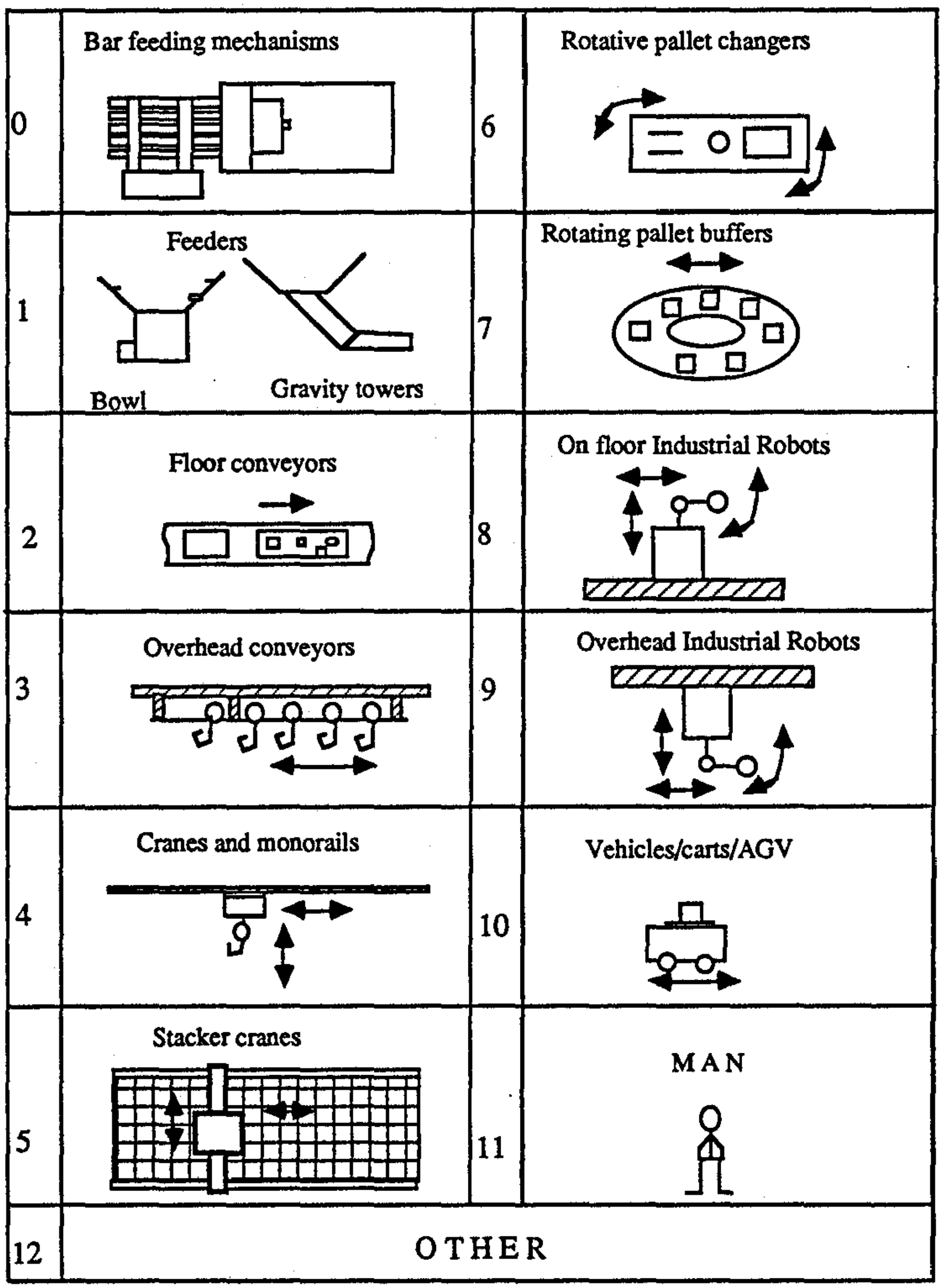


Fig.5.6	Basic work transport and handling elements for FMS work flow systems

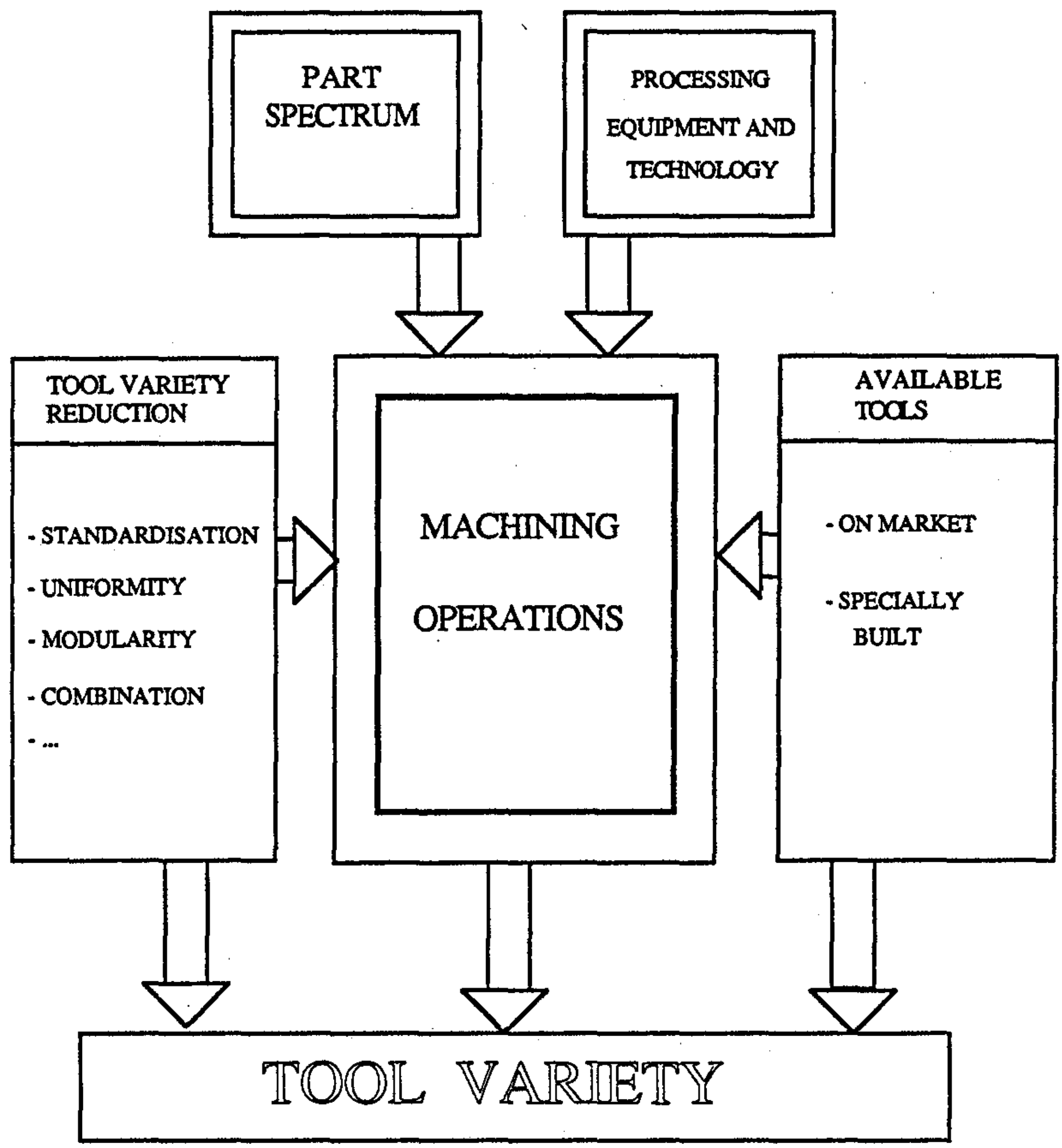


Fig. 5.7	Intervening factors for tool variety determination

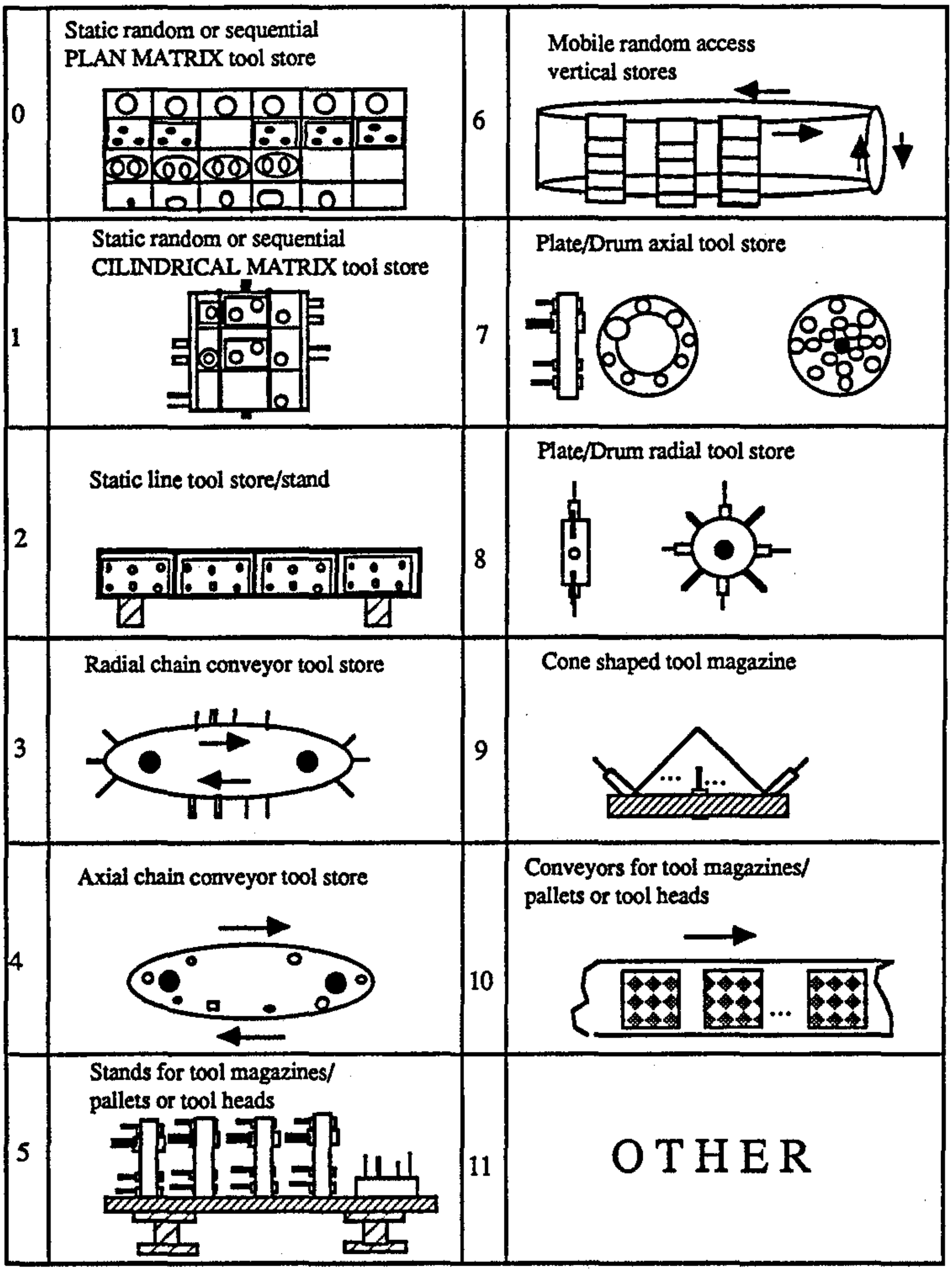


Fig. 5.8 Basic tool buffer and storage elements for FMS Tool Flow Systems

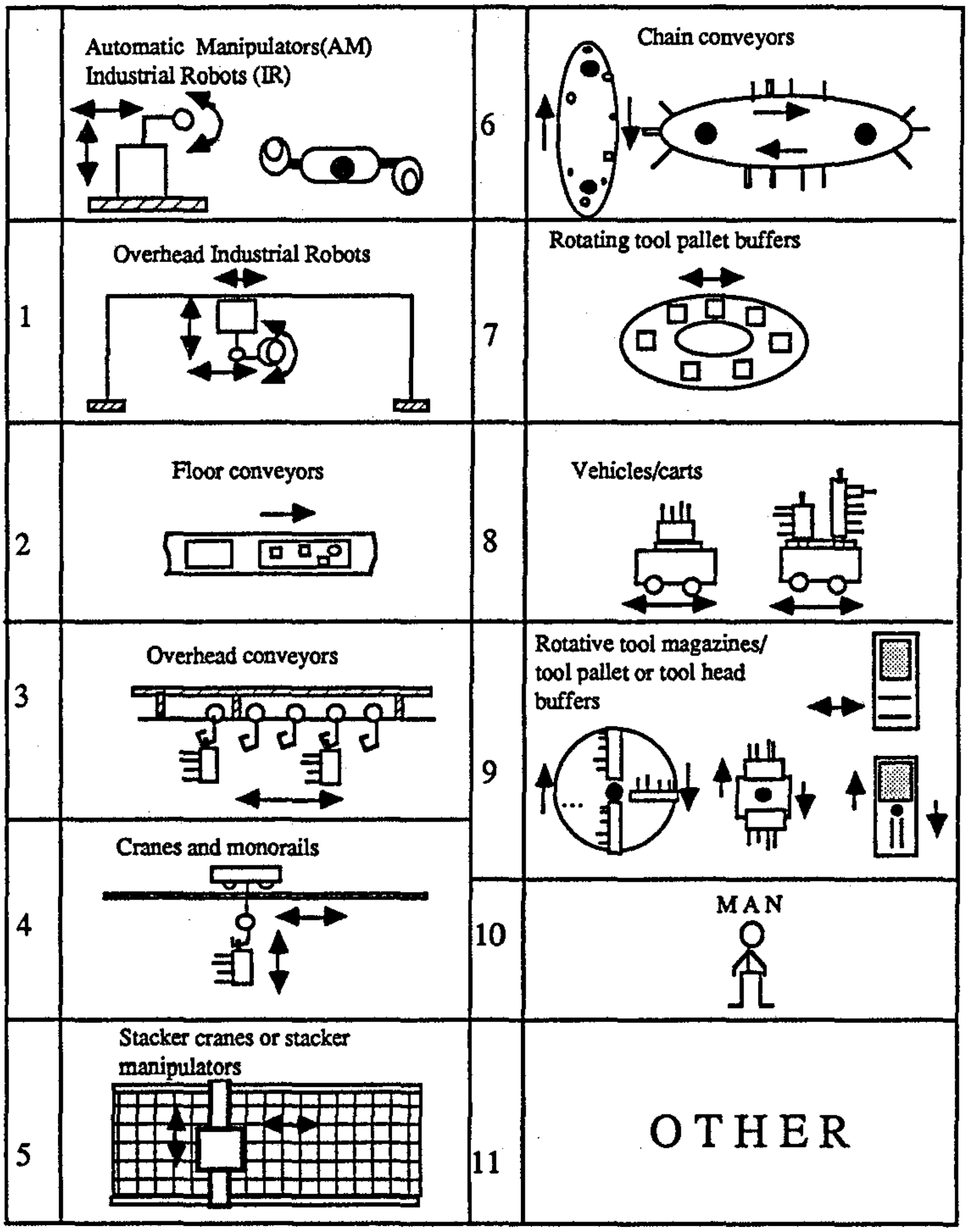


Fig. 5.9 Basic tool transport and handling elements for FMS Tool Flow Systems

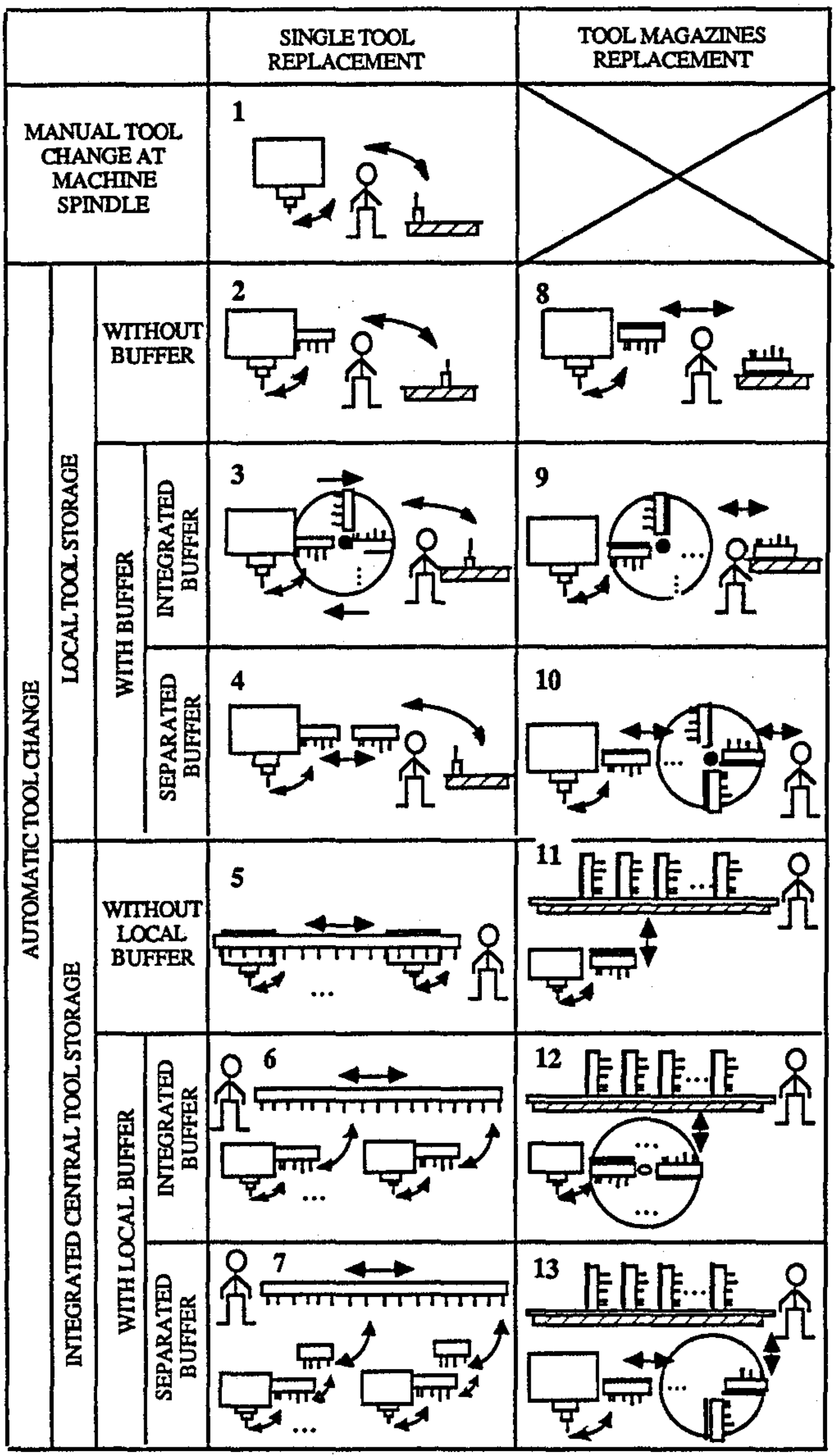


Fig.5.10 Tooling System Configurations for FMS

LEGEND :

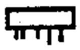
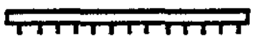
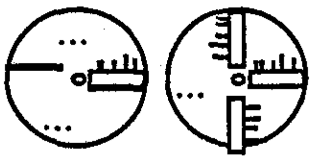
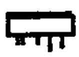
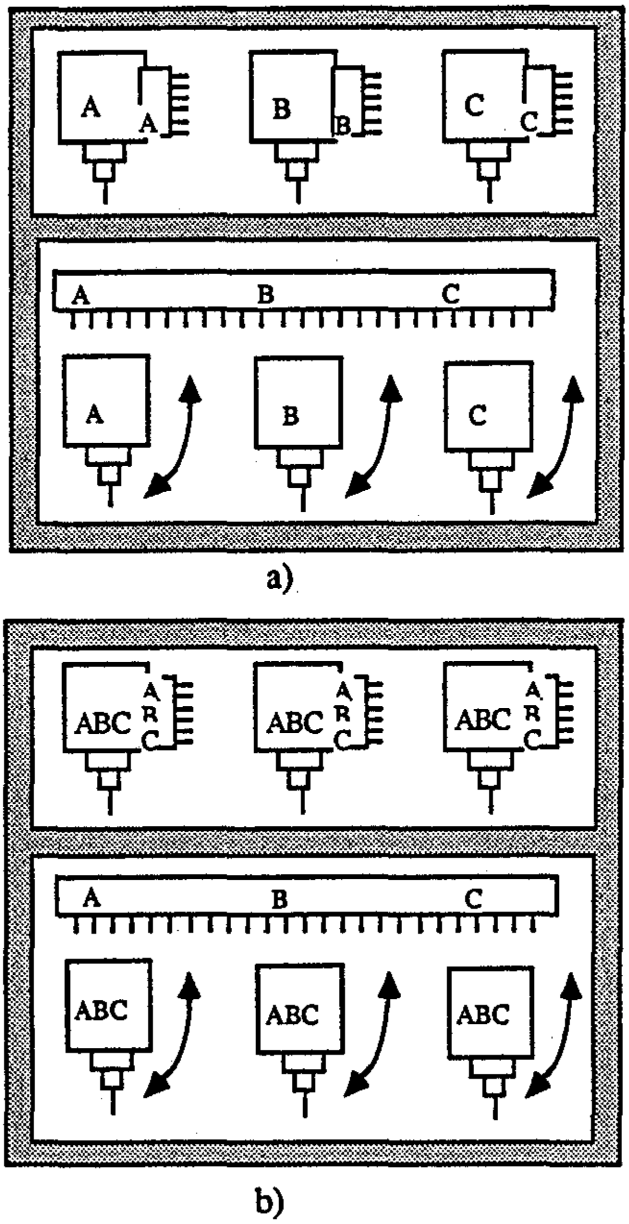
	Machining centre with attached tool magazine
	Unreplaceable tool magazine
	Central tool store for tool by tool reeplacement
	Multimagazine tool buffers
	Machining centre with replaceable tool magazine
	Replaceable tool magazine
	Central store for replaceable tool magazines
	Manipulating entity

Fig.5.10 (cont.)	Legend of the symbols used in the figure



Tools used	Routing Flexibility
T	None
T	None
T	None
T	Good

Legend:

a) - Single purpose machines/Multi-stage Systems
b) - Multiple purpose machines/Single Stage Systems
T - Minimum number of tools to process a part mix
A B C - Tool Central Store

Fig.5.11	The use of a central store for direct tool change into the spindle of the machines works best for Single Stage Systems.

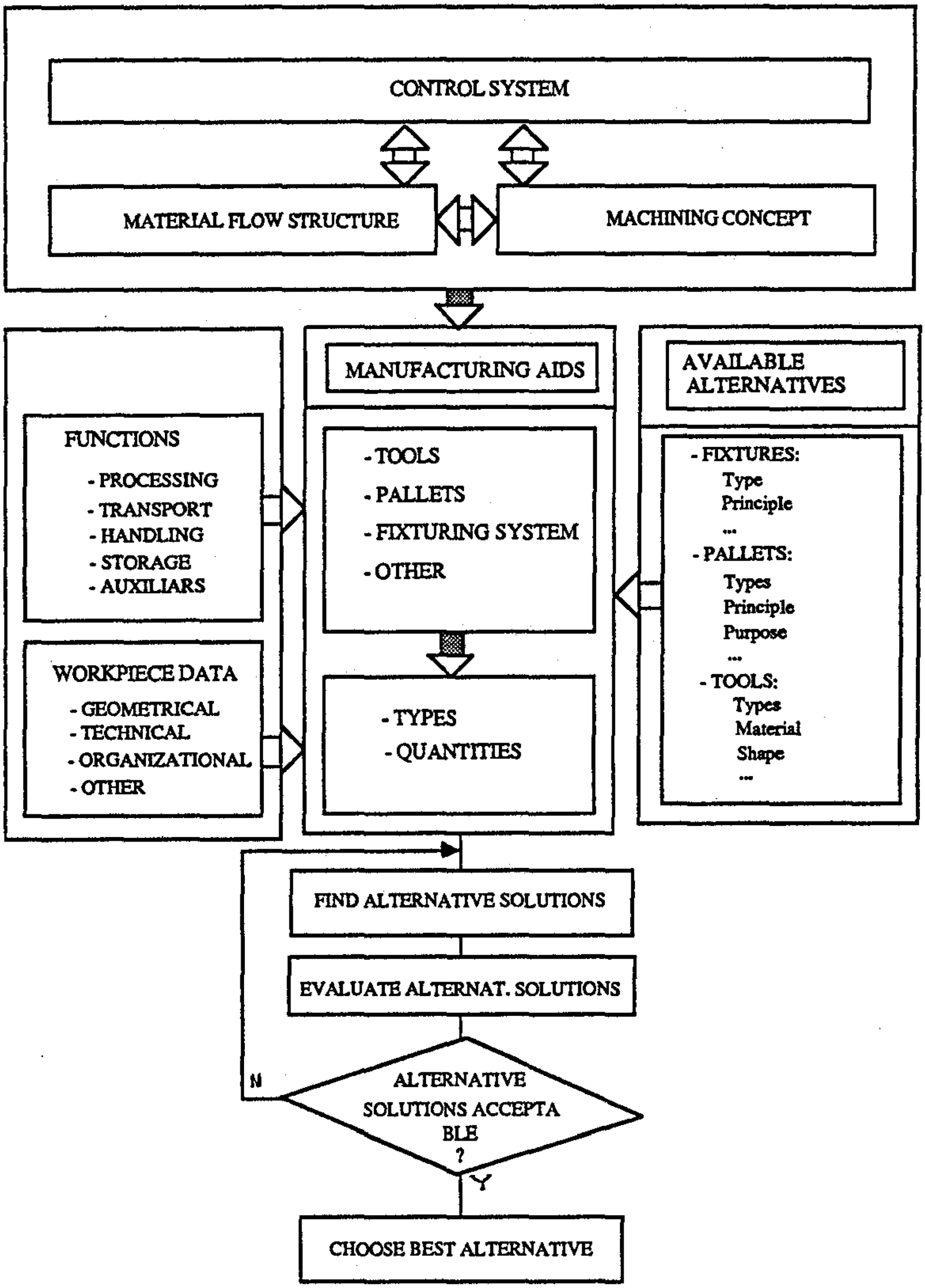


Fig. 6.1	Planning Manufacturing Aids

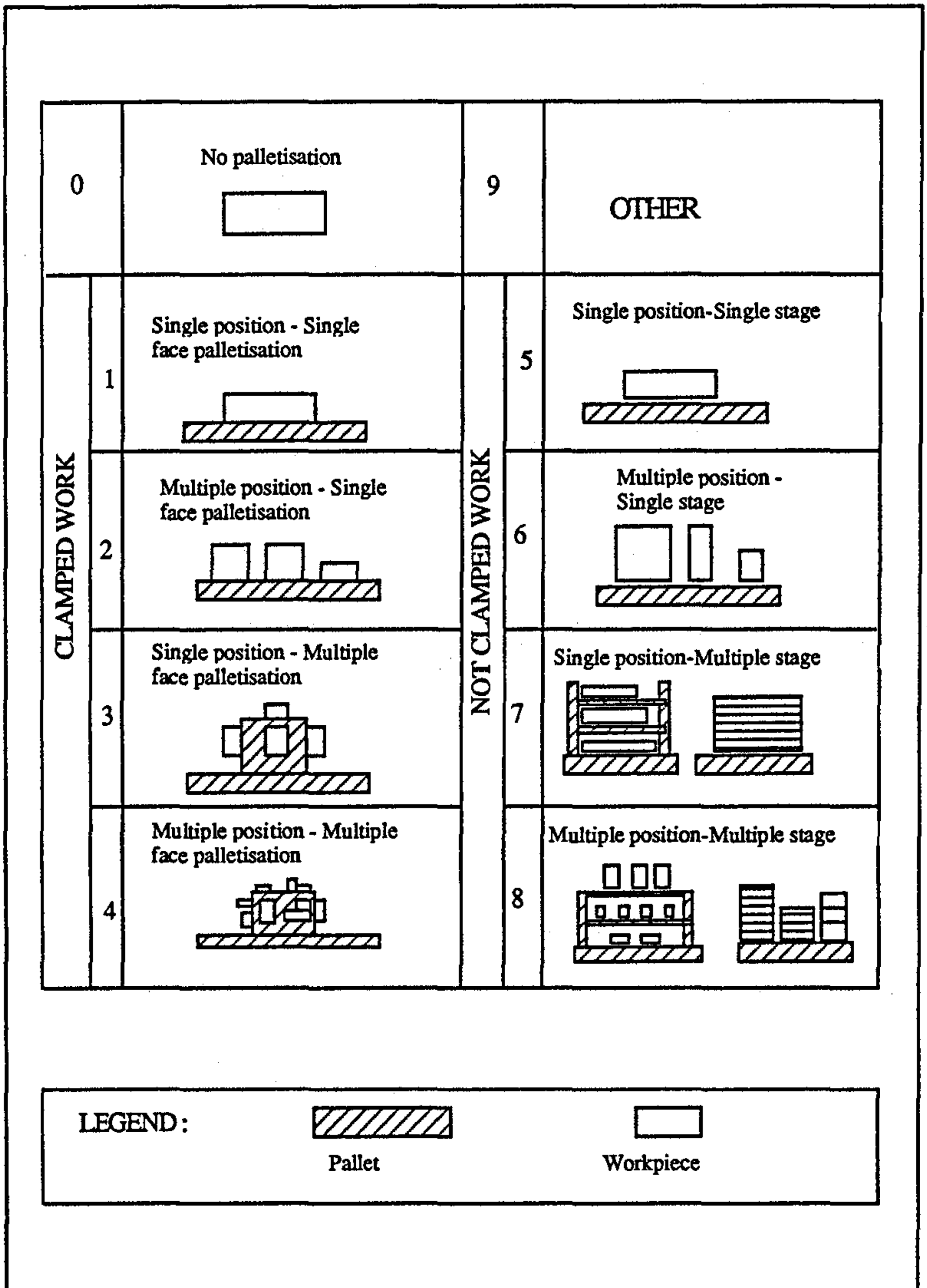


Fig. 6.2 Basic workpiece palletising solutions

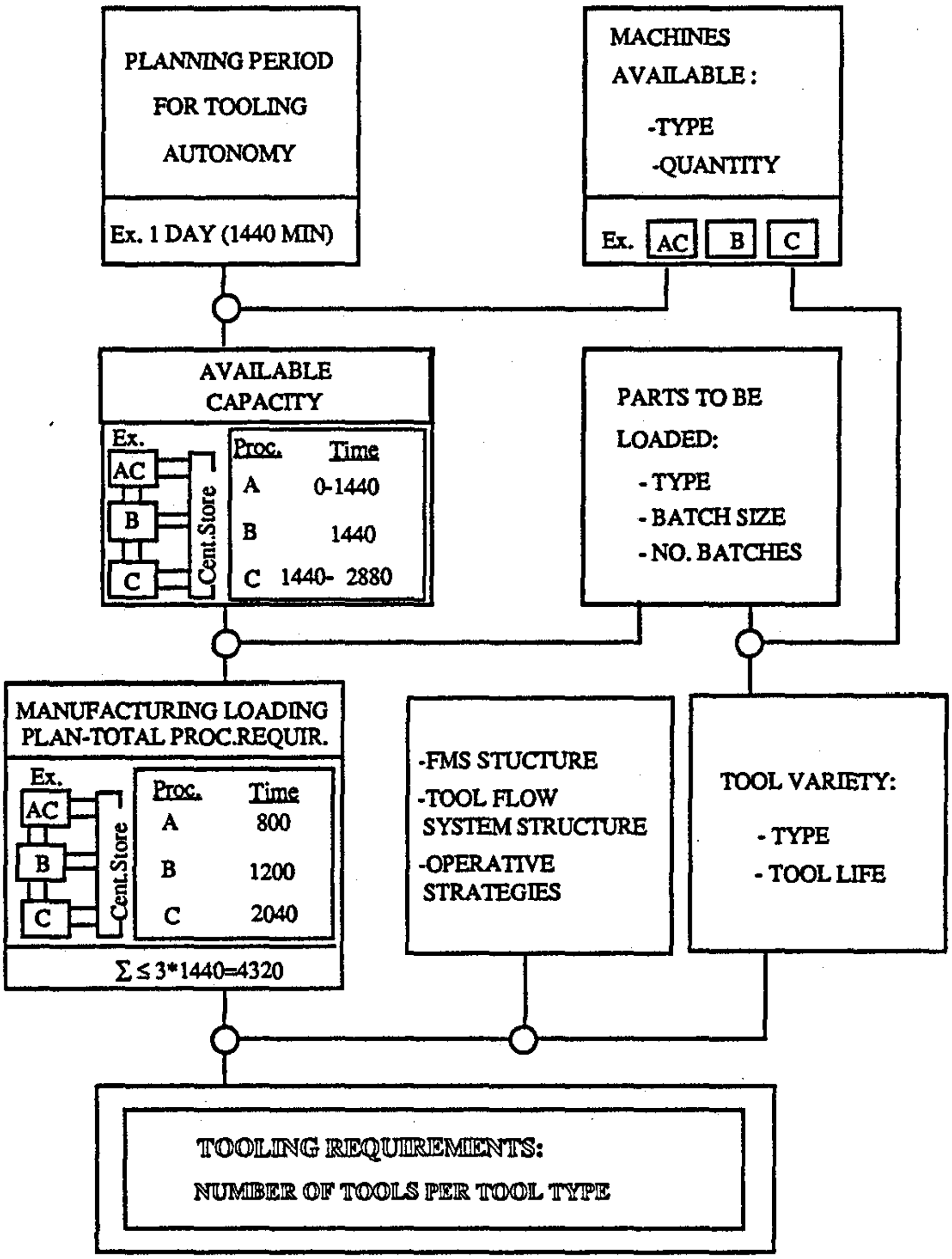


Fig. 6.3 Tool requirements for a manufacturing planned period with tooling autonomy

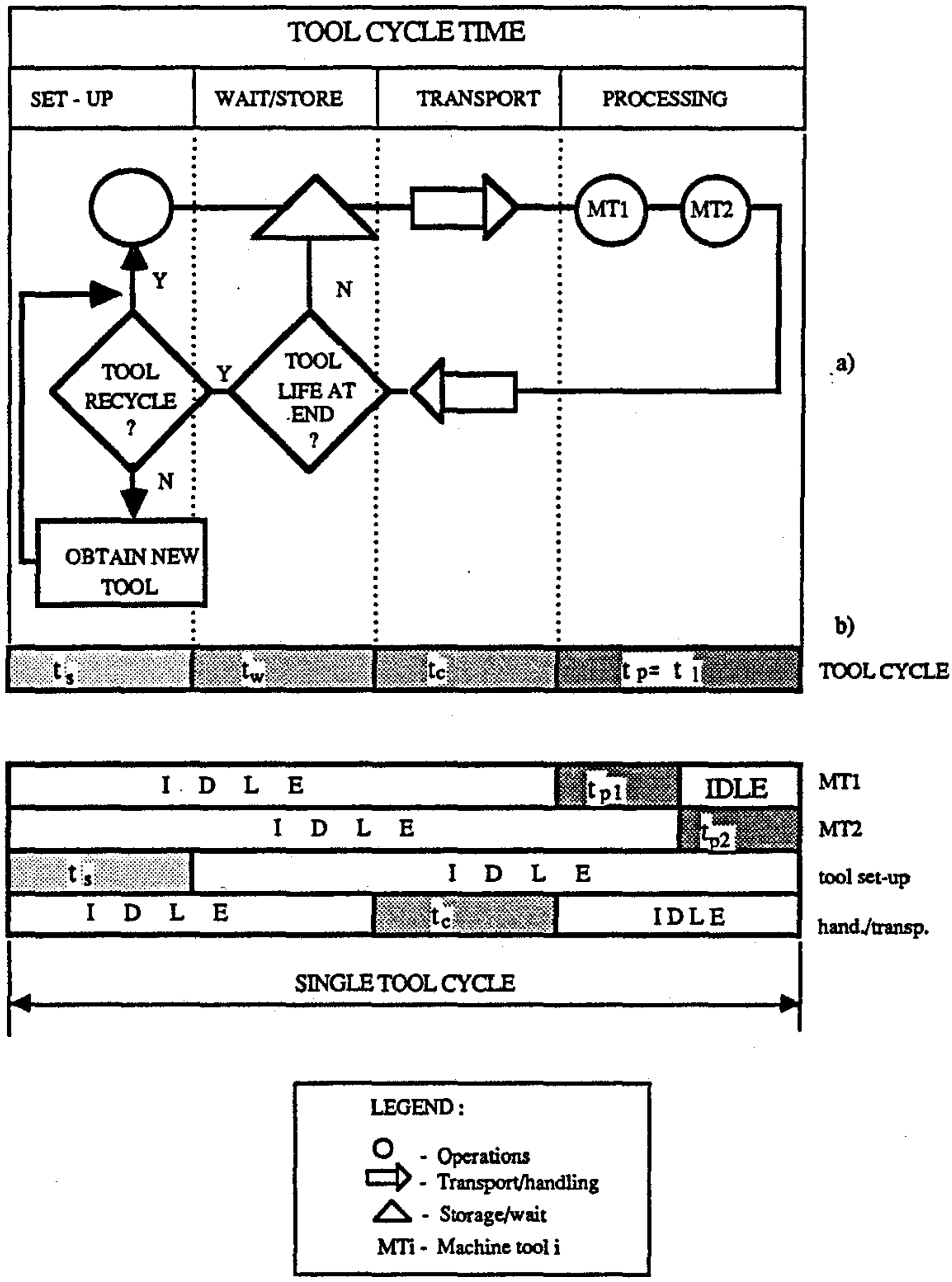


Fig. 6.4	a) - Schematic representation of the tool cycle time in a FMS b) - Multiple activity cycle diagram for a single tool

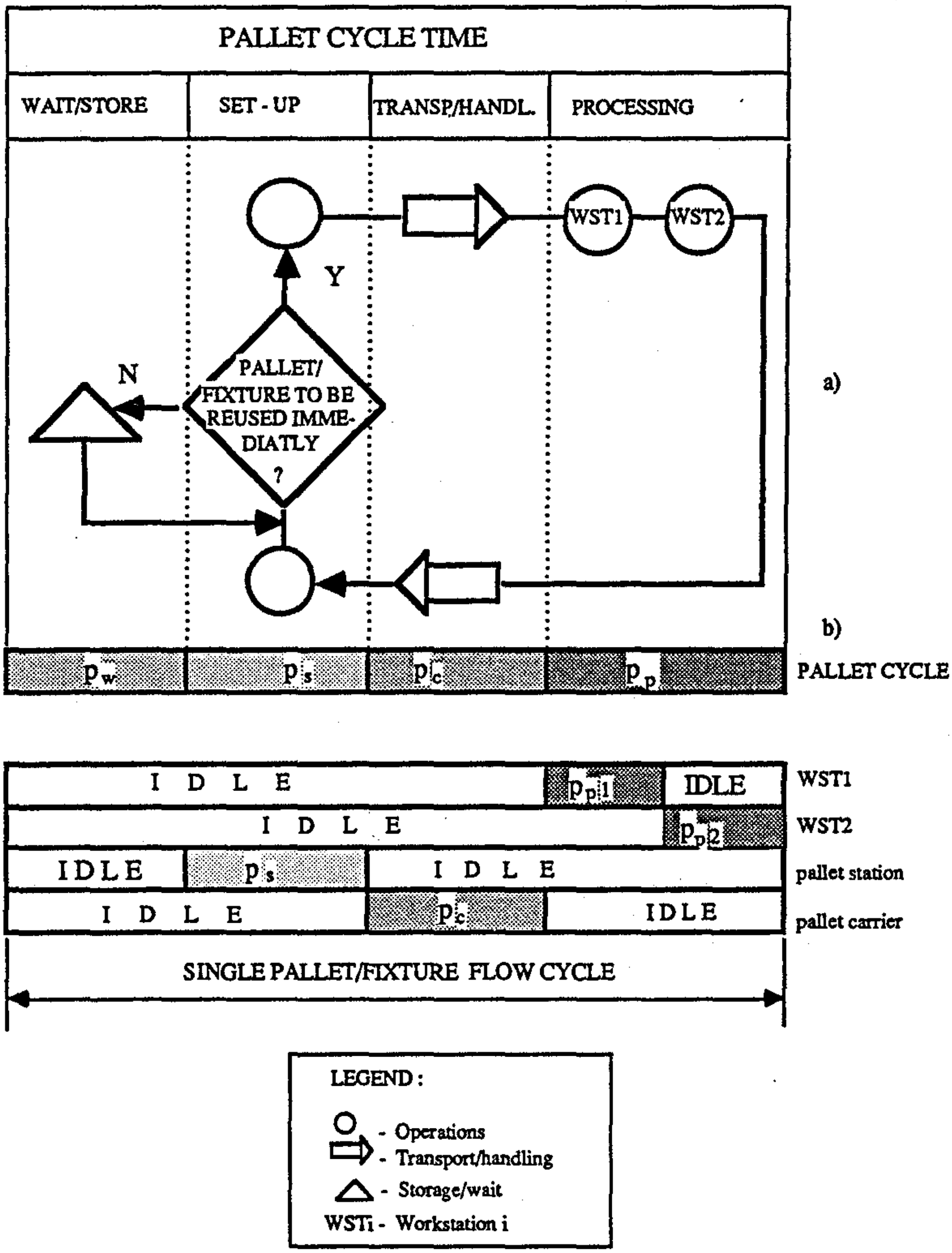


Fig. 6.5

a) - Schematic representation of the pallet cycle time in a FMS

b) - Multiple activity cycle diagram for a single pallet

t	$G_t = \sum_{n=1}^{t} G_n^t$
1	1
2	2
3	5
4	15
5	52
6	203
7	877
8	4140
9	21147
10	114589
11	667481

G_n^t - Number of tooling configurations with n tool groups formed from t basic tool sets

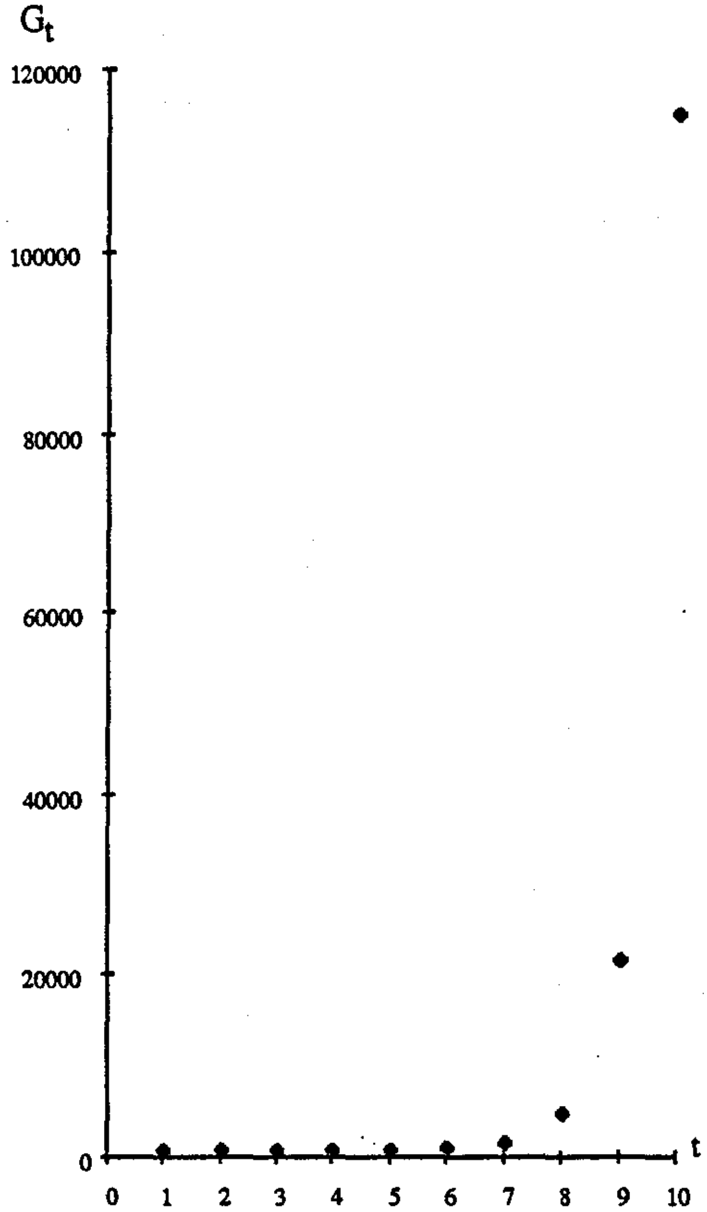


Fig. 8.1

Growth of the number of different tooling configurations, Gt as a function of the number of different basic tool sets, t, or corresponding part-operations in the part-mix

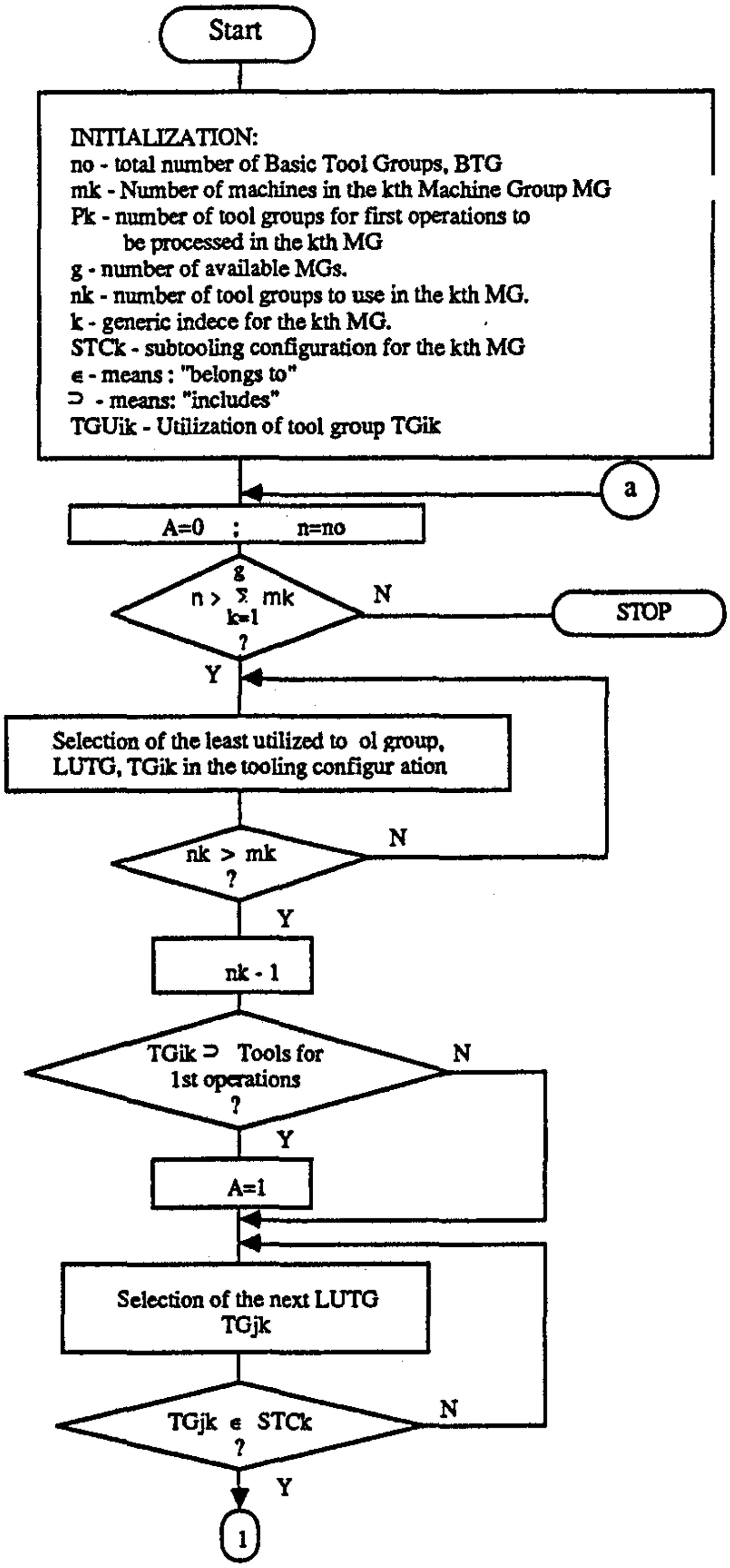


Fig. 8.2	Flow diagram for Tool Grouping Heuristic Rule A

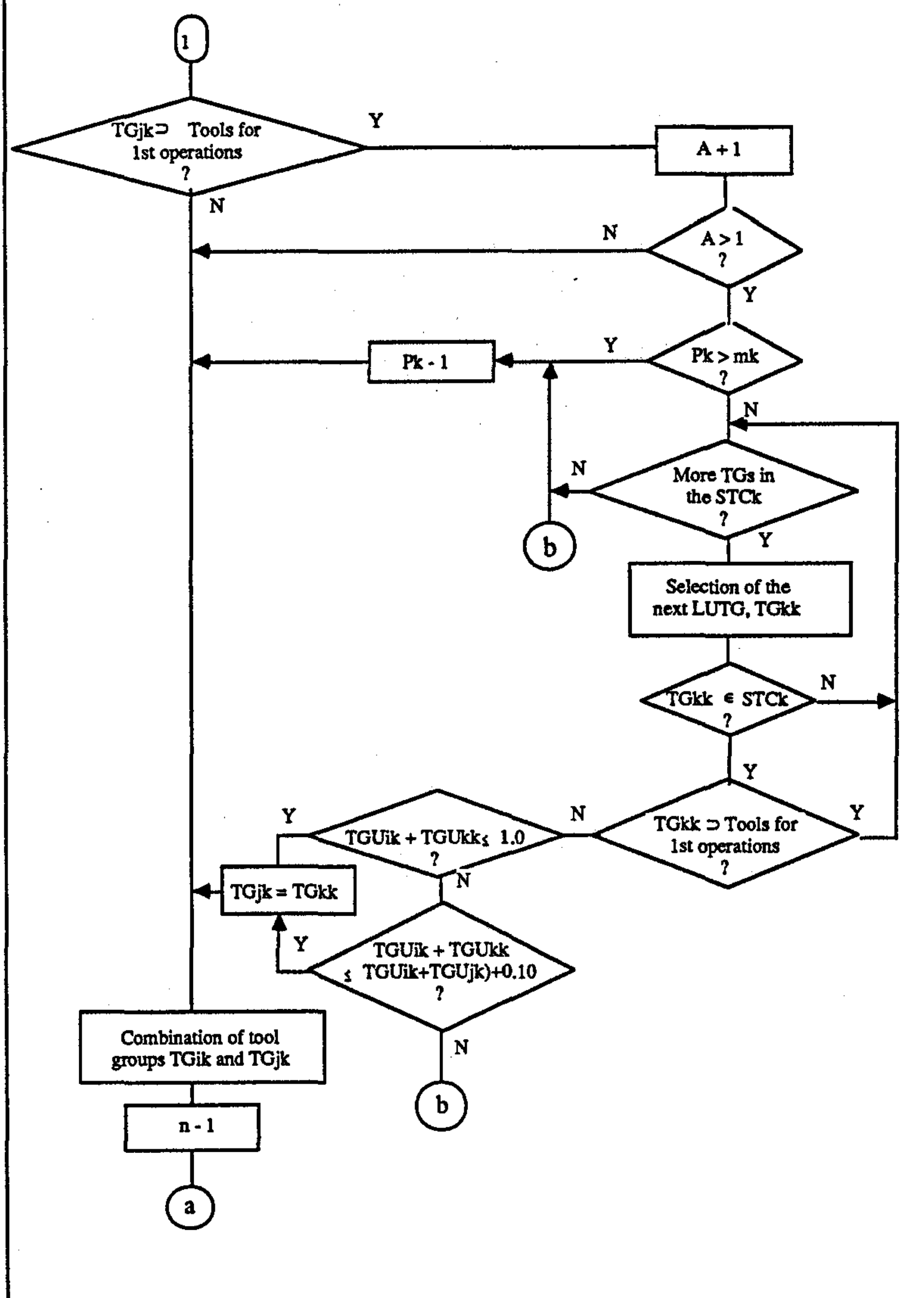


Fig. 8.2 (cont.)	Flow diagram for Tool Grouping Heuristic Rule A

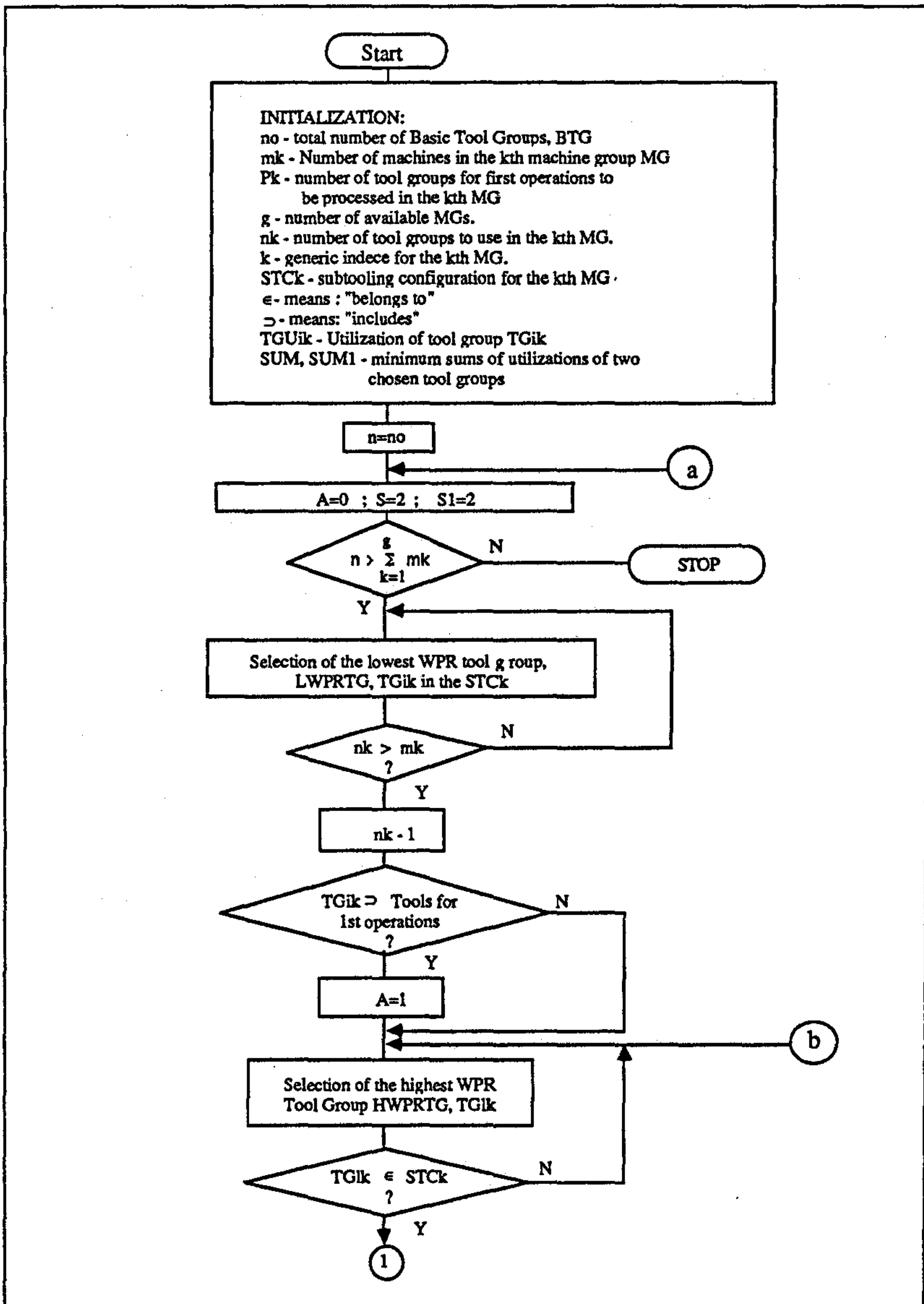


Fig. 8.3	Flow diagram for Tool Grouping Heuristic Rule B

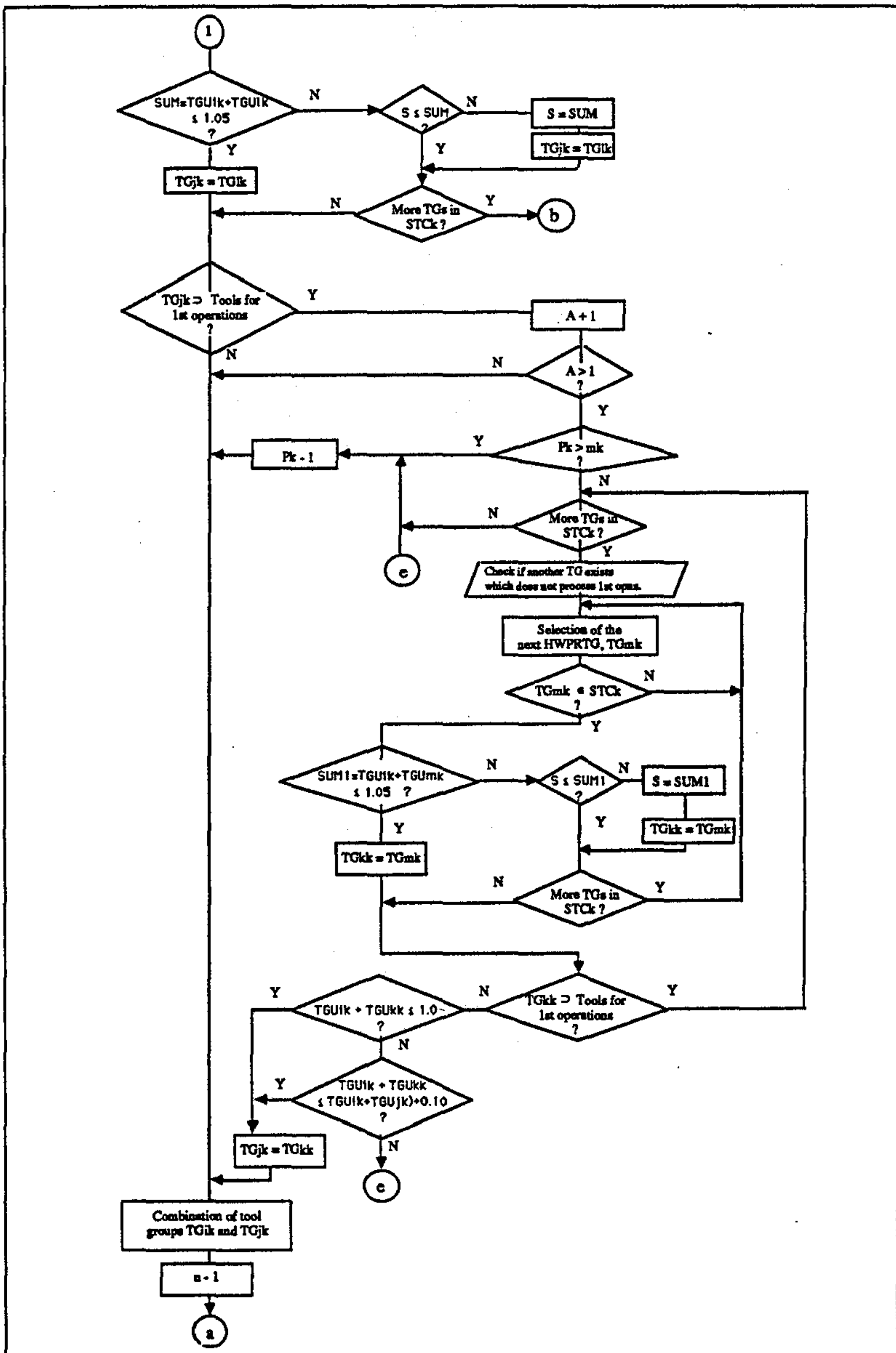
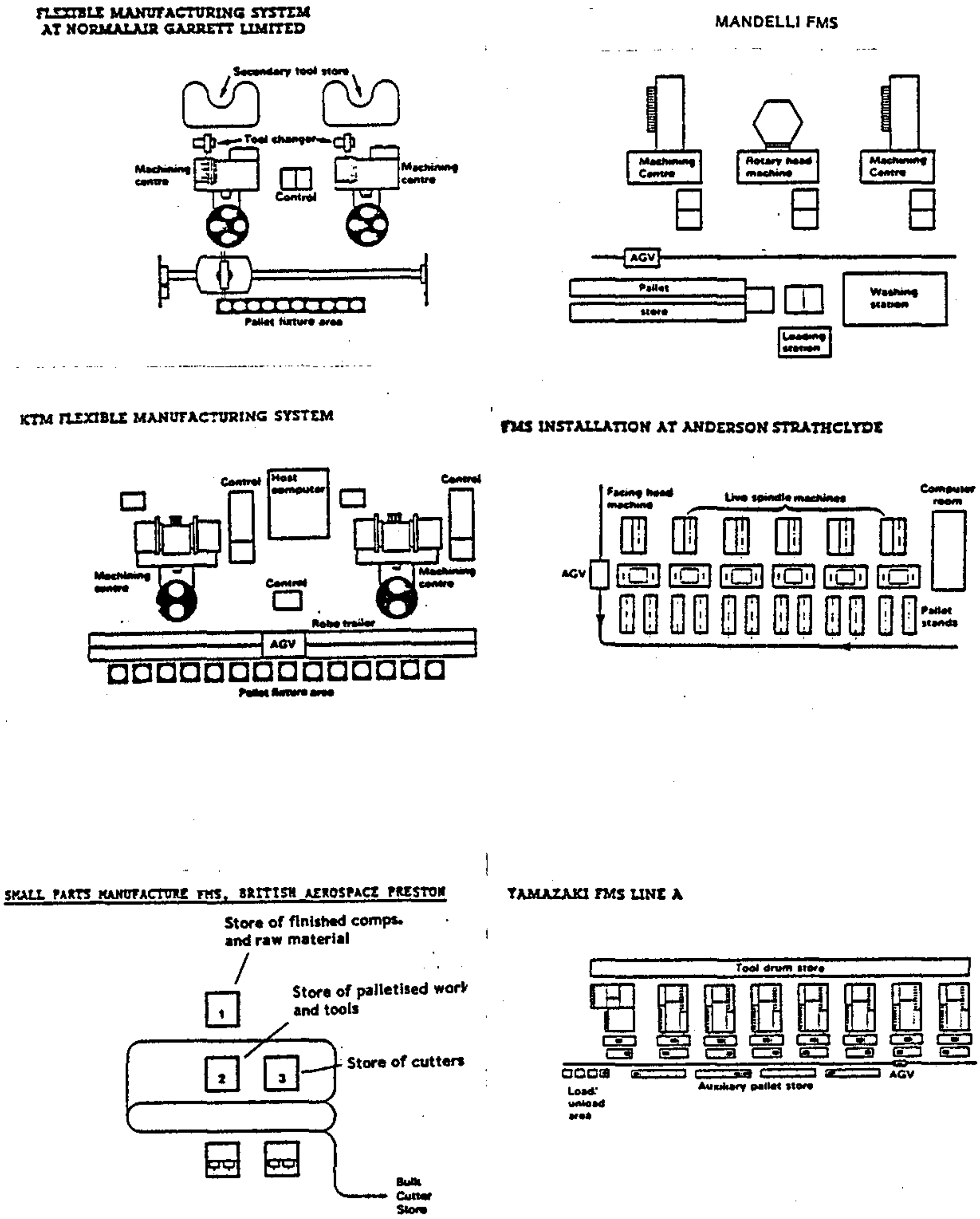
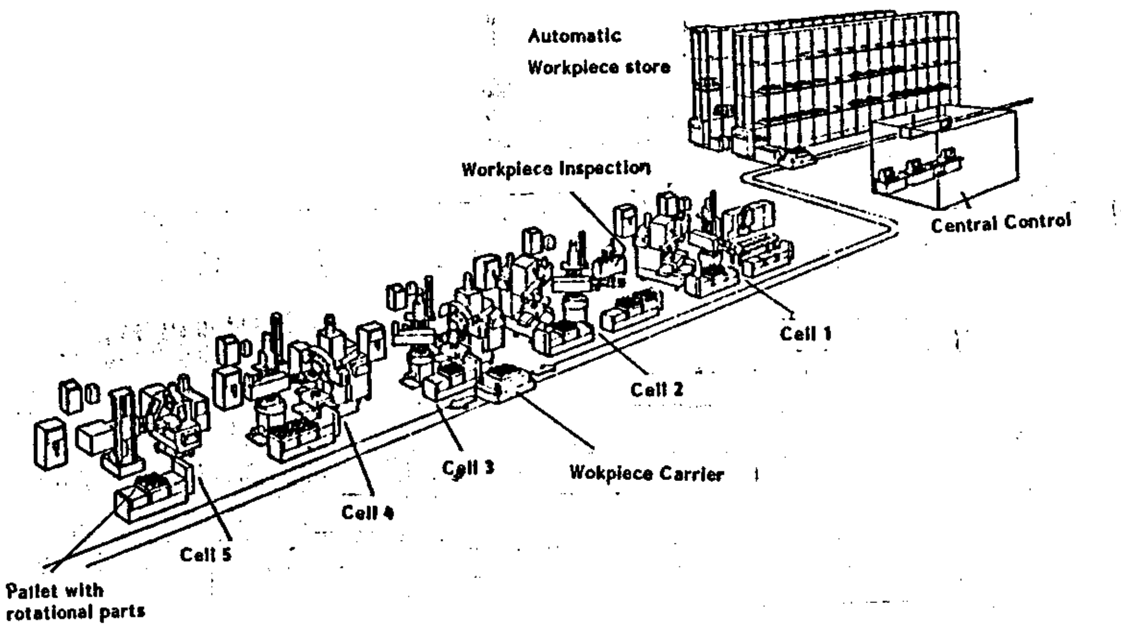


Fig. 8.3 (cont.)	Flow diagram for Tool Grouping Heuristic Rule B



Bibl.source: (33)

Fig. 9.4.1	Some typical FMS which can be studied with the developed simulation model.



Bibl.source: (146)

Fig. 9.4.1 (cont.)	Some typical FMS which can be studied with the developed simulation model.

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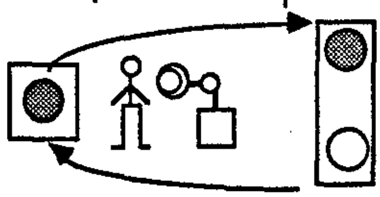
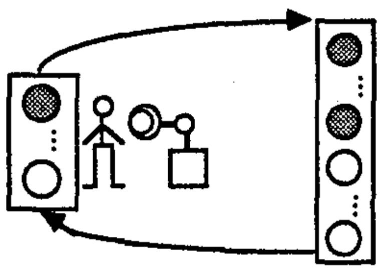
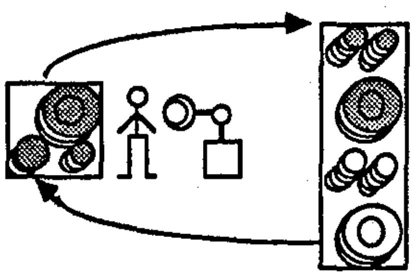
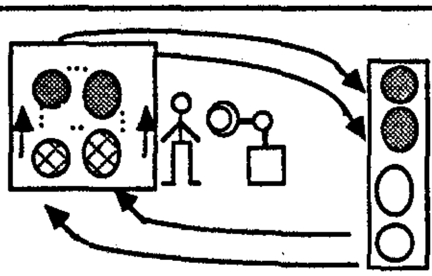
	CASE EXAMPLE			DESCRIPTION	
	Pallet	palletising entity	Parts stand	Part on pallet	Part/blank
1				Single part on pallet Single part operation	Unload finished part Load single blank
2				Multiple identi-cal parts on pallet Single part operation	Unload all finished parts Load a new set of iden-tical blanks
3				Multiple diffe-rent parts on pallet Single part operation	Unload all finished parts Load new sets of different blanks
4				Multiple diffe-rent parts on pallet Multiple part operations	Unload finished parts Transfer semi--processed parts Load new sets of different blanks

Legend:
- ○ Unprocessed part
- ⊗ Semi-processed part
- ● Processed part

Fig. 9.4.2	Typical examples of palletising stations and tasks

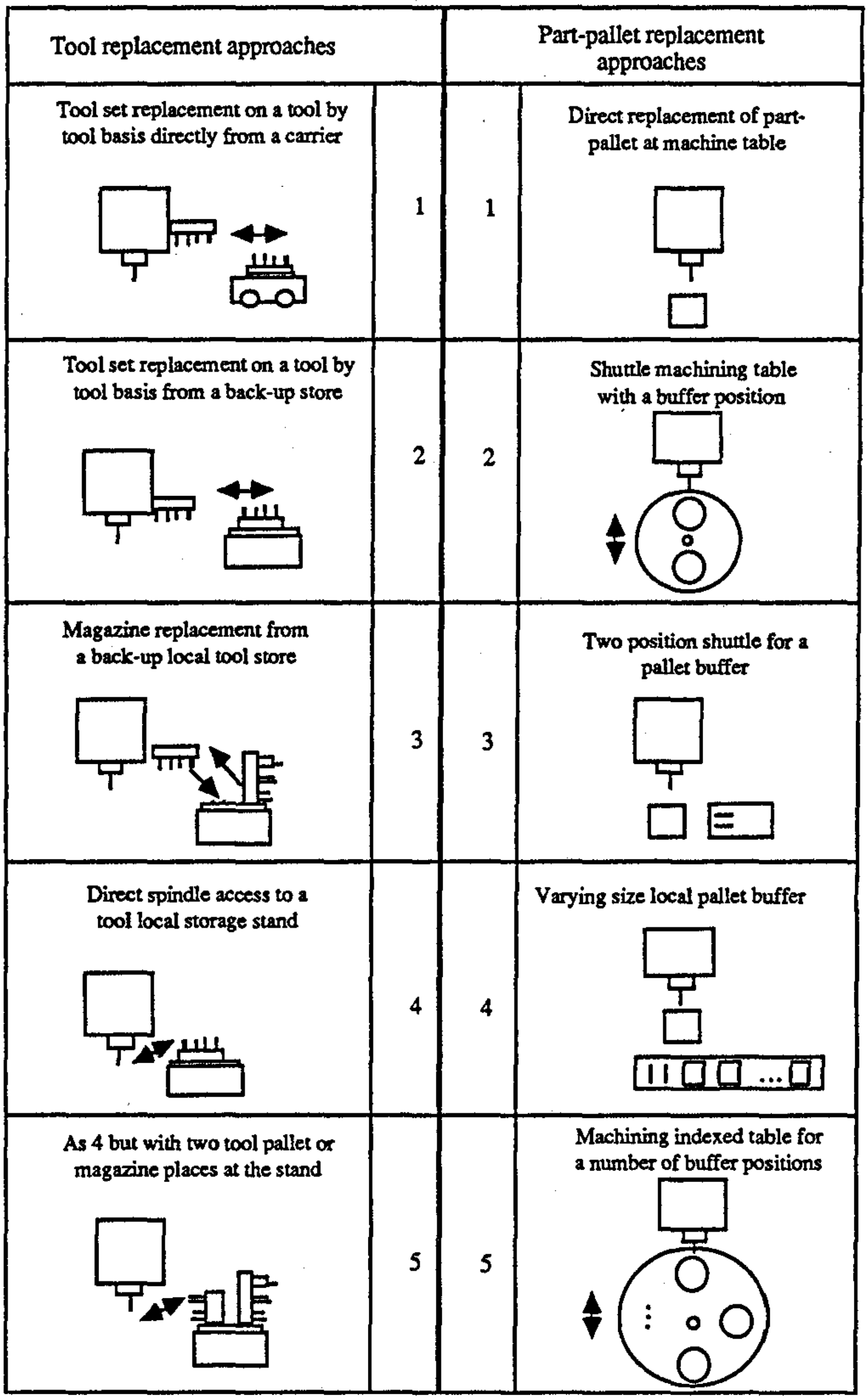


Fig. 9.4.3 Schematic representation of typical part and tool replacement approaches which may be combined to configure a variety of machining stations.

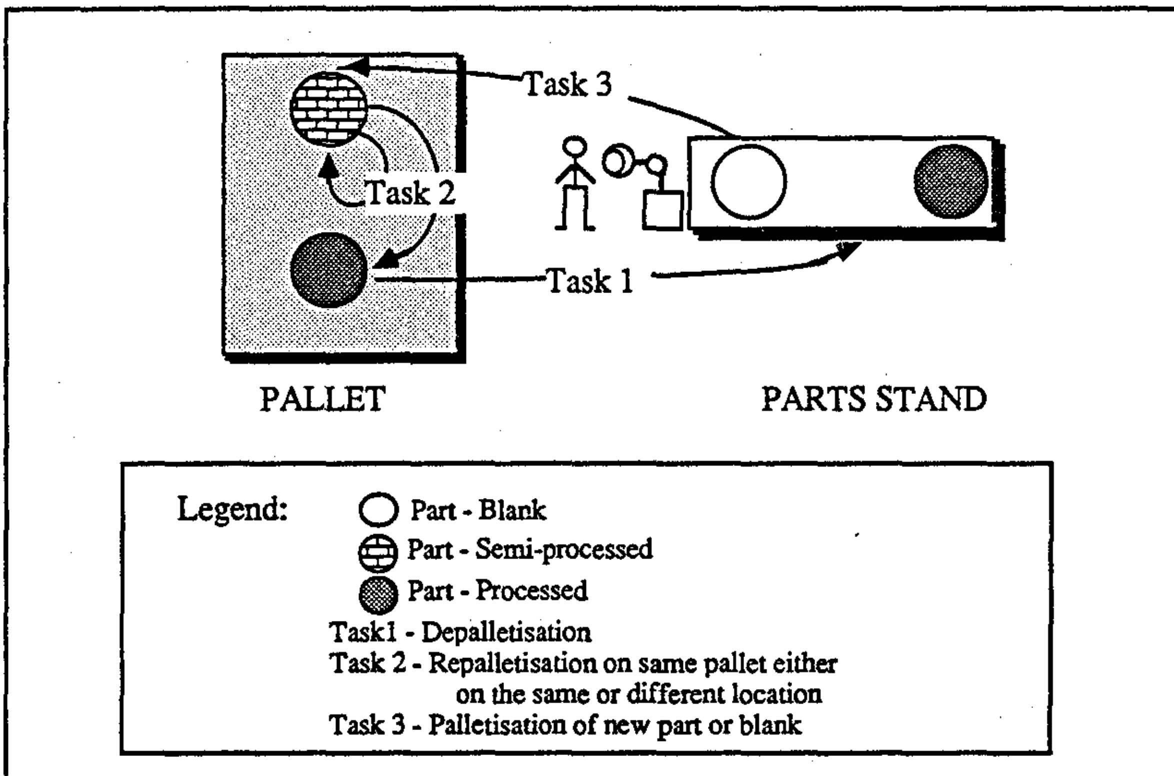


Fig. 9.5.1 Basic palletisation tasks

to \ From (FMS STATIONS)	1	2	...	i	k	n
1	0	t_{21}	...	t_{i1}	t_{k1}	... t_{n1}
2	t_{12}	0	...	t_{i2}	t_{k2}	... t_{n2}
⋮	⋮	⋮	⋮	⋮	⋮	⋮
i	t_{1i}	t_{2i}	...	0	t_{ki}	... t_{ni}
k	t_{1k}	t_{2k}	...	t_{ik}	0	... t_{nk}
⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	t_{1n}	t_{2n}	...	t_{in}	t_{kn}	... 0

(Rows: FMS STATIONS)

Legend:

t_{ik} Transport time from station i to station k

t_{ki} Transport time from station k to station i

Fig. 9.5.2 The transport times between stations are specified though a matrix

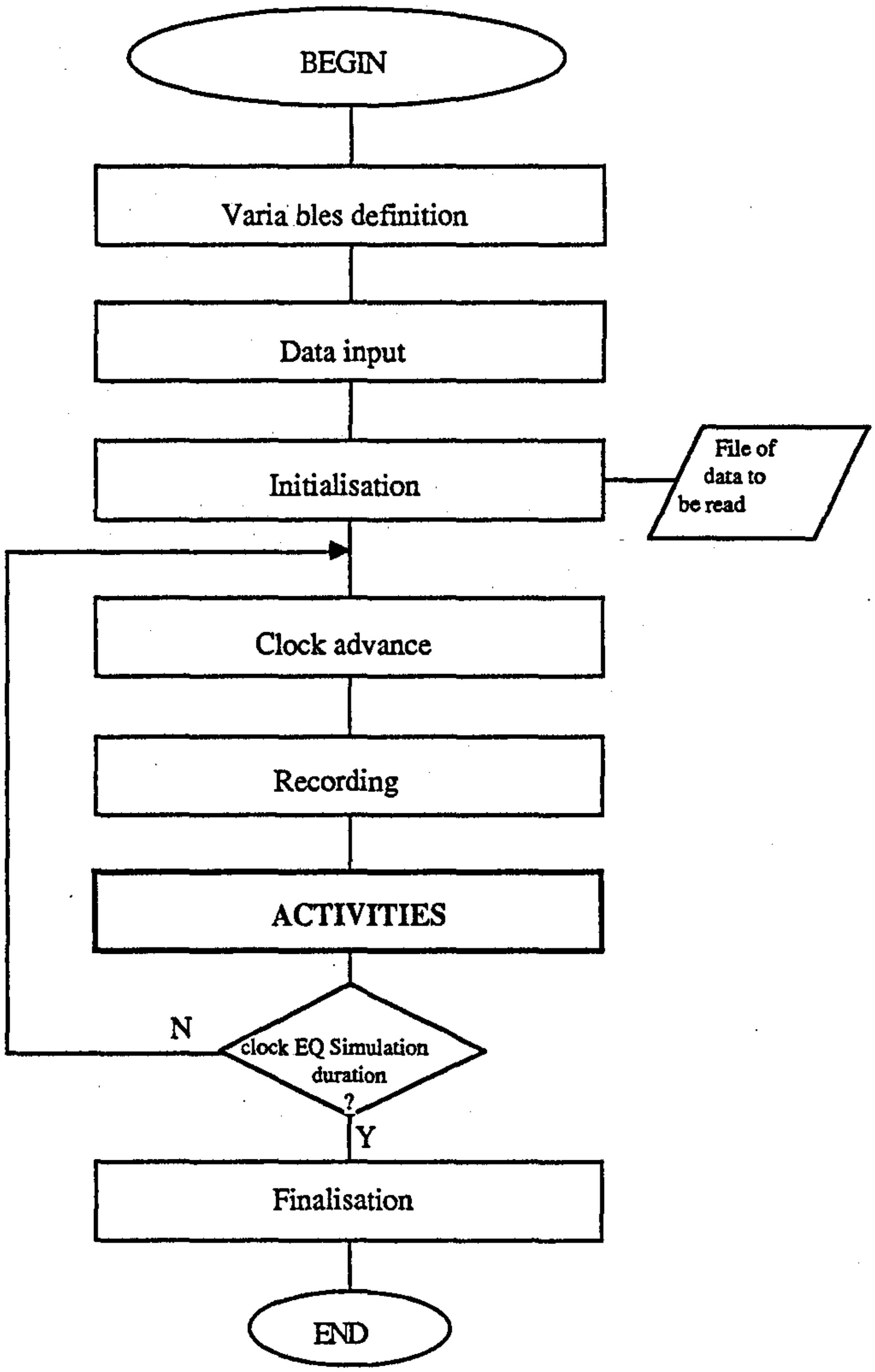


FIG. 9.6.1	Overall Simulation Model Block Diagram

BEGIN
DEFINITION
OF VARIABLES

ENTITIES

- -BATCHES TO RELEASE
- -ASSEMBLY SETS
- -PARTS
- -TOOL SETS
- -GOUPS OF TOOLS SETS
- -FIXTURED PALLETS
- -LOCATIONS ON PALLETS FOR PARTS
- -MACHINES
- -HANDLING DEVICES
- -OPERATORS

ATTRIBUTES AND QUEUES

BATCHES' ATTTRIBUTES

- -TYPE OF BATCH
- -SIZE OF BATCH
- -GENERALIZED PRIORITY FACTOR OF BATCH
- -BATCH DUE DATE
- -TOTAL PROCESSING TIME OF BATCH

QUEUES OF BATCHES

- -QUEUE OF ALL BATCHES

ASSEMBLY SETS' ATTRIBUTES

- -TYPE OF ASSEMBLY SET
- -NUMBER OF PARTS IN THE SET
- -TOTAL SET PROCESSING TIME
- -SET THROUGHPUT TIME
- -TIME THE FIRST PART OF THE SET BECOMES PALLETISED
- -SET STATE (1-SET LOADED INTO THE FMS; 0-SET NOT YET LOADED INTO THE FMS)

QUEUES OF ASSEMBLY SETS

- -QUEUE OF ALL SETS
- -ASSEMBLY SETS BEING PROCESSED

PARTS' ATTRIBUTES

- -TYPE
- -TIME CELL
- -NEXT OPERATION TO BE PROCESSED
- -NUMBER OF OPERATION STILL TO BE PROCESSED
- -GENERALIZED PRIORITY FACTOR OF PART
- -DUE DATE OF THE PART
- -CUMULATIVE PROCESSED TIME
- -PART THROUGHPUT TIME
- -TIME A PART BECOMES PALLETISED

PART QUEUES

- -QUEUE OF ALL PARTS
- -PARTS TO BE PALLETISED
- -PARTS COMPLETED
- -PARTS PALLETISED ON A PALLET BUT NOT YET MACHINED
- -PARTS PALLETISED ON A PALLET BUT MACHINED
- -PARTS NOT YET ASSIGNED TO MACHINES
- -PARTS ASSIGNED TO MACHINES
- -PARTS ASSIGNED TO A MACHINE
- -PARTS LOADED TO A MACHINE
- -HELP QUEUES

TOOL SETS' ATTRIBUTES

- -TYPE OF TOOL SET

TOOL SETS' QUEUES

- -QUEUE OF ALL TOOL SETS
- -TOOL SETS IN A TOOL GROUP

TOOL GROUPS' ATTRIBUTES

- -TYPE OF TOOL GROUP
- -NUMBER OF TOOL SETS
- -NUMBER OF TOOLS PER TOOL GROUP
- -TIME CELL
- -TOOL GROUP UTILIZATION

TOOL GROUPS' QUEUES

- -CENTRAL STORE OF TOOL GROUPS TO LOAD INTO THE MACHINES
- -TOOL GROUPS LOADED INTO A MACHINE
- -TOOL GROUPS ASSIGNED TO A MACHINE
- -HELP QUEUES

FIXTURES PALLETS' ATTRIBUTES

- -TYPE OF PALLET
- -NUBER OF PARTS PALLETISED
- -GENERALIZED PRIORITY FACTOR OF PALLET
- -TIME CELL
- -TIME PALLET IS NOT USED

FIXTURED PALLETS' QUEUES

- -CENTRAL PALLET STORE
- -LOCAL PALLET STORAGE AND PALLETISING AREA
- -PALLETS WAITING LOAD INTO MACHINES
- -PALLETS LOADED INTO A MACHINE

LOCATION ON PALLETS' ATTRIBUTES

- -TYPE OF LOCATION

LOCATION OF PALLETS' QUEUES

- -QUEUE OF ALL LOCATIONS ON PALLETS
- -EMPTY LOCATIONS ON A PALLET
- -OCCUPIED LOCATIONS ON A PALLET

MACHINES' ATTRIBUTES

- -TYPE
- -TIME CELL
- -WORK LOAD
- -PALLET BUFFER SIZE
- -STATE (1 - Working; 0 - Not working)
- -TOOLS' MAGAZINE SIZE
- -PROCESSING/TAPE TIME

MACHINE QUEUES OR SETS

- -MACHINES' QUEUE
- -MACHINES TO BE LOADED
- -HELP QUEUES

HANLING DEVICES/CARRIERS' ATTRIBUTES

- -PALLET CARRYING CAPACITY
- -TIME CELL
- -LOCATION OF THE CARRIER IN THE PLANT
- -PALLET AT CARRIER UNLOADED FROM A MACHINE
- -UTILIZED TIME

CARRIERS QUEUES OR SETS

- -QUEUE OF ALL CARRIERS
- -CARRIERS AVAILABLE

OPERATORS' ATTRIBUTES

- -TIME CELL
- -BUSY TIME
- -PALLETISING TIME

OPERATORS' QUEUES

- -QUEUE OF ALL OPERATORS
- -OPERATORS IDLE

OTHER VARIABLES

-A considerable number of other variables, particularly presented in the form of histograms and one, two and three dimensional real and integer arrays, for control of and recording information from the simulation process also have been defined.

END
DEFINITION
OF VARIABLES

Fig. 9.6.2	Definition of Variables

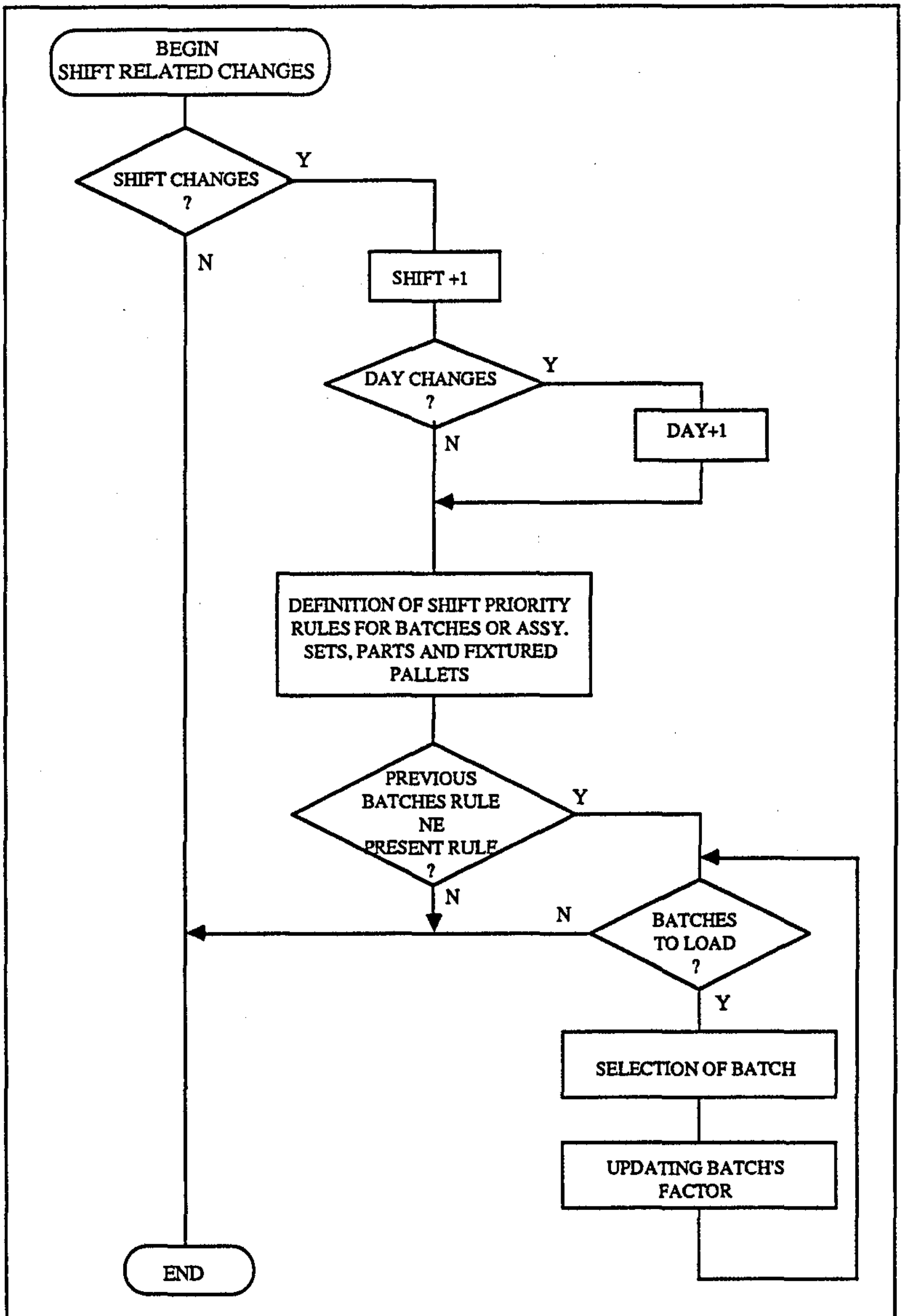


Fig. 9.6.3	Flow Diagram of shift related variable changes

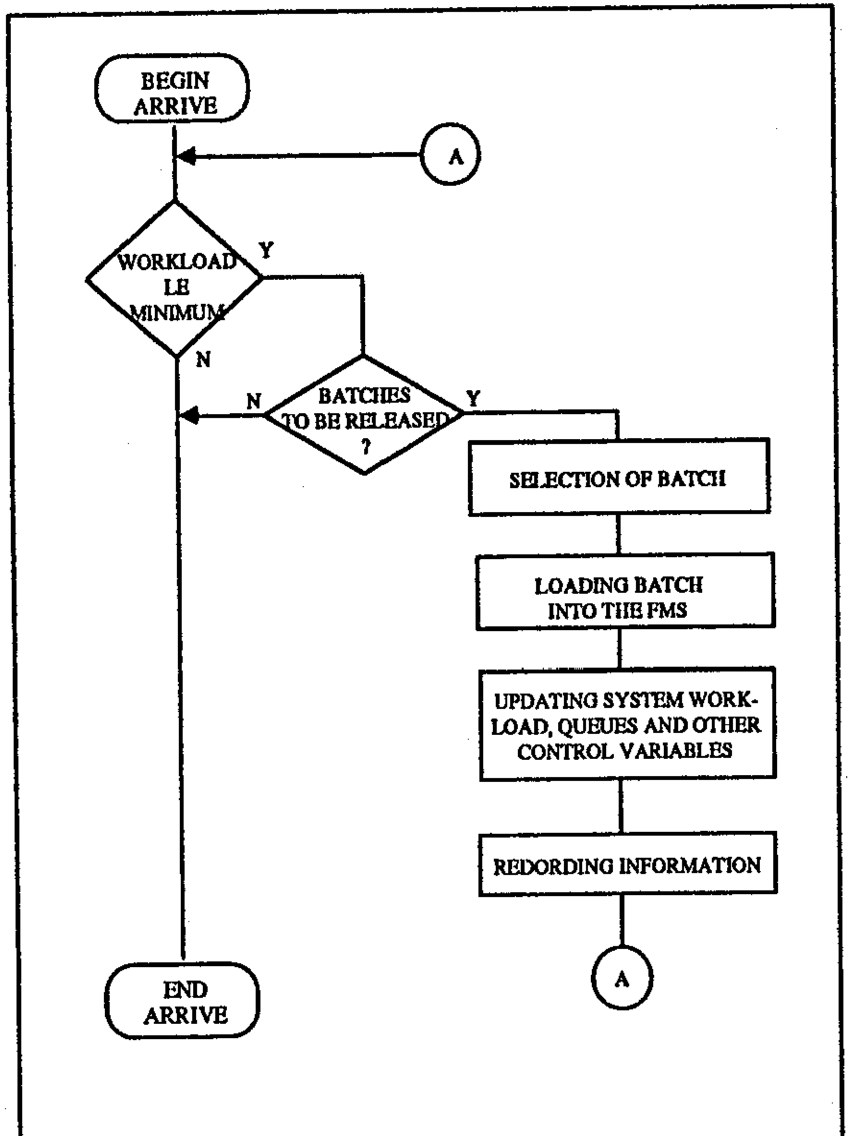


Fig. 9.6.4	Flow Diagram of the Activity ARRIVE

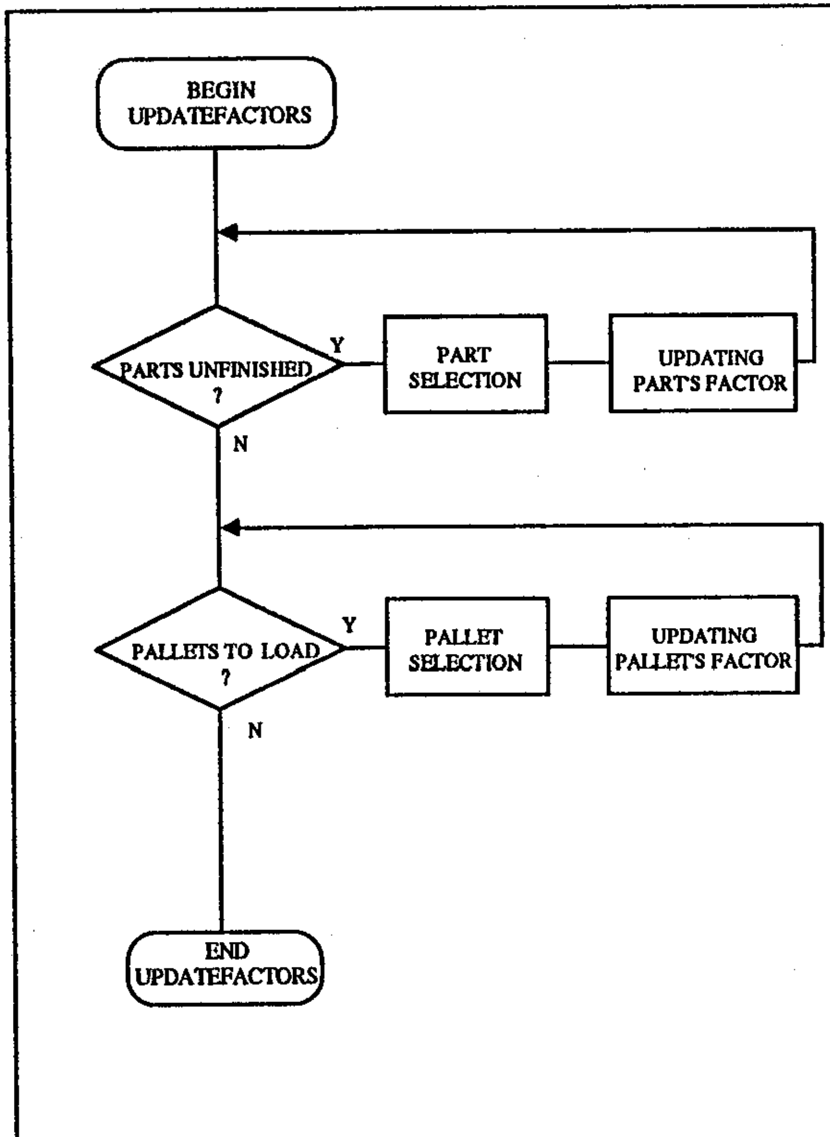


Fig. 9.6.5	Flow Diagram of the Activity UPDATEFACTORS

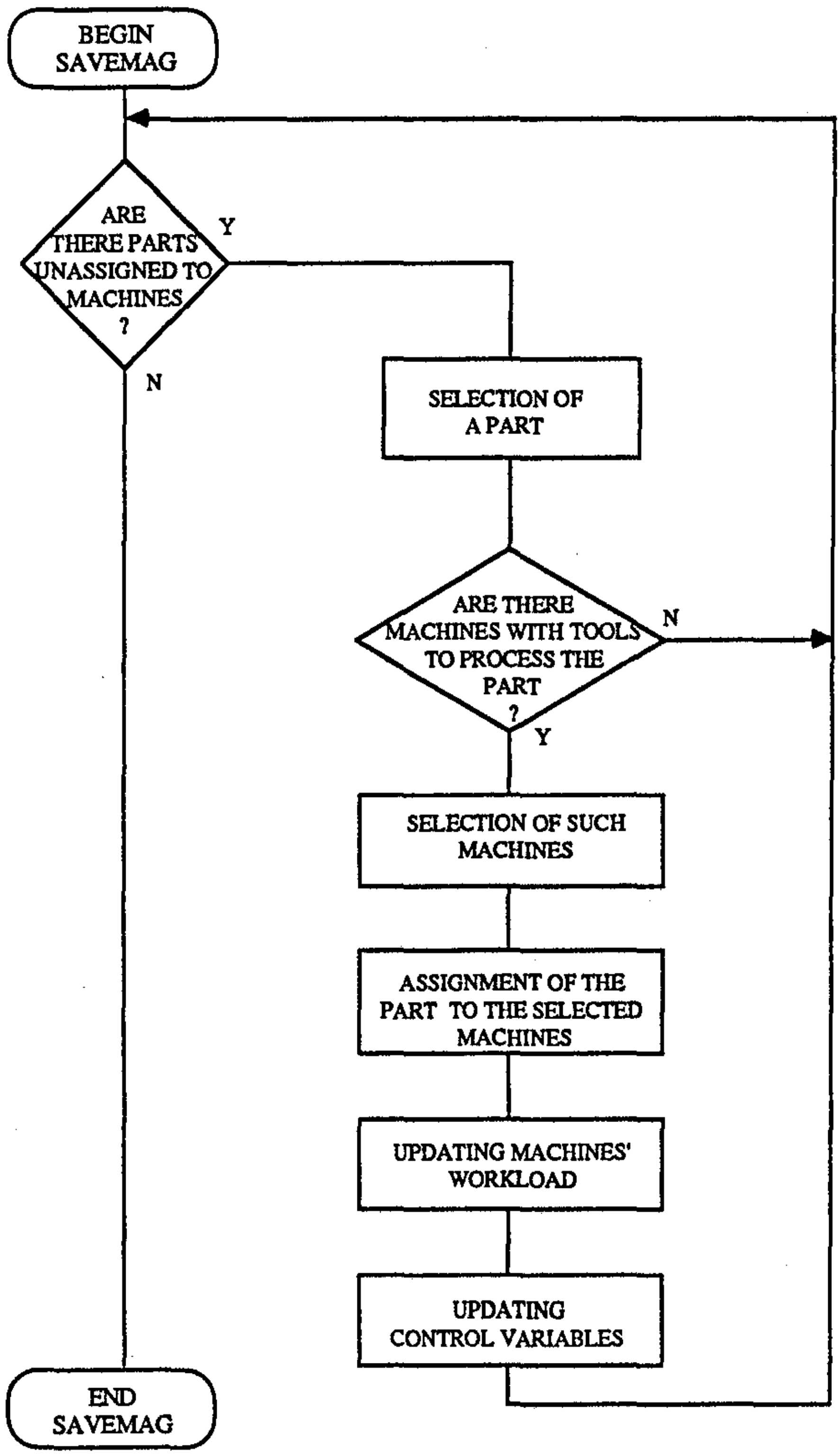


Fig. 9.6.6	Flow Diagram of the Activity SAVEMAG

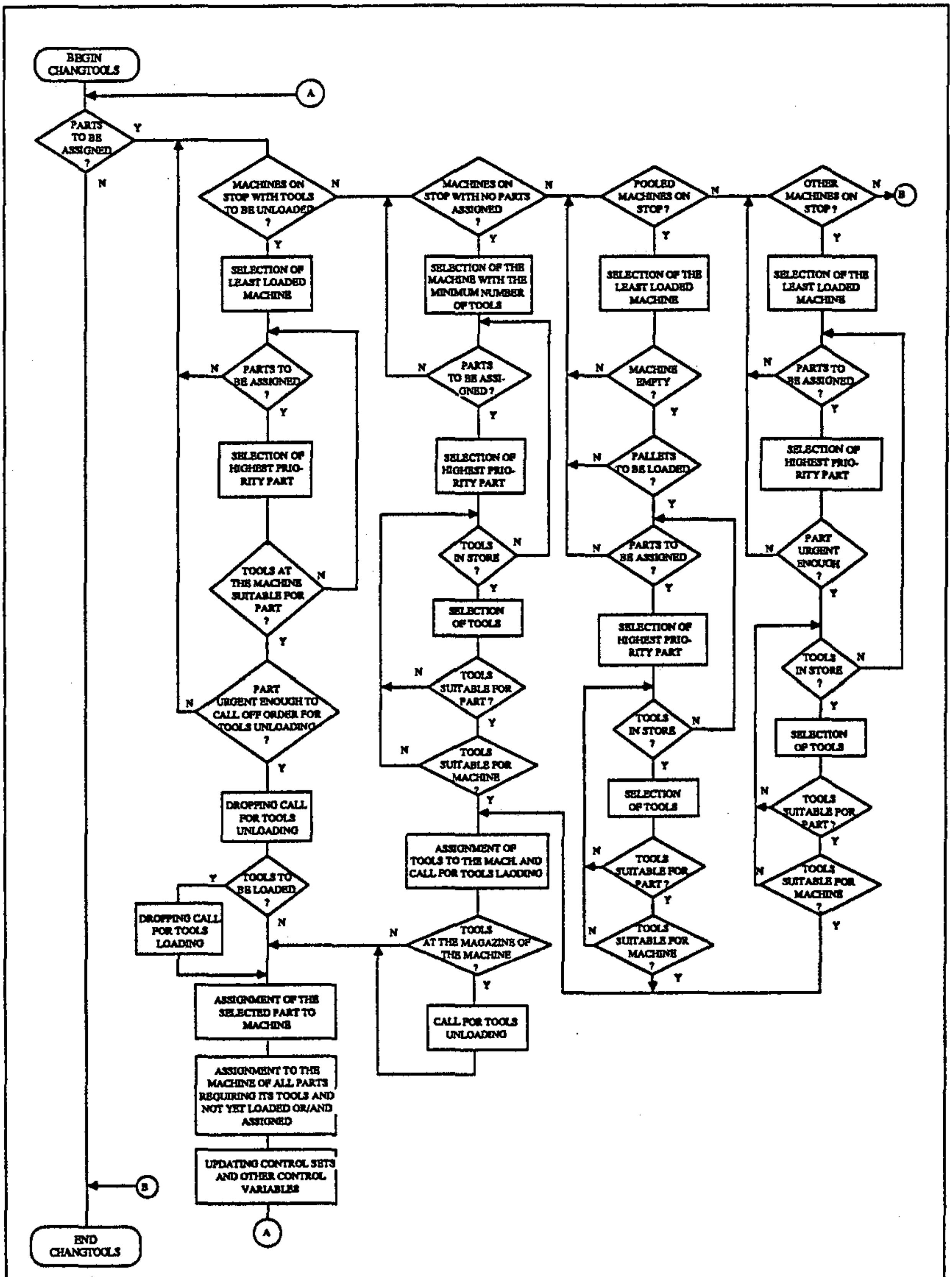


Fig. 9.6.7	Flow Diagram of the Activity CHANGTOOLS

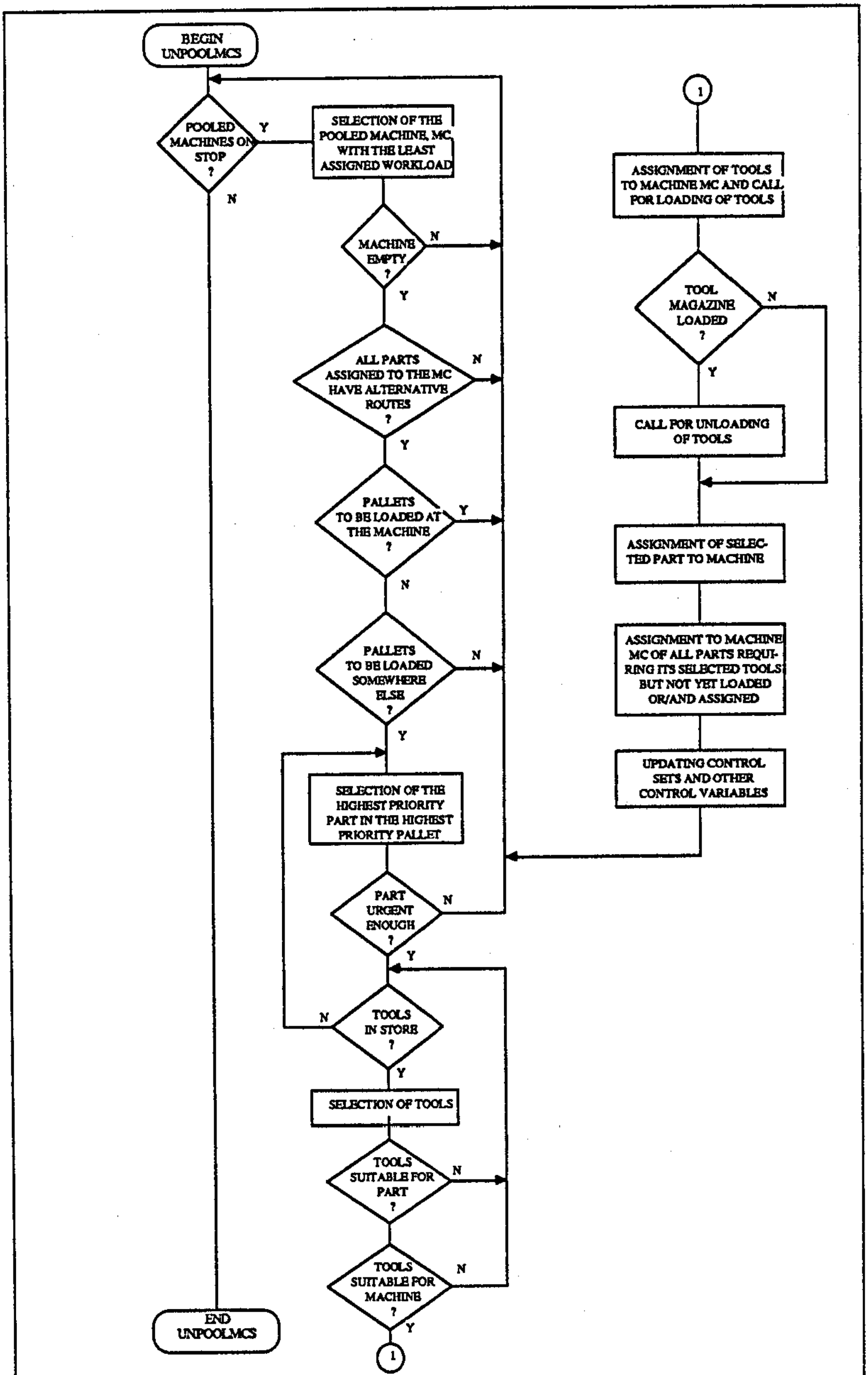


Fig.9.6.8	Flow Diagram of the Activity UNPOOLMCS

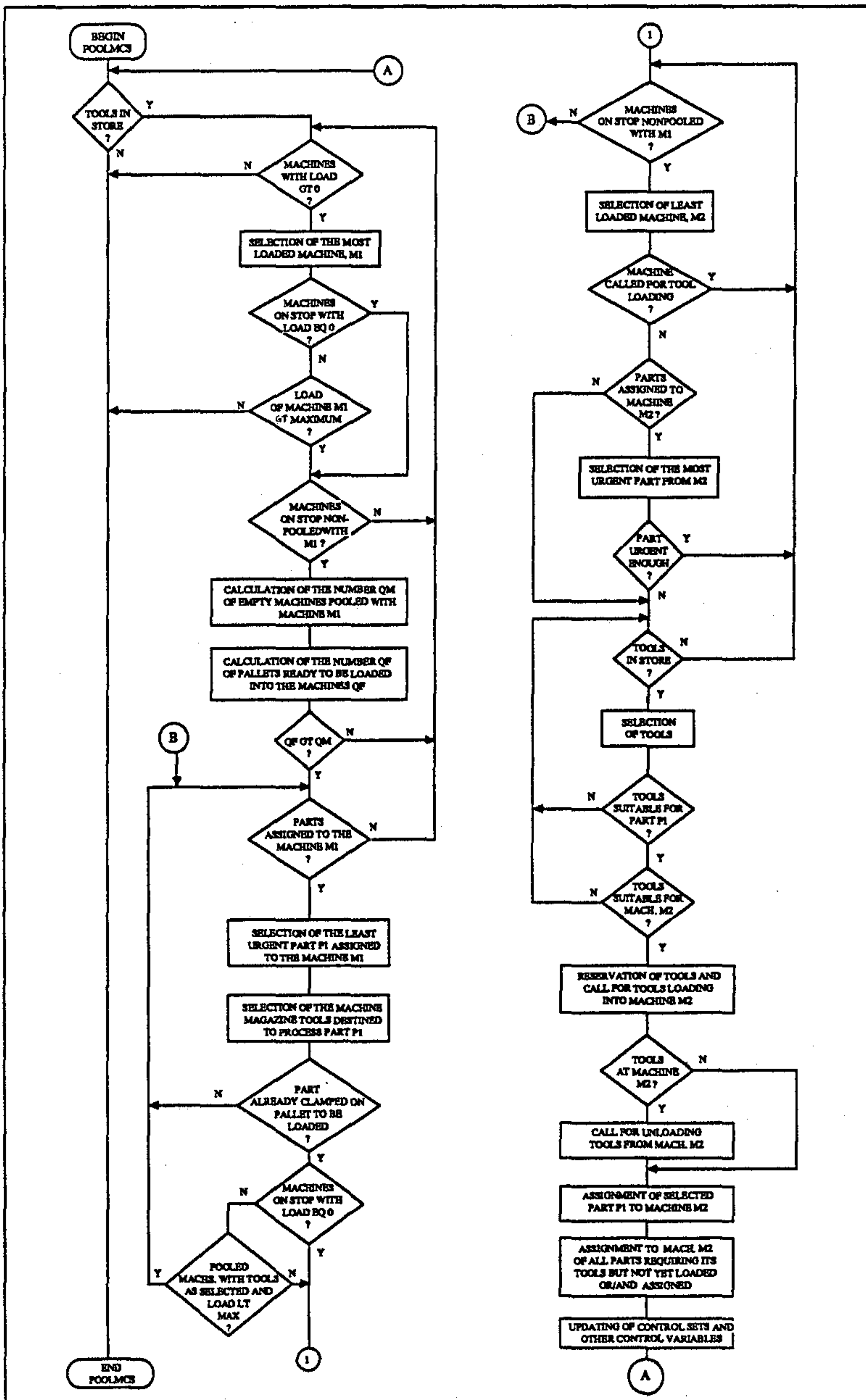


Fig. 9.6.9	Flow Diagram of the Activity POOLMCS

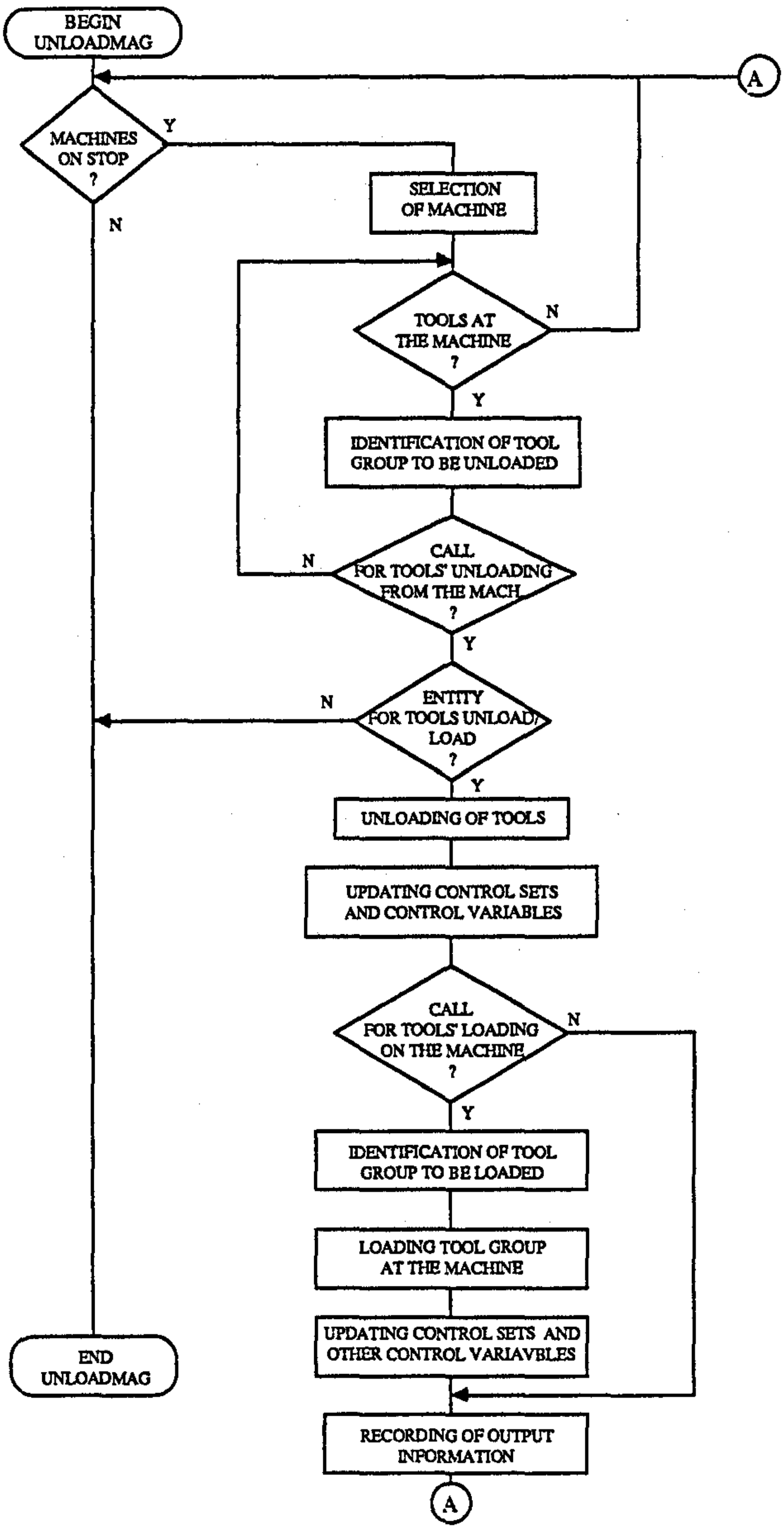


Fig. 9.6.10	Flow Diagram of the Activity UNLOADMAG

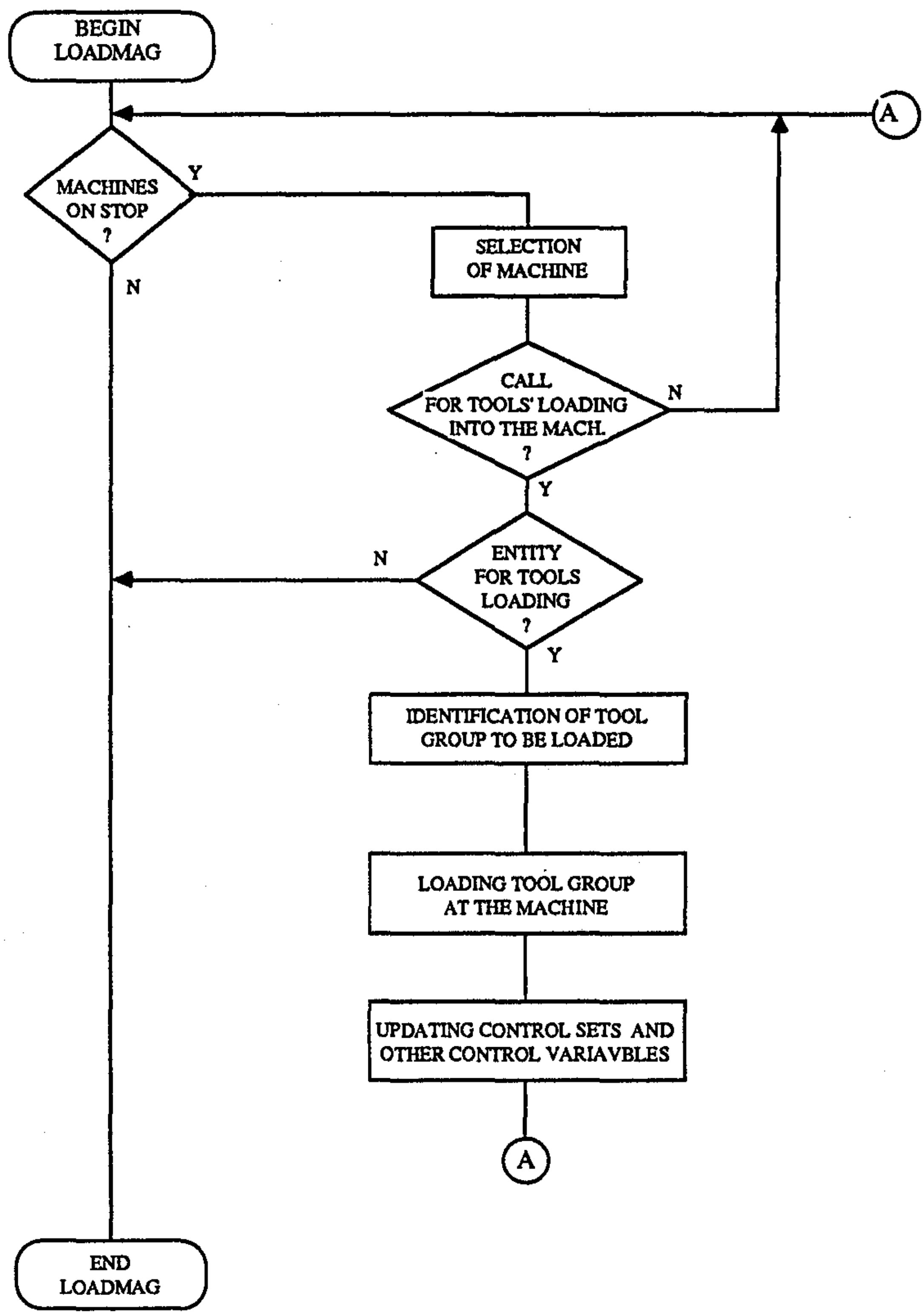


Fig. 9.6.11	Flow Diagram of the Activity LOADMAG

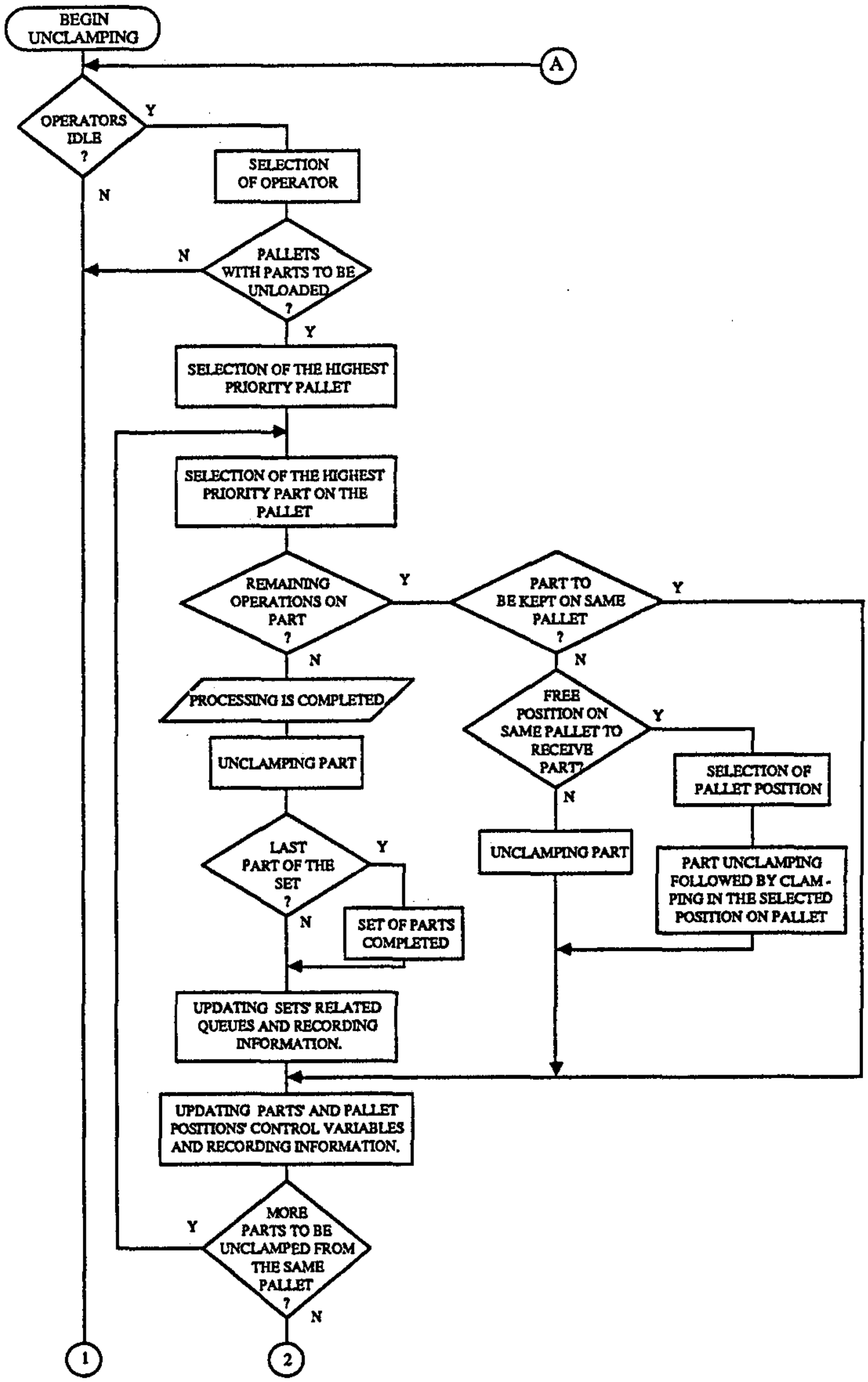


Fig. 9.6.12	Flow Diagram of the Activity UNCLAMPING

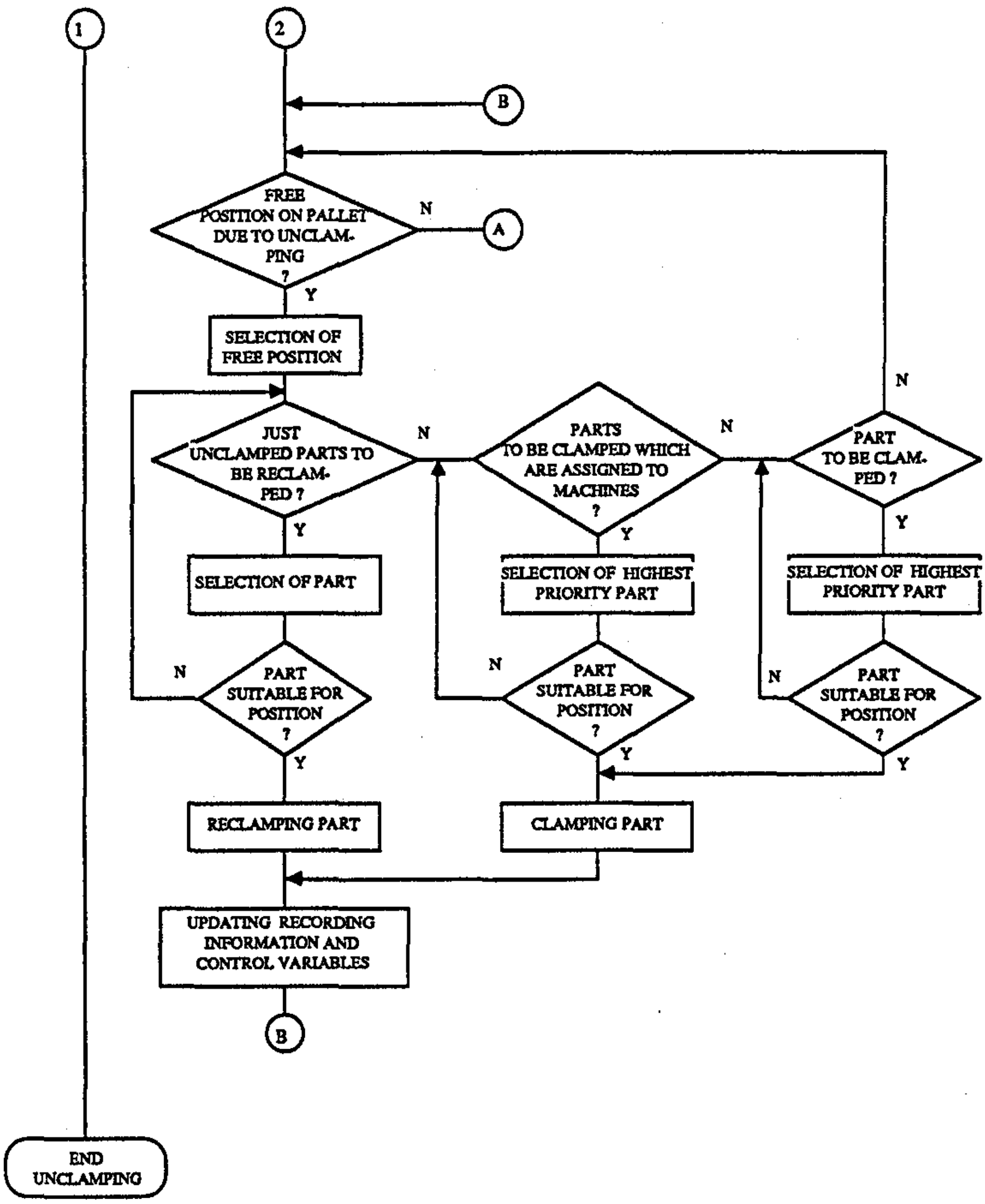


Fig. 9.6.12 (cont.)	Flow Diagram of the Activity UNCLAMPING

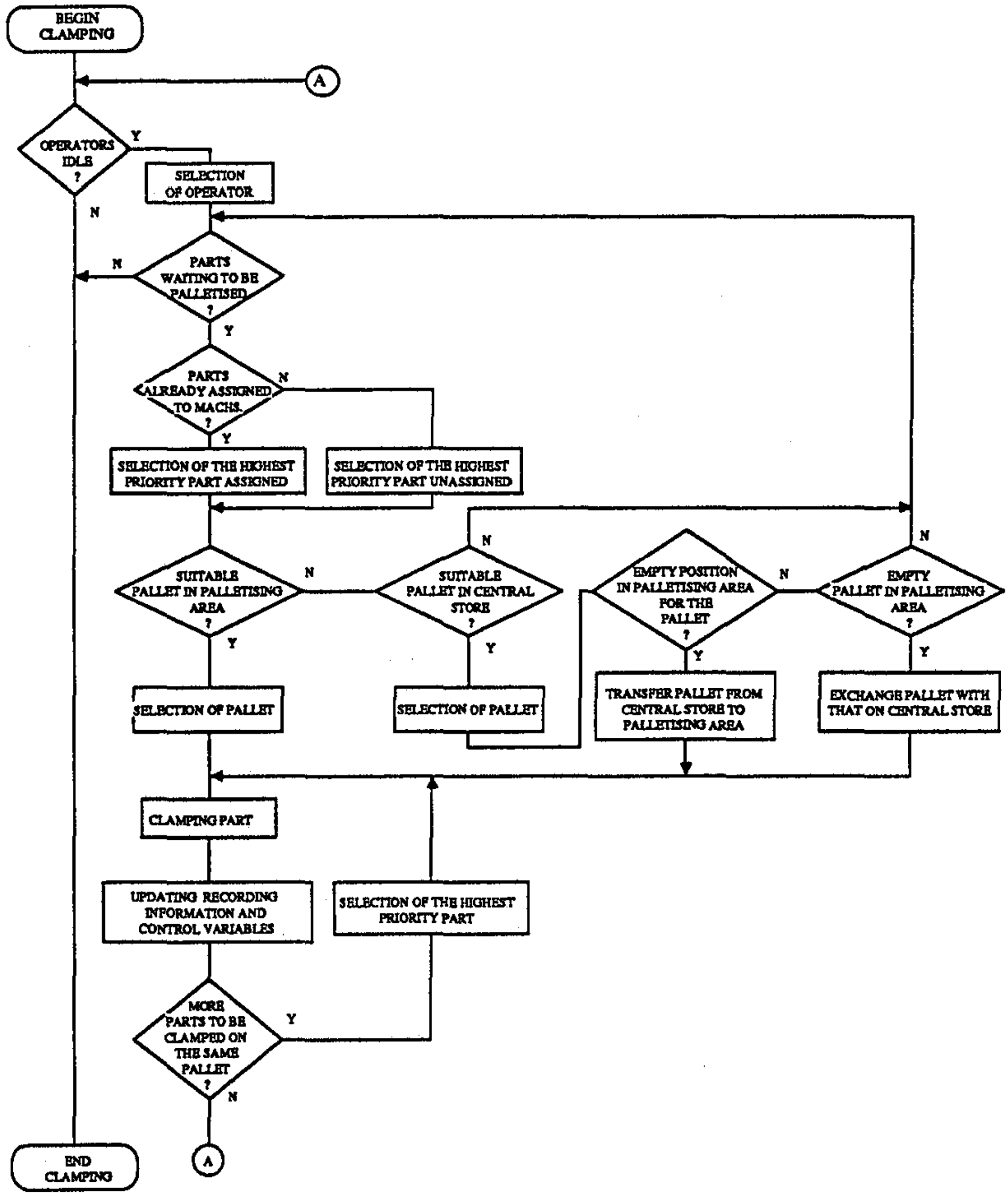


Fig. 9.6.13	Flow Diagram of the Activity CLAMPING

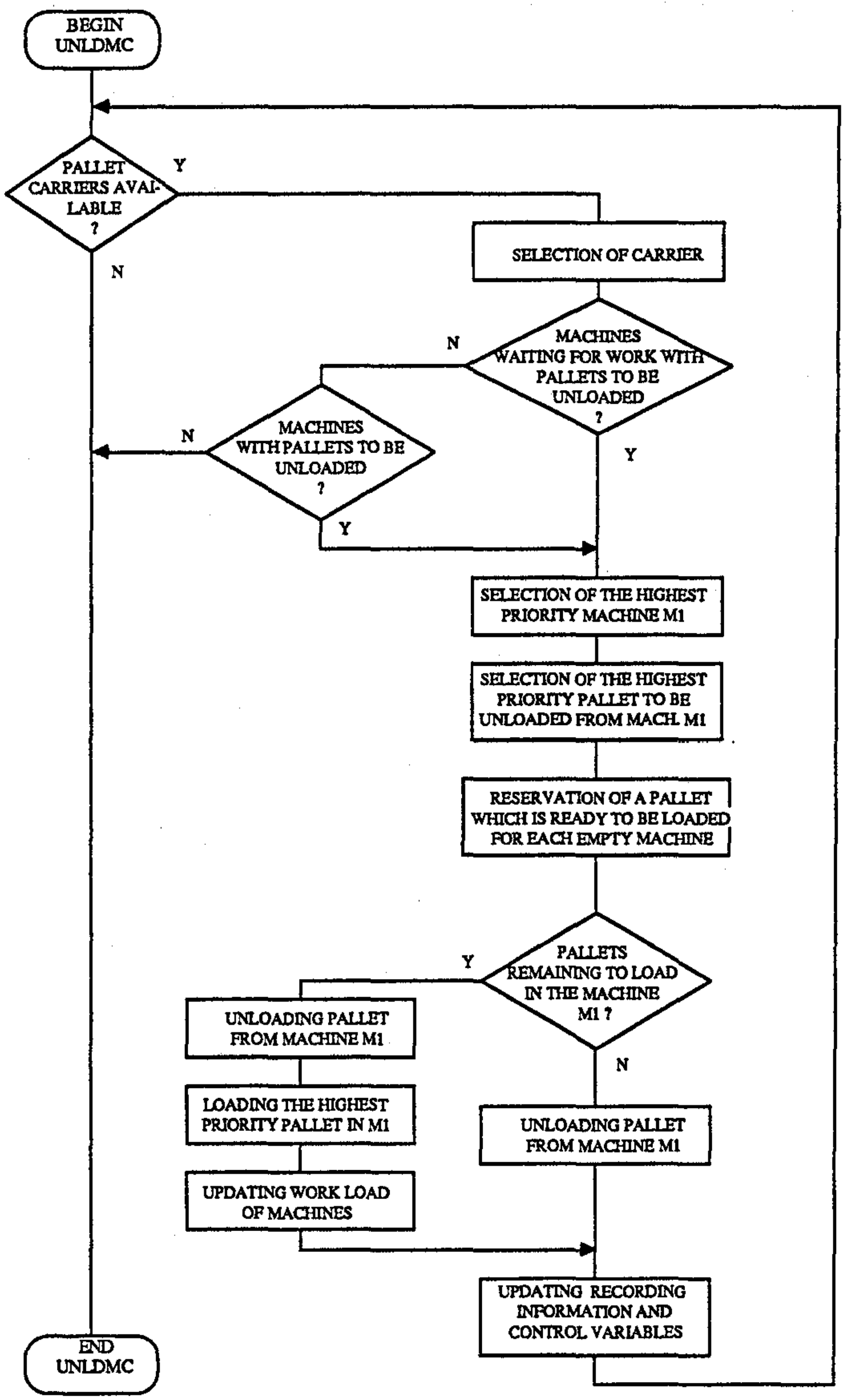


Fig. 9.6.14	Flow Diagram of the Activity UNLDMC

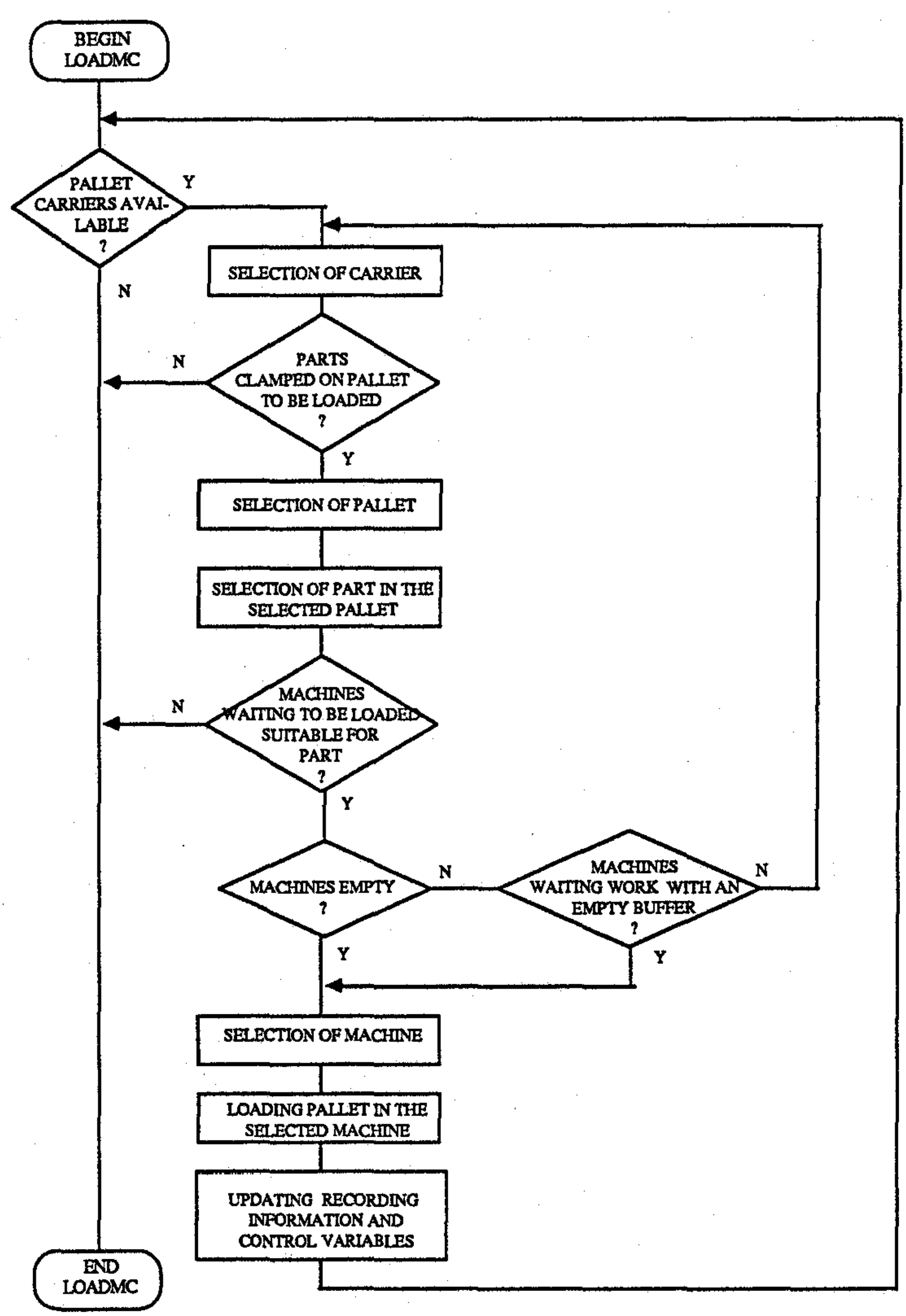


Fig. 9.6.15	Flow Diagram of the Activity LOADMC

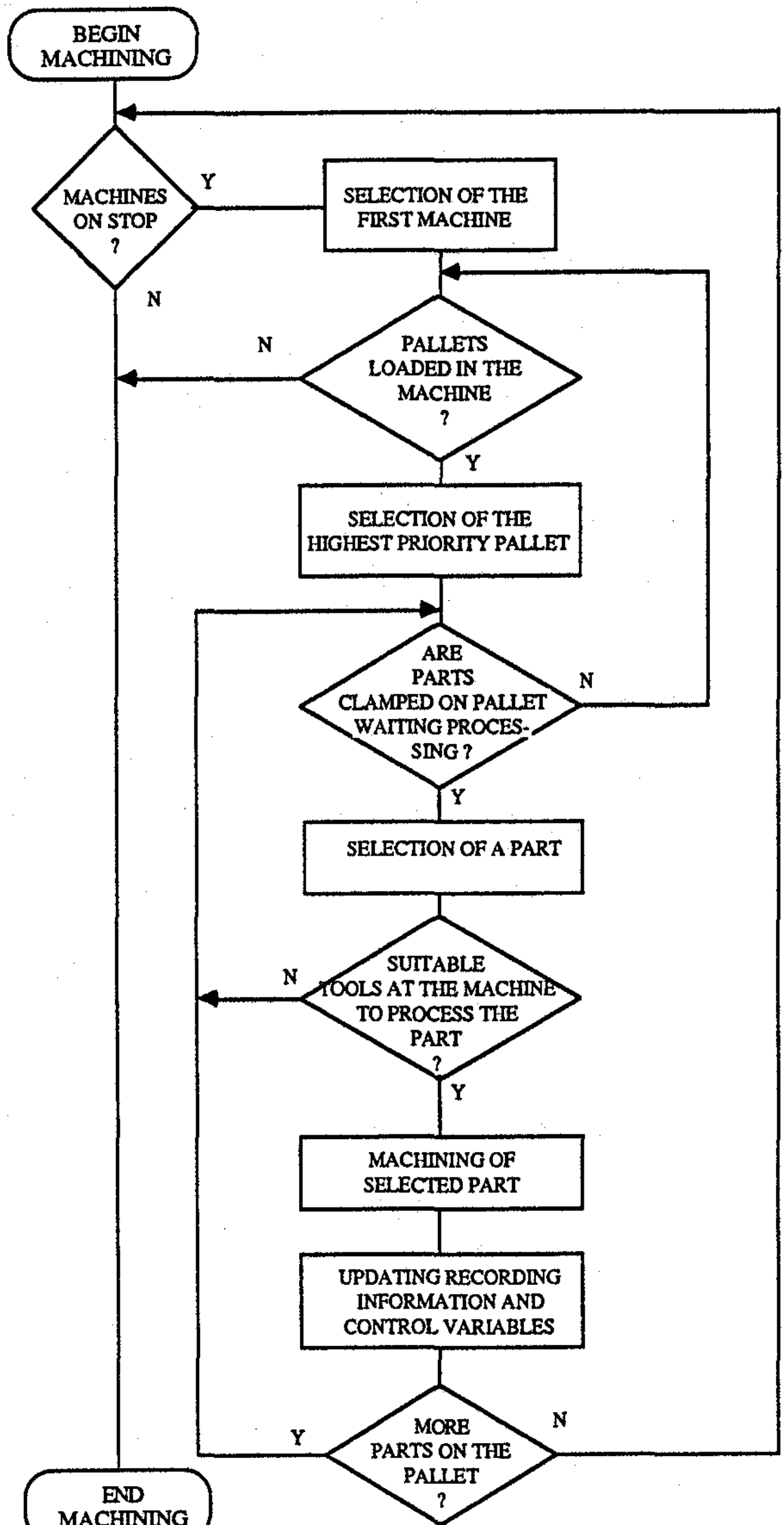


Fig. 9.6.16	Flow Diagram of the Activity MACHINING

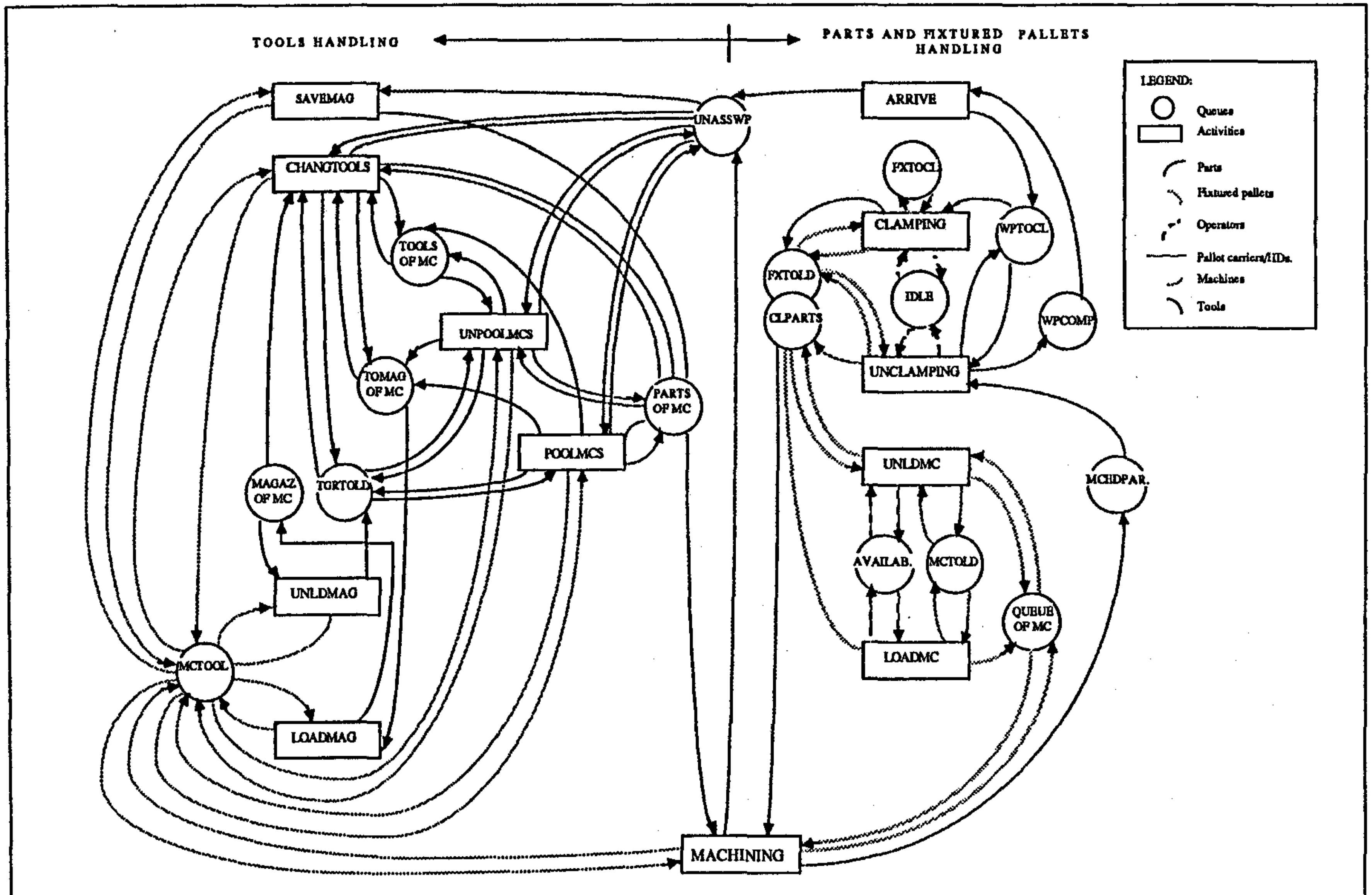


Fig. 9.6.17 Simulation Model Cycle Diagram

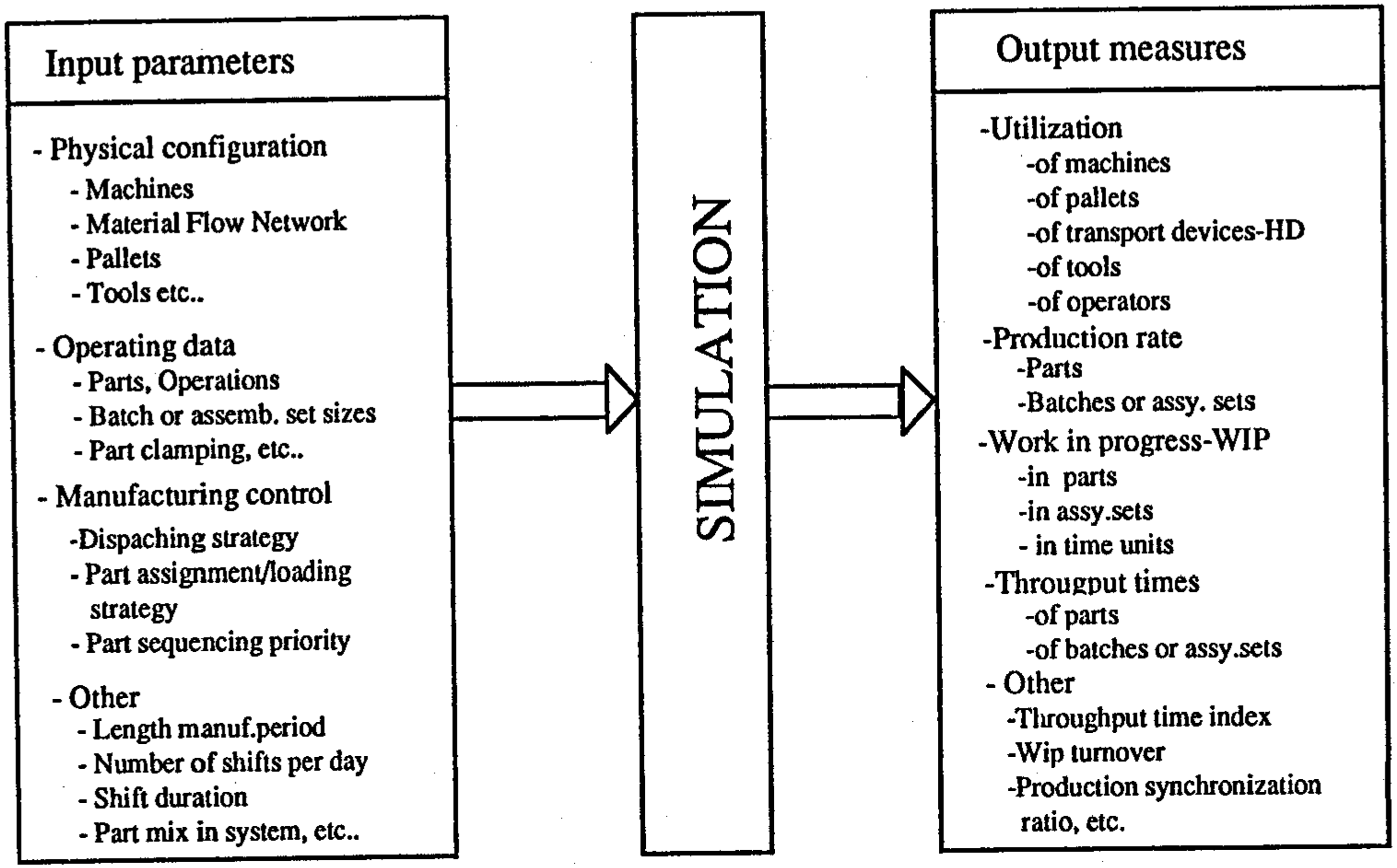


Fig. 9.7.1 The use of simulation of manufacturing systems as a mean of evaluating the influence of input parameters on measures of system performance

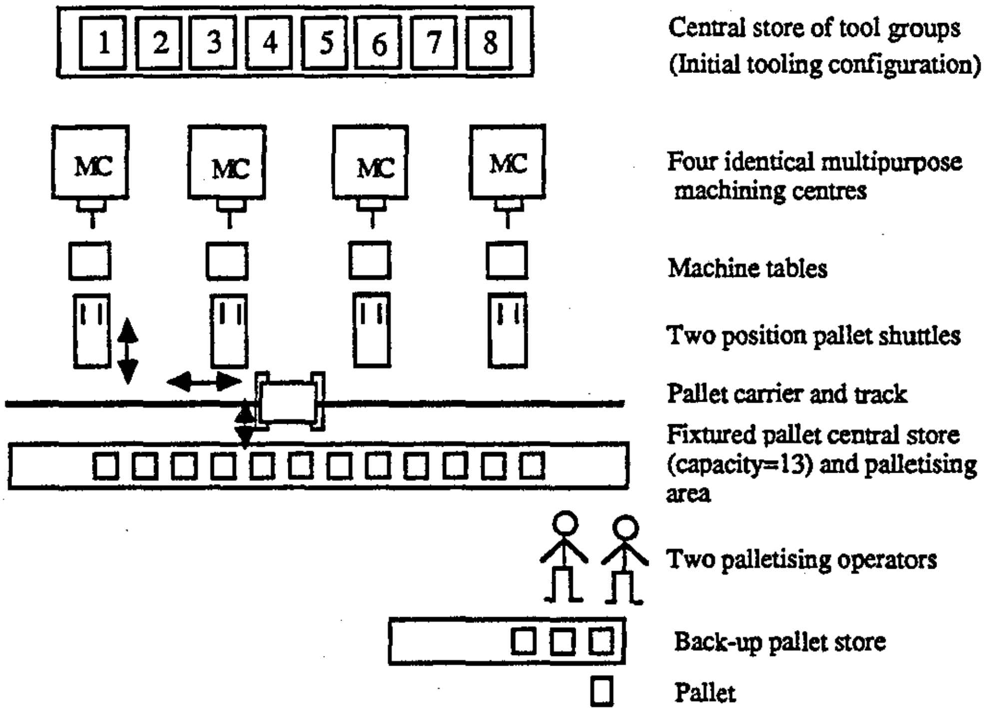


Fig.10.2.1	Schematic representation of the basic FMS configuration for experimentation

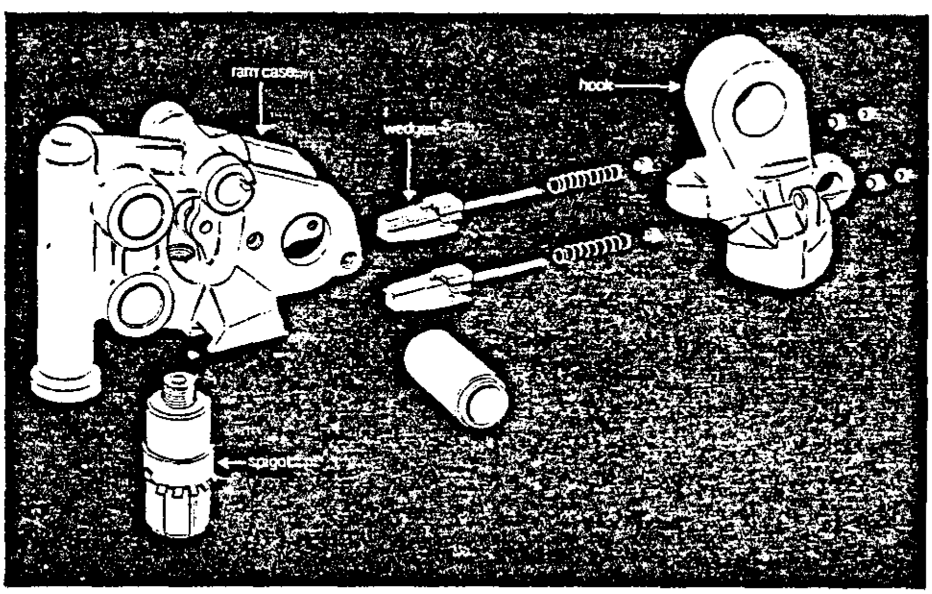


Fig.10.2.2	Sample of the main part mix used for experimentation (Source: Westland Aircraft catalogue)

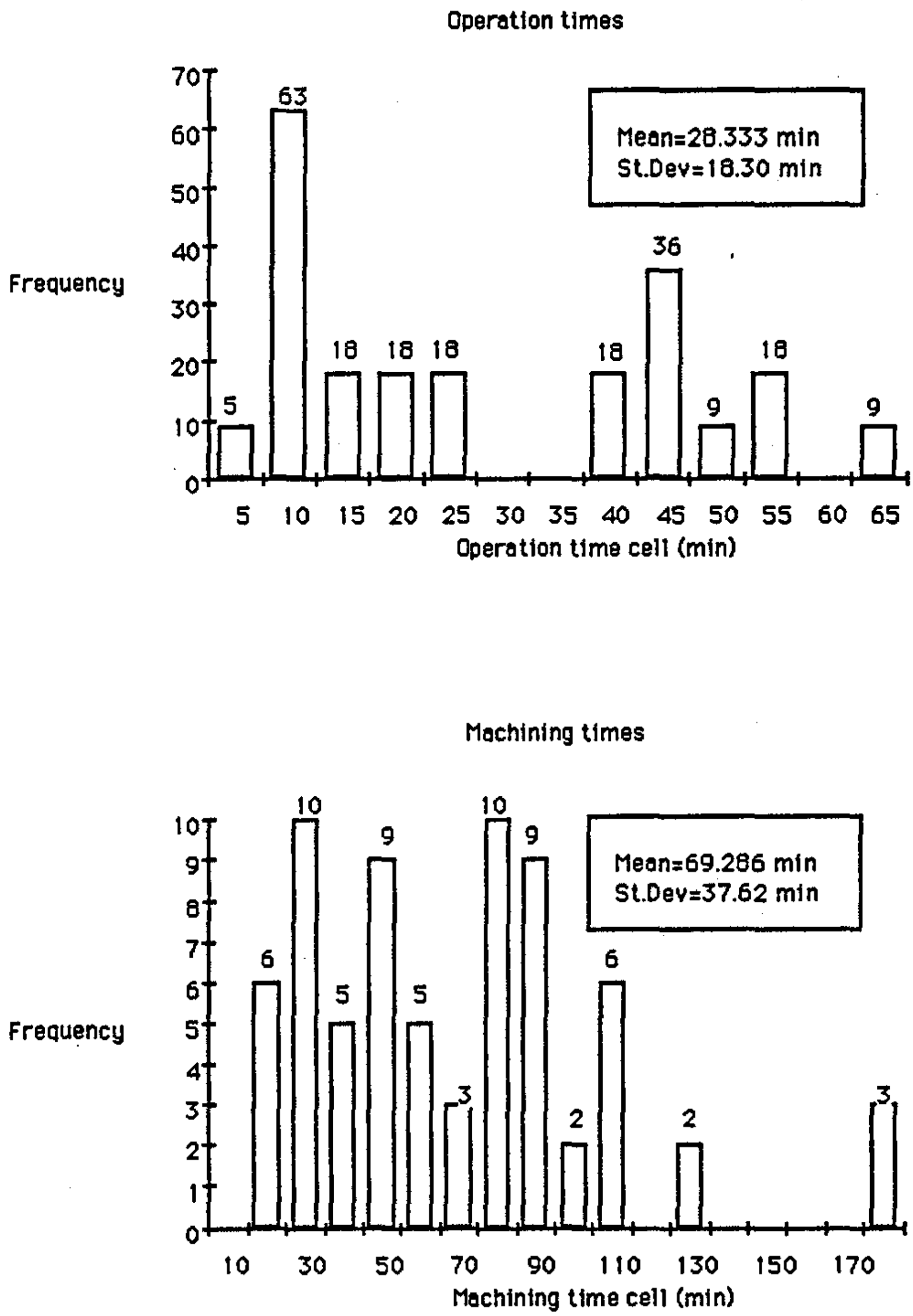


Fig.10.2.3	Typical frequency time distributions of operation times and machining times per pallet load

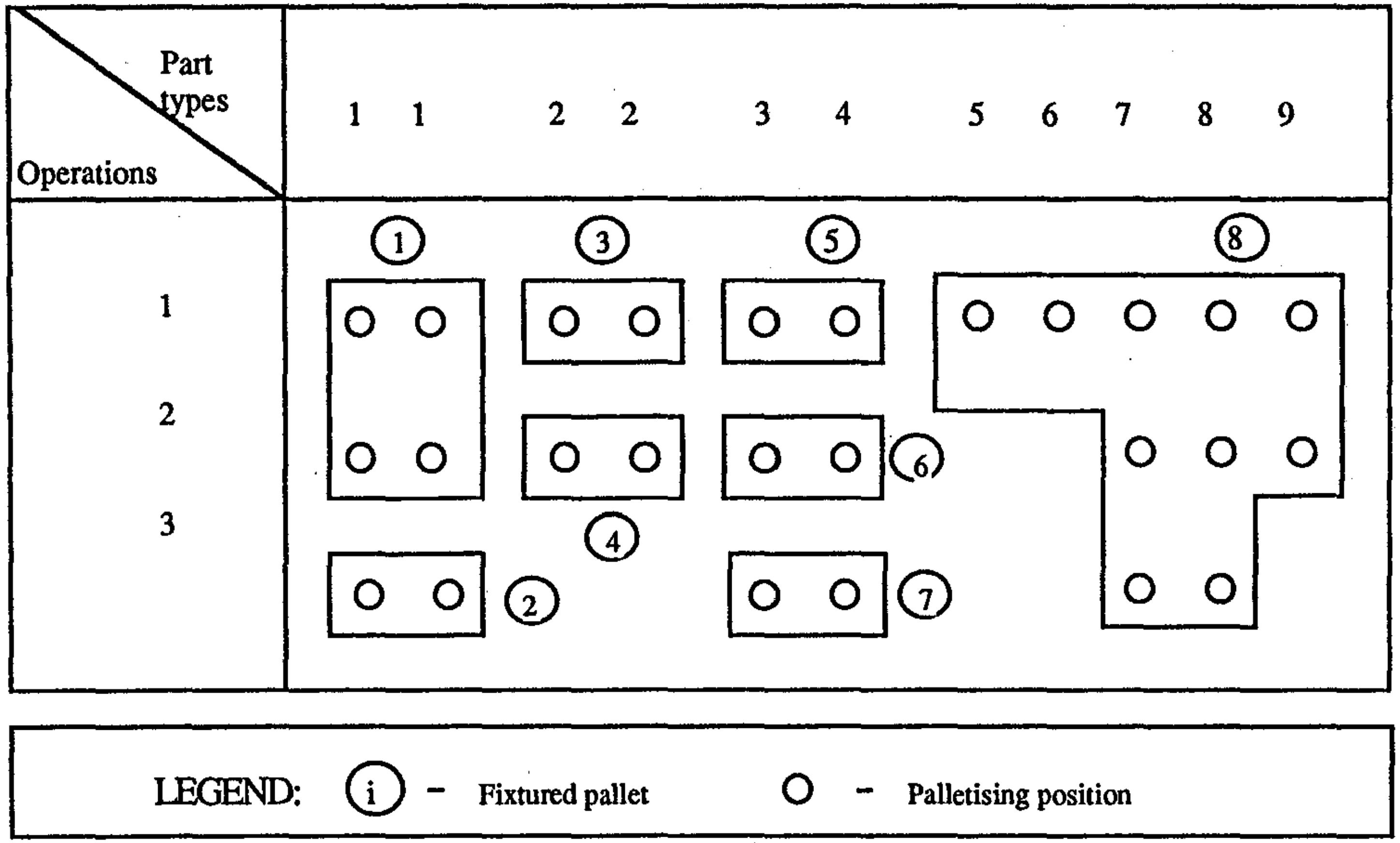


Fig. 10.2.4 Part mix clamping structure for each part-operation

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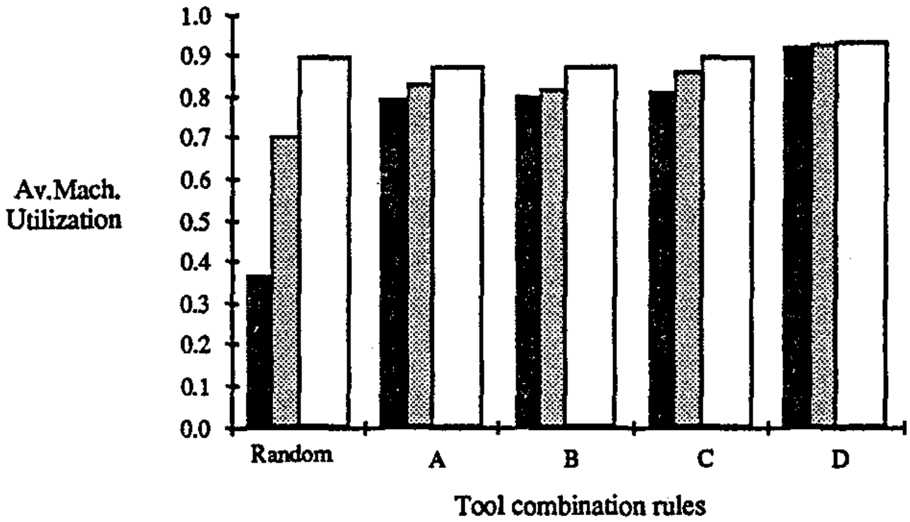
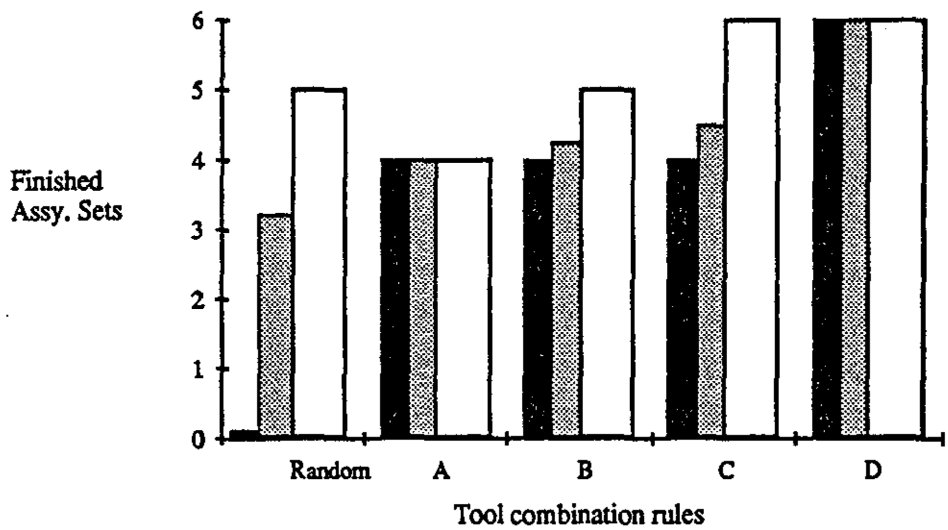




LEGEND: Minimum Average Maximum

A,B,C,D Heuristic rules

Summarized system set-up:

-Sched.Rule: FCFS
-4 identical Multipurpose MC
- No tool set duplication

Fig.10.4.1	Efficiency of different tool combination rules for tooling configuration design under no tool set duplication

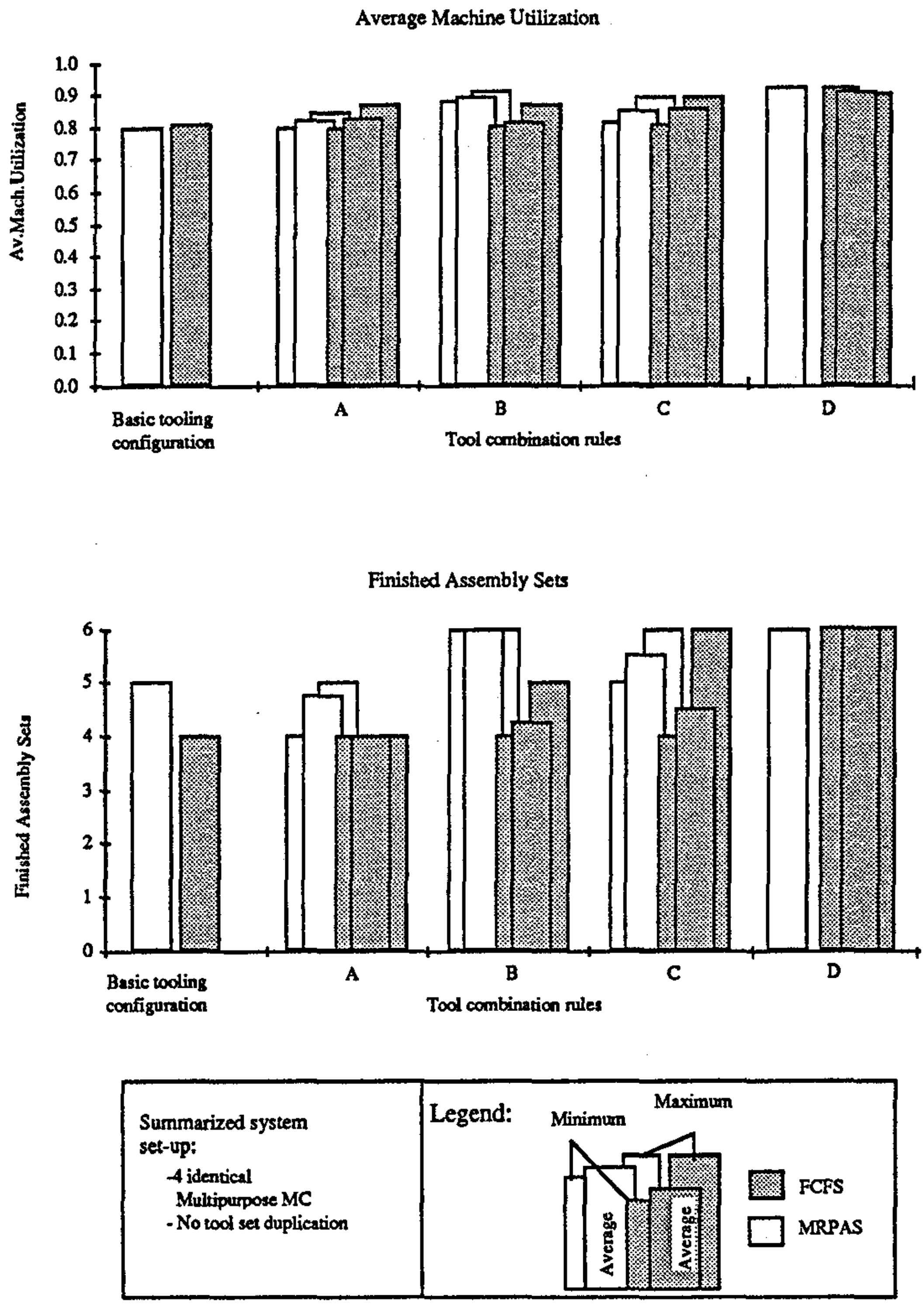


Fig.10.4.2	The efficiency of generated tooling configurations by using three tool combination rules under two different scheduling rules, namely FCFS and MRPAS rules.

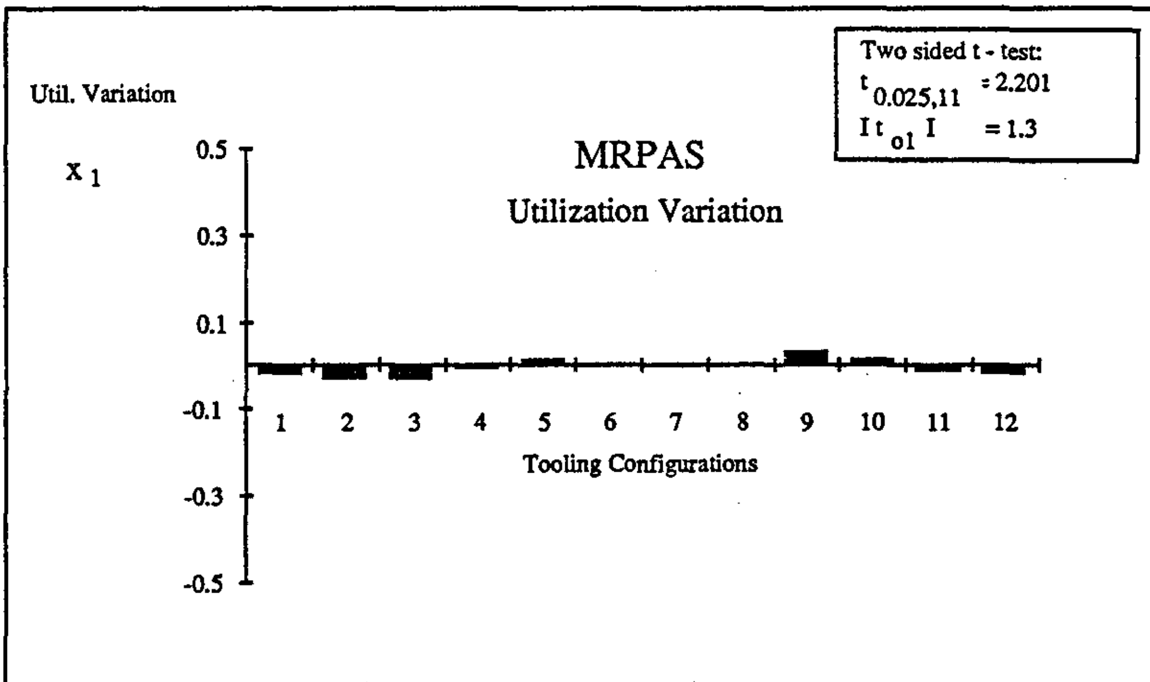


Fig. 10.5.1	Difference in average machine utilization between the randomized AS part type release and the deterministic ordered part release under the MRPAS scheduling rule.

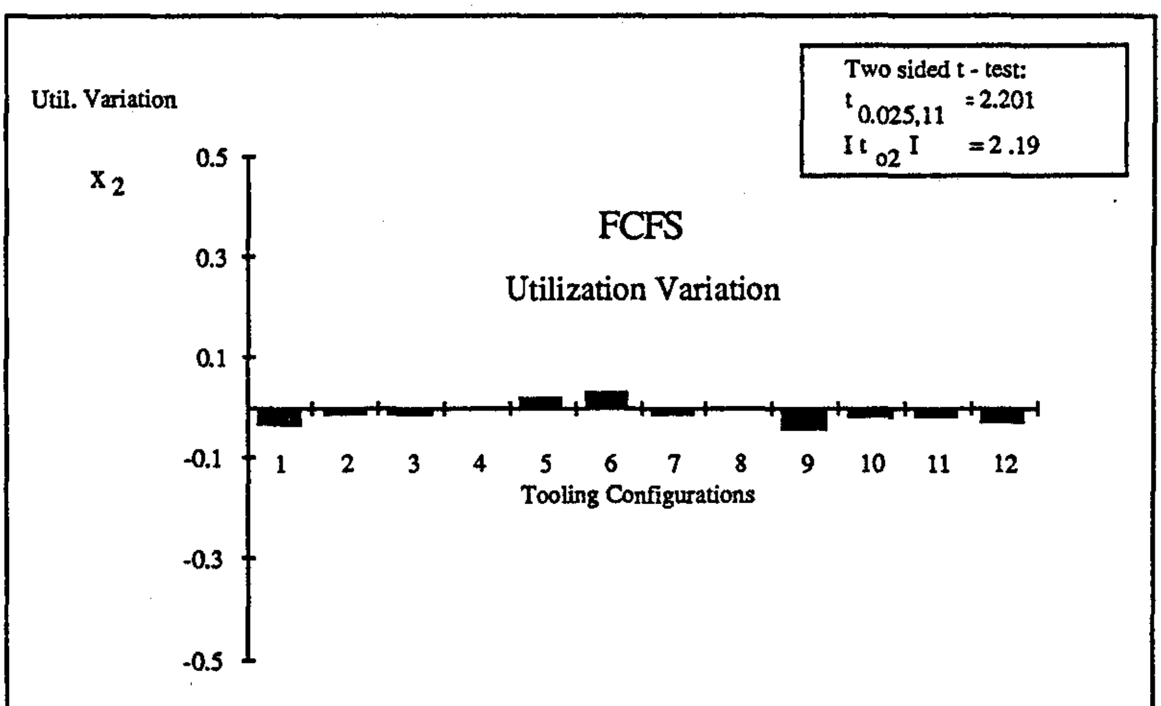


Fig.10.5.2	Difference in average machine utilization between the randomized AS part type release and the deterministic ordered part release under the FCFS scheduling rule.

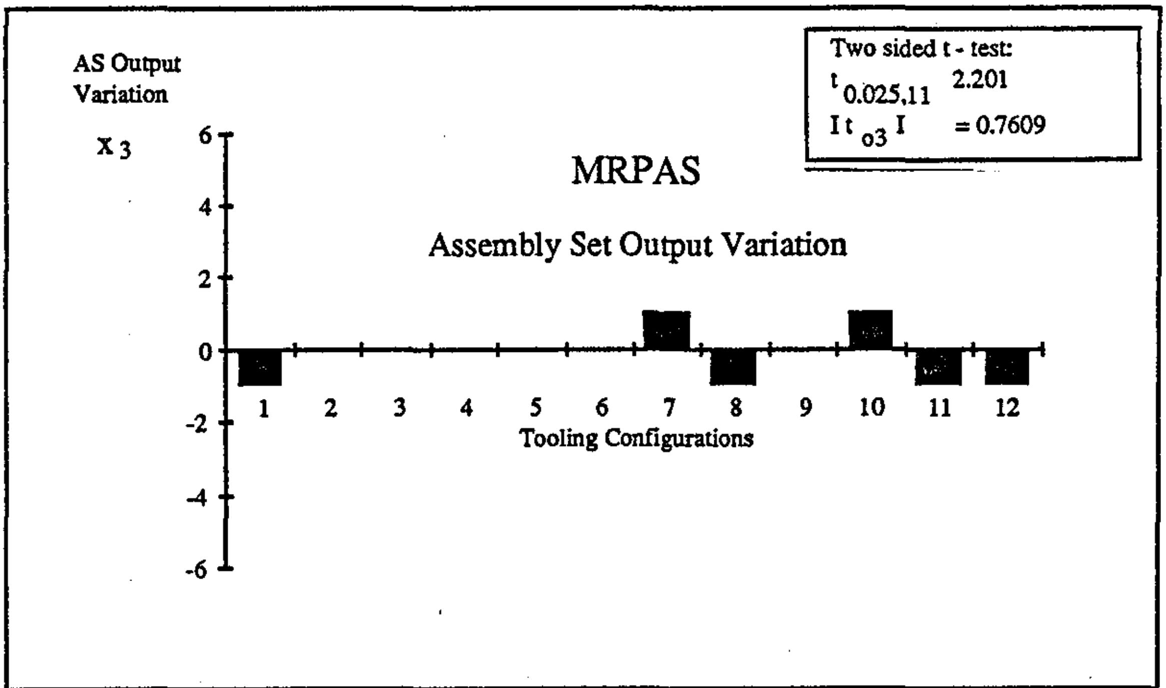


Fig.10.5.3	Difference assembly set output between the randomized AS part type release and the deterministic ordered part release under the MRPAS scheduling rule.

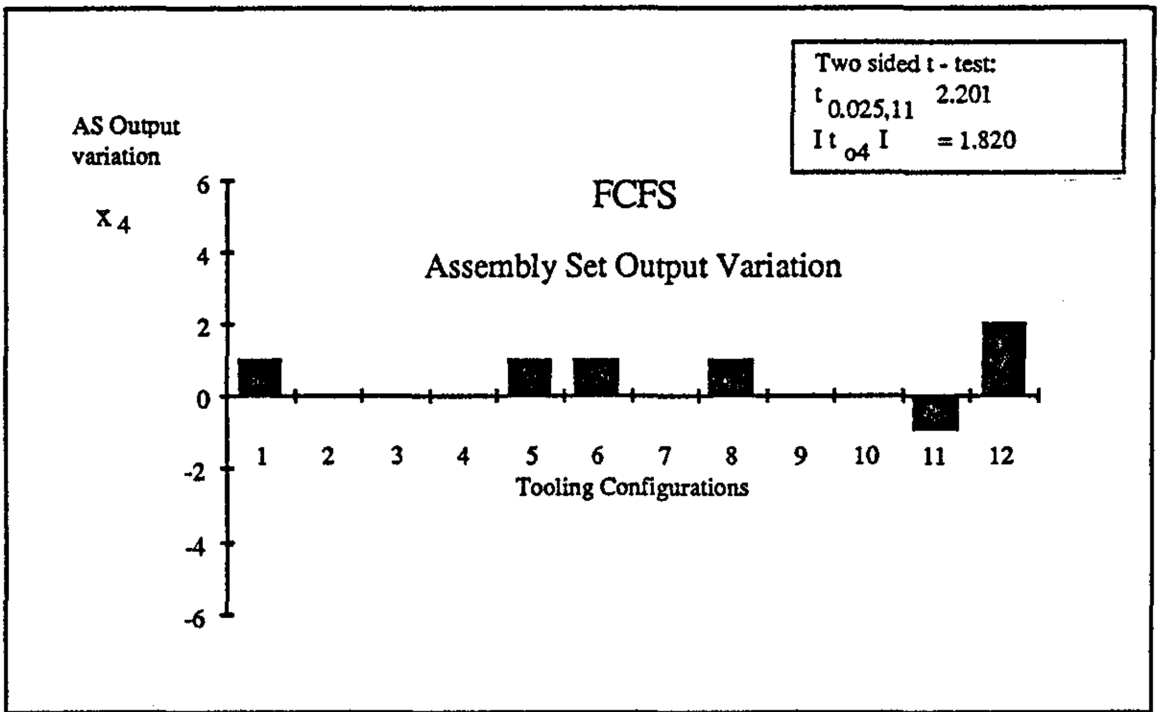


Fig.10.5.4	Difference in assembly set output between the randomized AS part type release and the deterministic ordered part release under the FCFS scheduling rule.

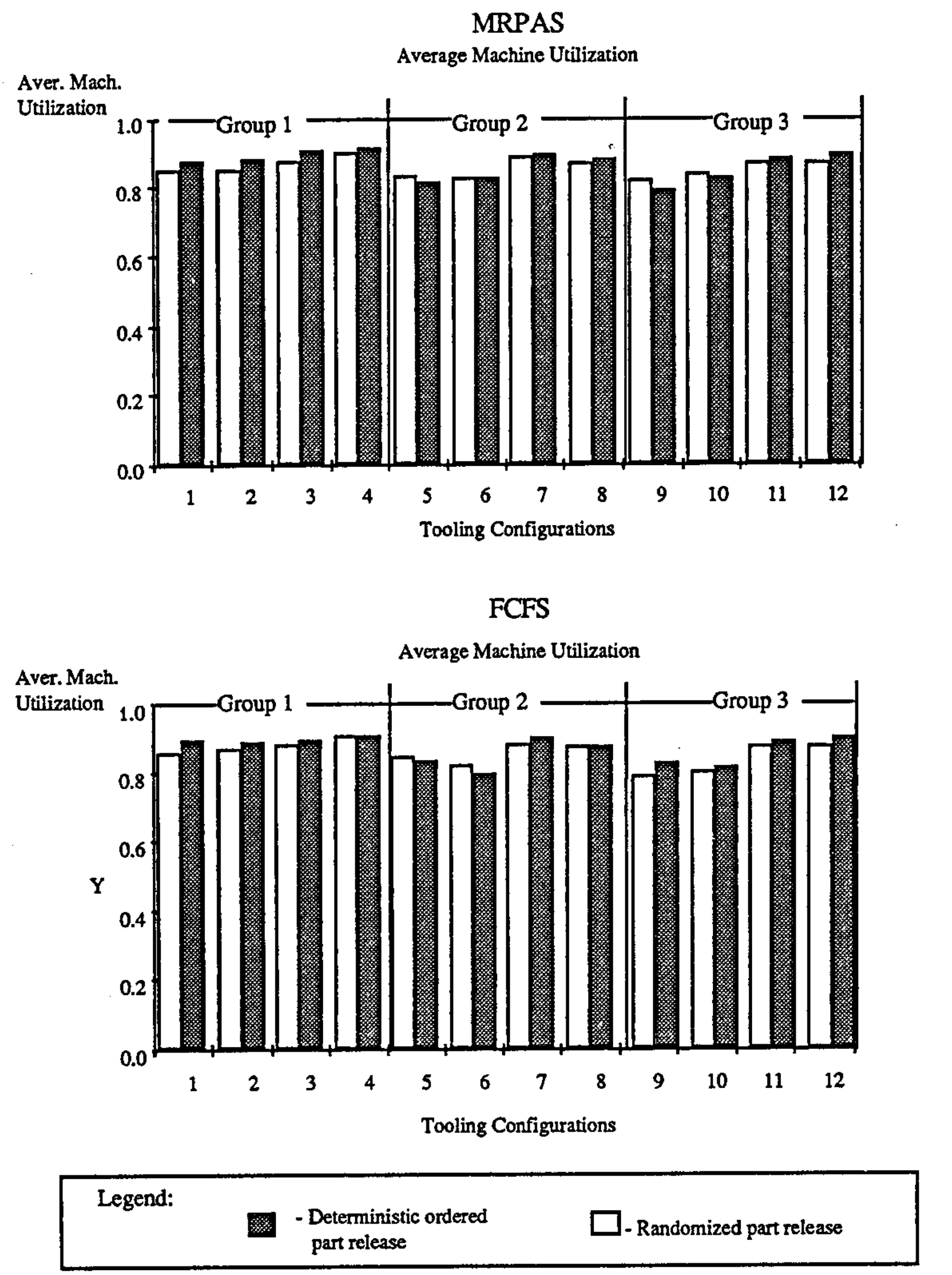
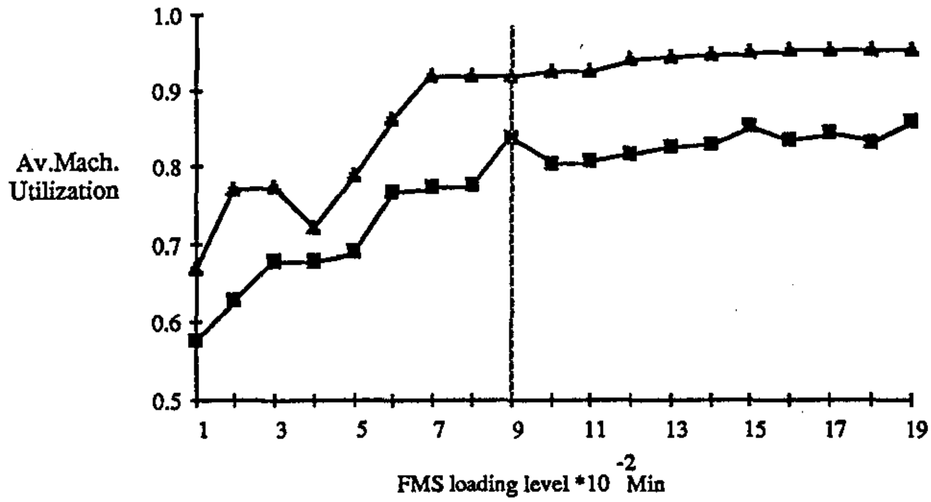
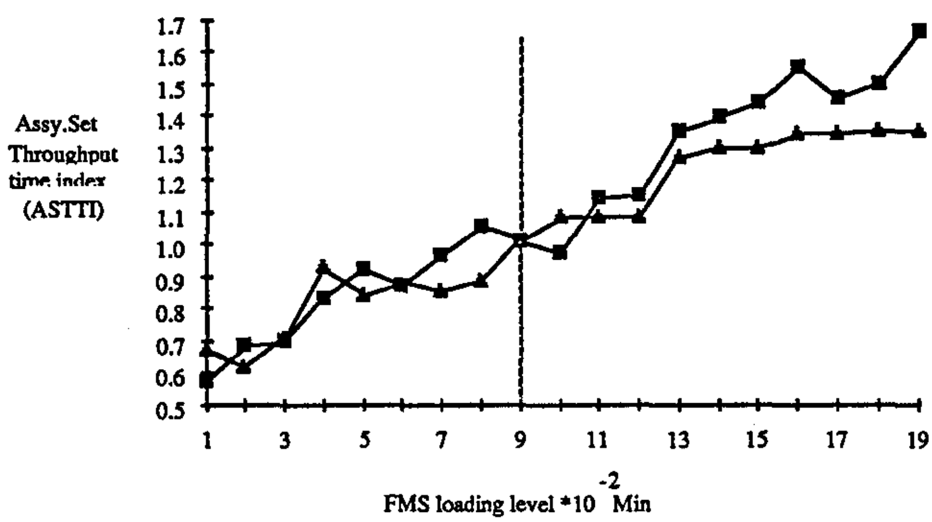


Fig. 10.5.5	Average Machine Utilization under both randomized and determistic AS parts release for the FMS operated under the MRPAS and the FCFS scheduling rules



Legend	Summarized system set-up:
▲ Tooling configuration TC14 ■ Basic toolig configuration TC1	-Sched.Rule: FCFS -4 identical Multipurpose MC - No tool set duplication

Fig.10.6.1	Utilization under different system loading levels for two different tooling configurations using the same unduplicated number of tool sets.



Legend:	Summarized system set-up:
▲ Tooling configuration TC14 ■ Basic toolig configuration TC1	- Sched.Rule: FCFS - 4 identical Multipurpose MC - No tool set duplication

Fig.10.6.2	Assembly Set Throughput Time Index for two typical tooling configurations as a function of FMS workload

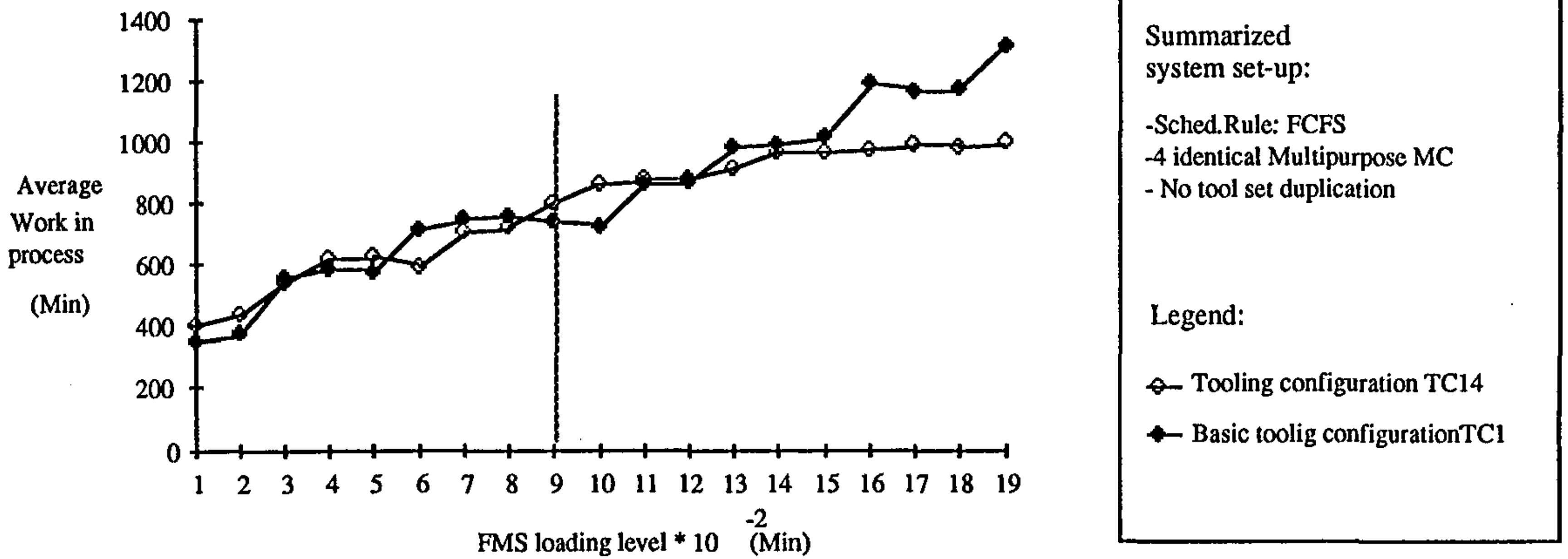


Fig.10.6.3	Average work in process - processed time of unfinished workpieces - for two tooling configuration under minimum tooling requirements.

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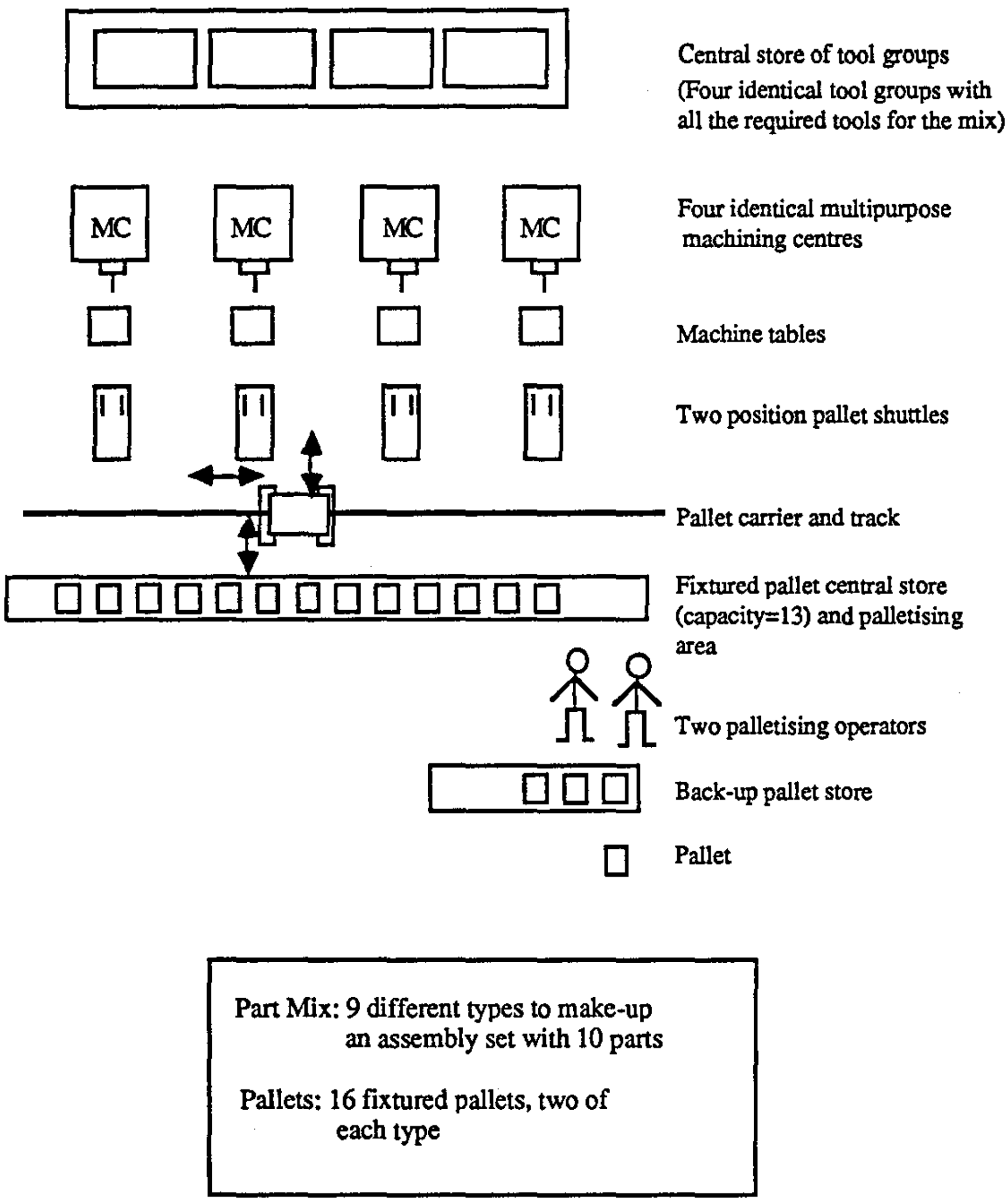


Fig.10.7.1 Schematic representation of the typical FMS configured under full tool replication

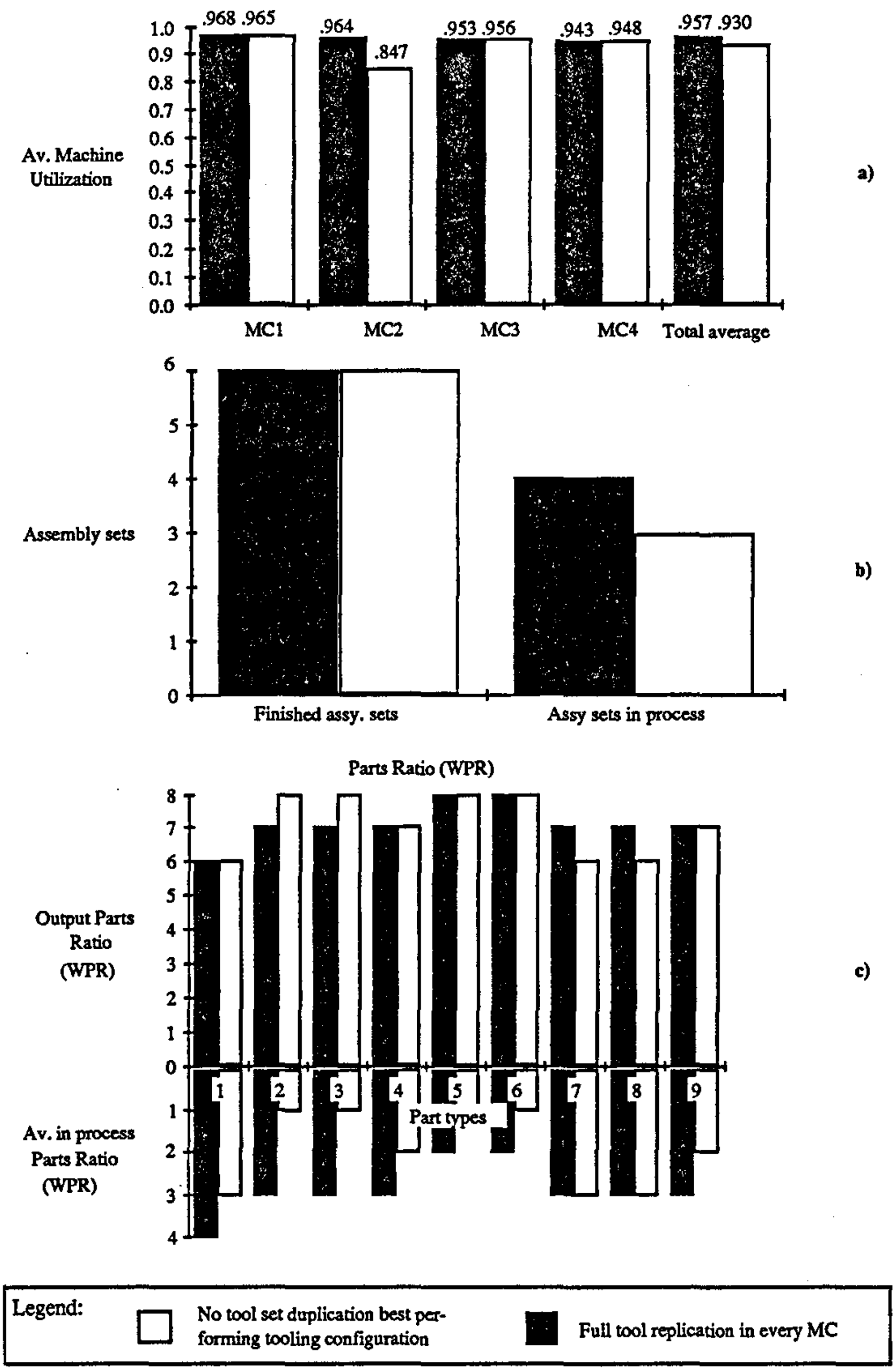


Fig. 10.7.2	Comparative FMS performance between the FMS run under full tool replication and run under no tool set duplication i.e. minimum tooling.

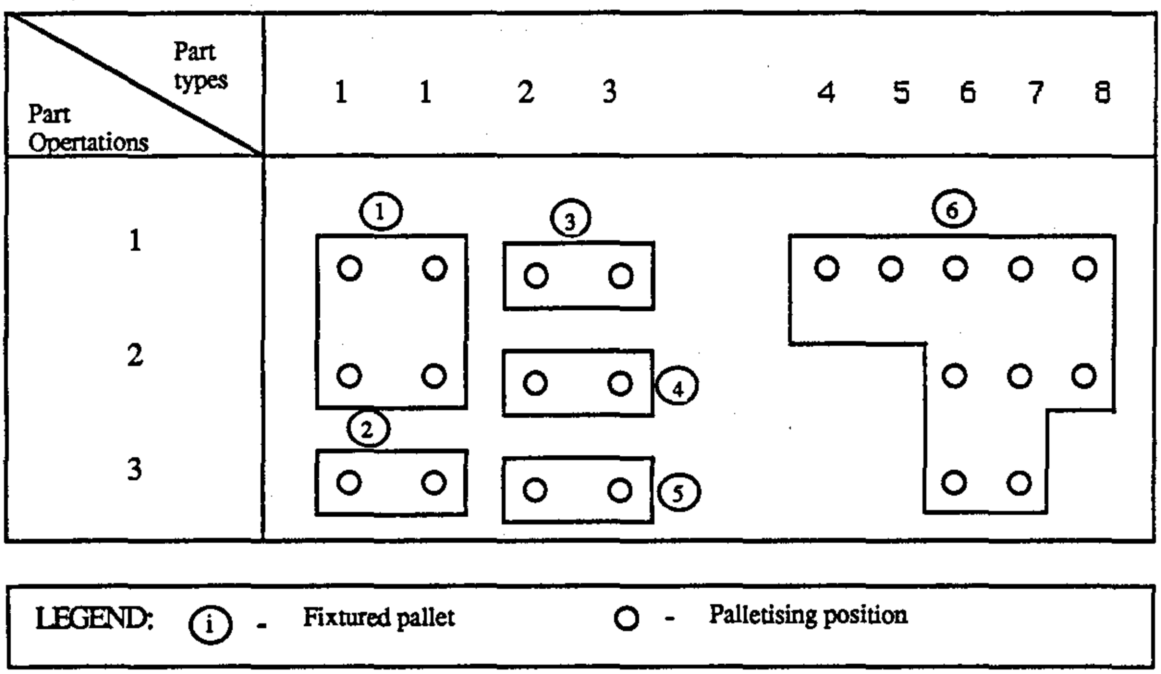


Fig. 10.8.1	Part mix A clamping structure for each part-operation

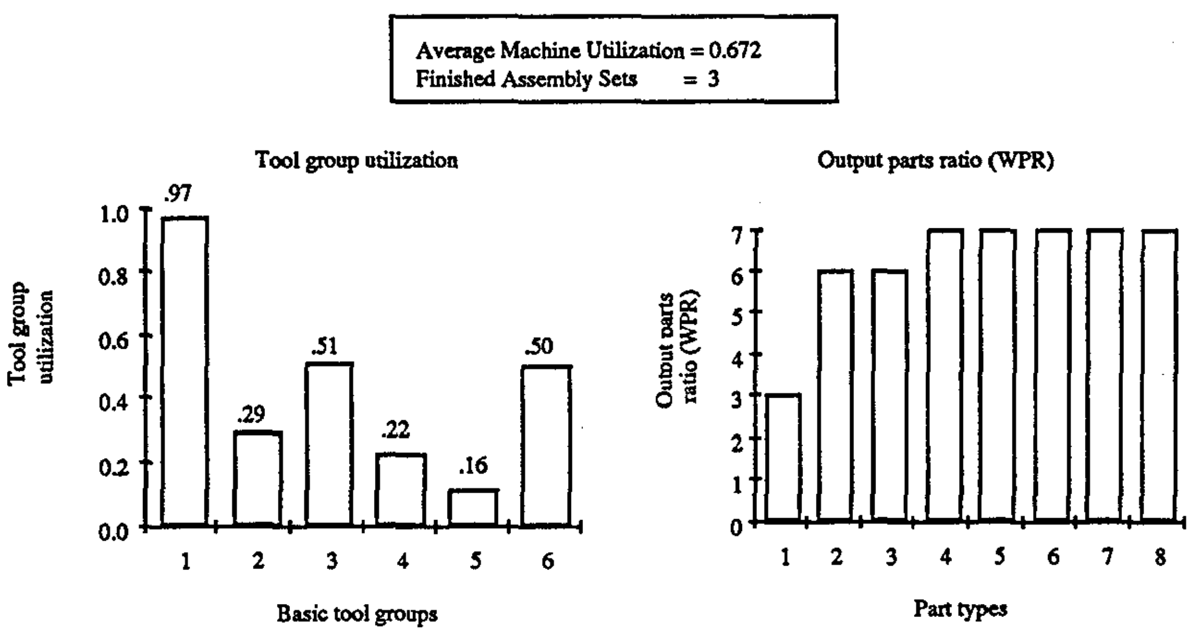


Fig. 10.8.2	Summarized FMS performance under the basic tooling configuration for part mix A

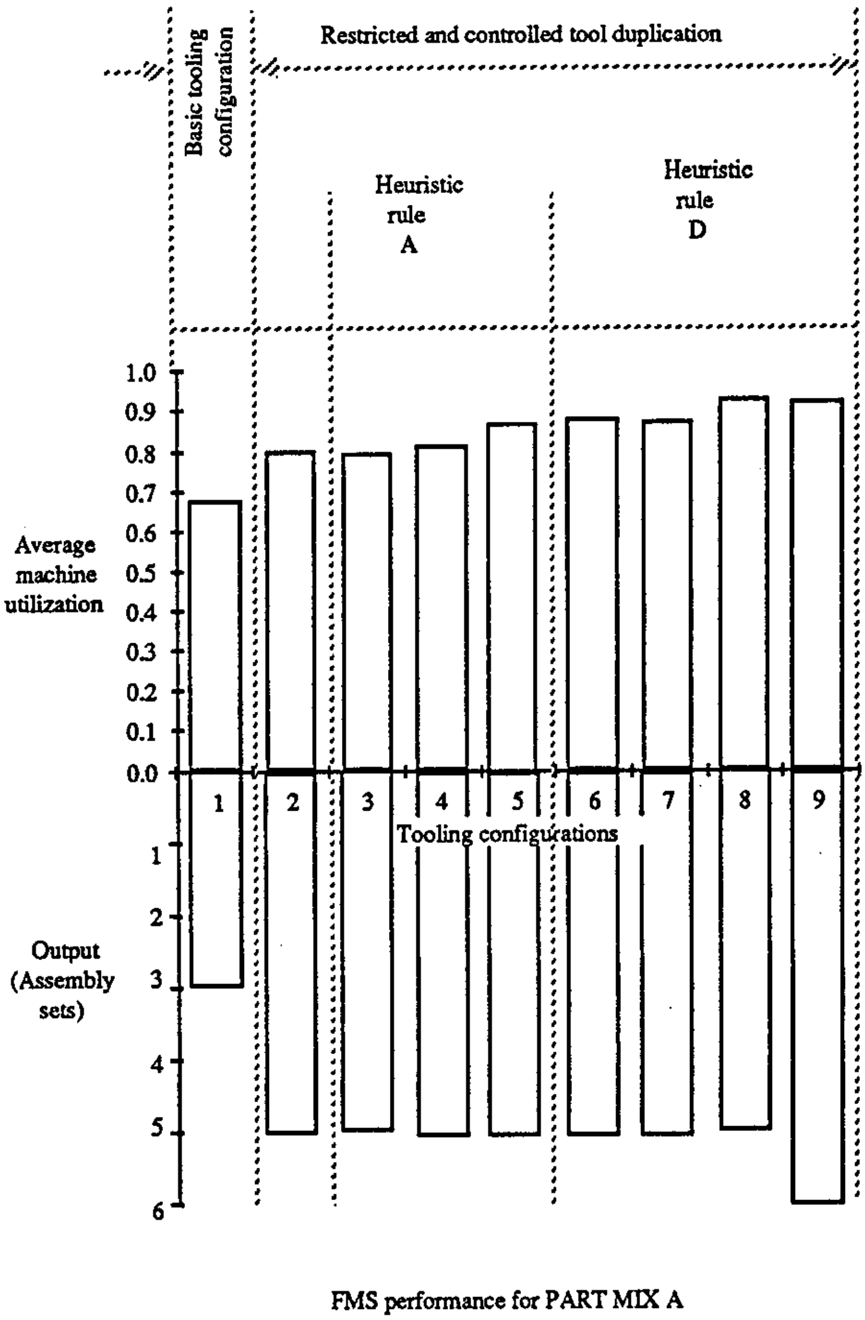


Fig. 10.8.3	Graphical representation of FMS performance measures under MRPAS scheduling rule for different tooling configurations with restricted and controlled tool duplication to process part mix A

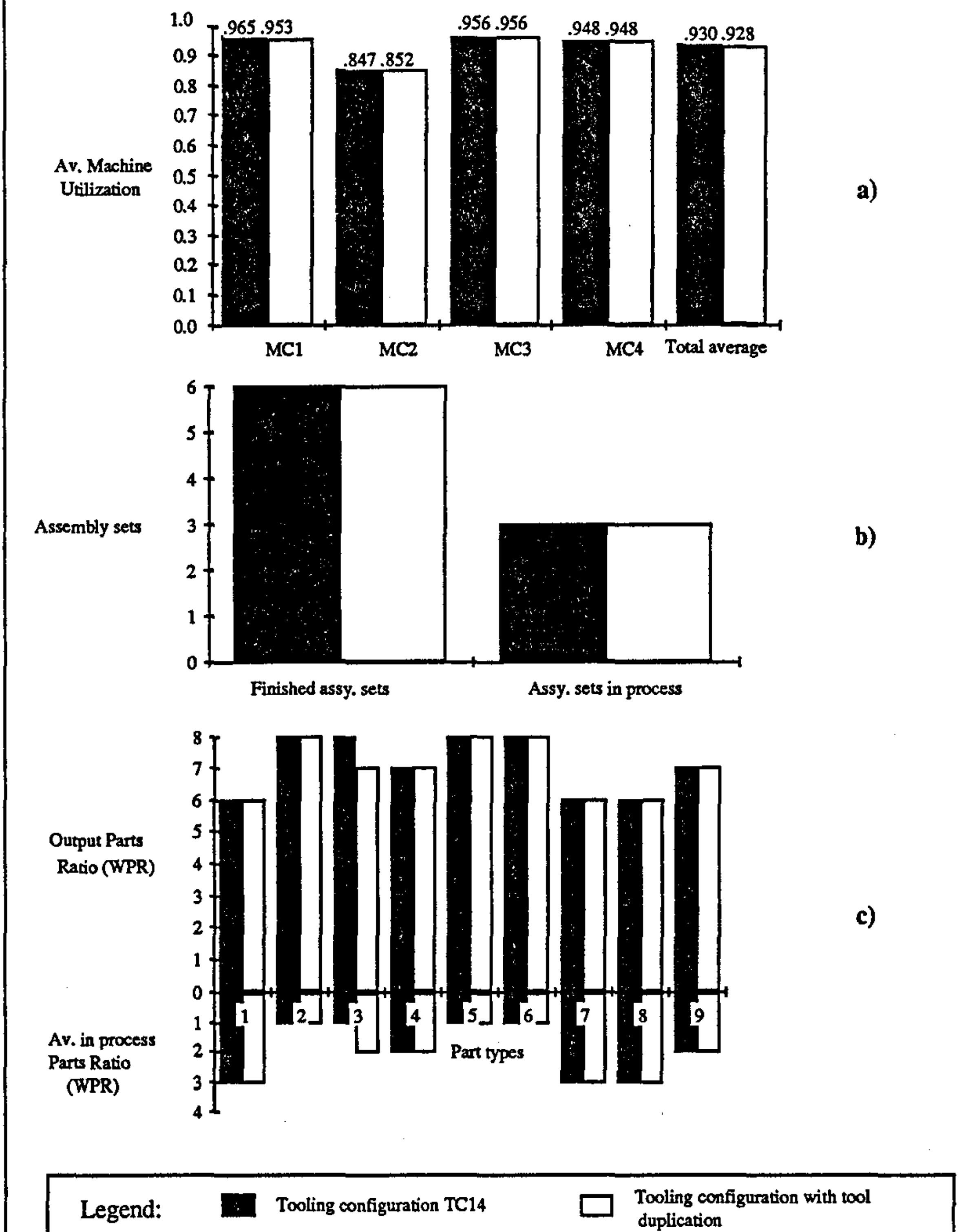


Fig. 10.8.4	Effect of tool duplication on FMS Performance to process part mix B in the configured FMS.

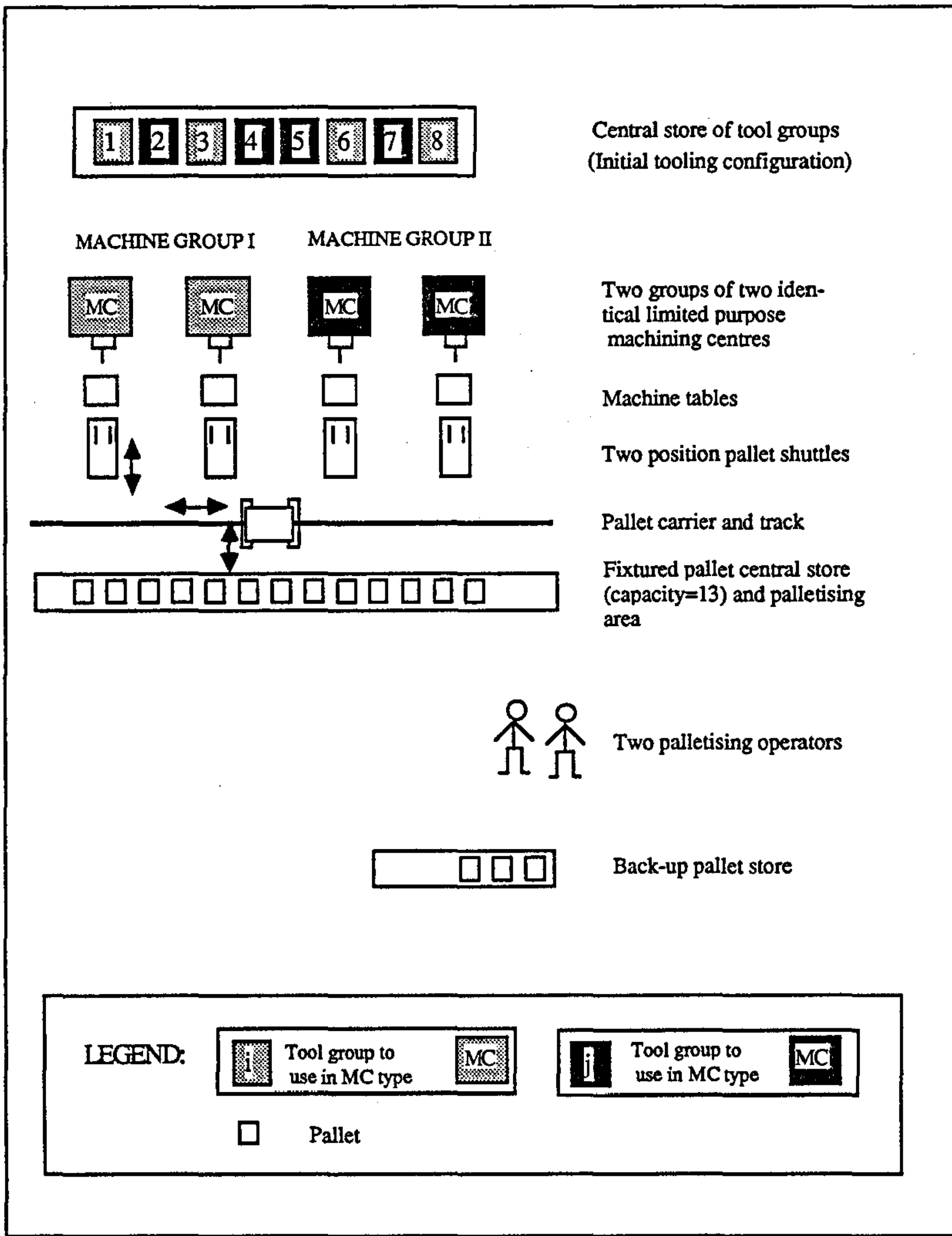


Fig.10.9.1	Schematic representation of the FMS configured with two types of limited purpose machining centres and respective tool groups to use in each type for minimum tooling.

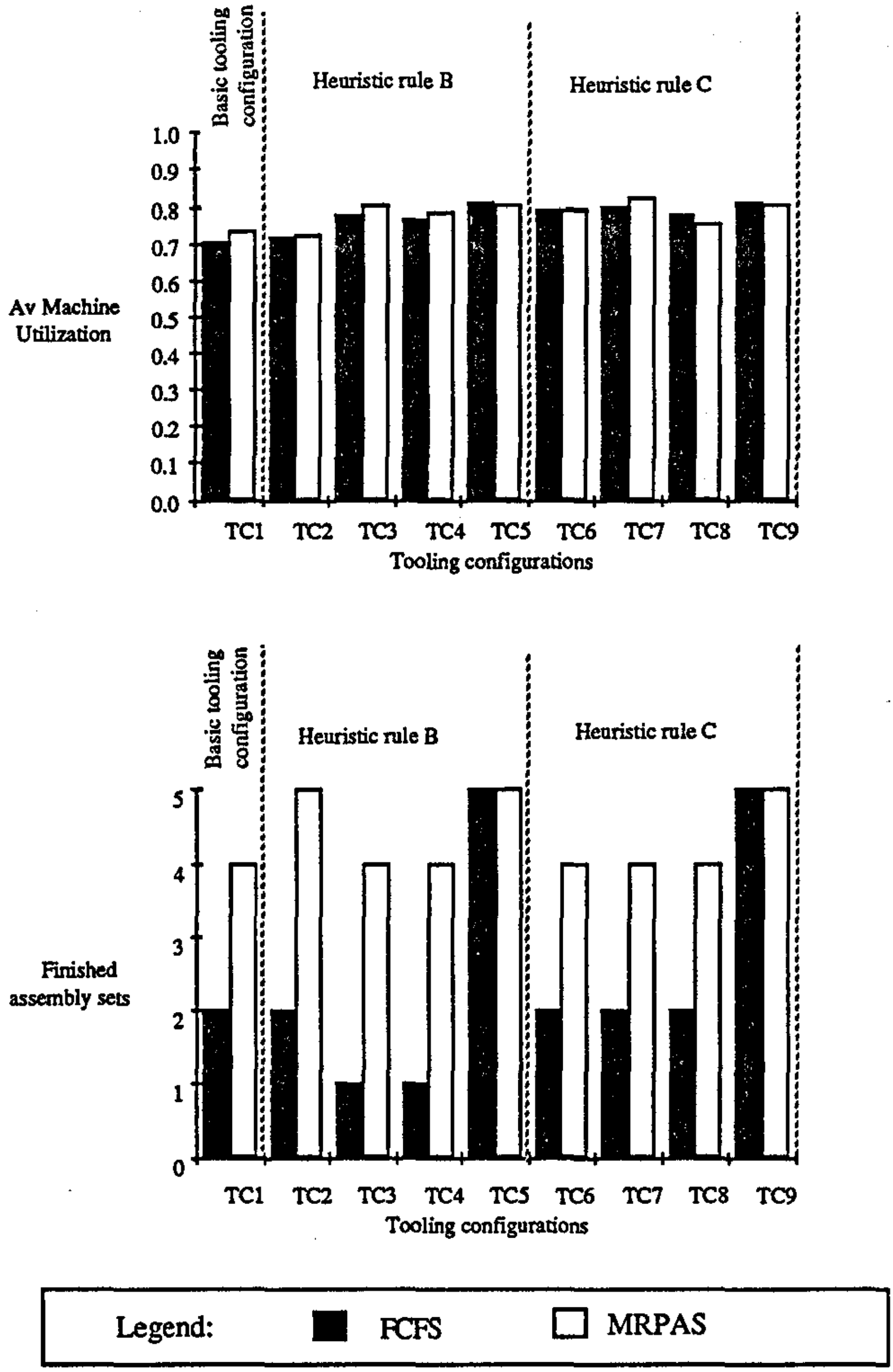


Fig.10.9.2	Performance of the limited purpose machining centres FMS under both FCFS and MRPAS scheduling rules for tooling configurations generated under FCFS using two tool combination heuristics, namely C and B

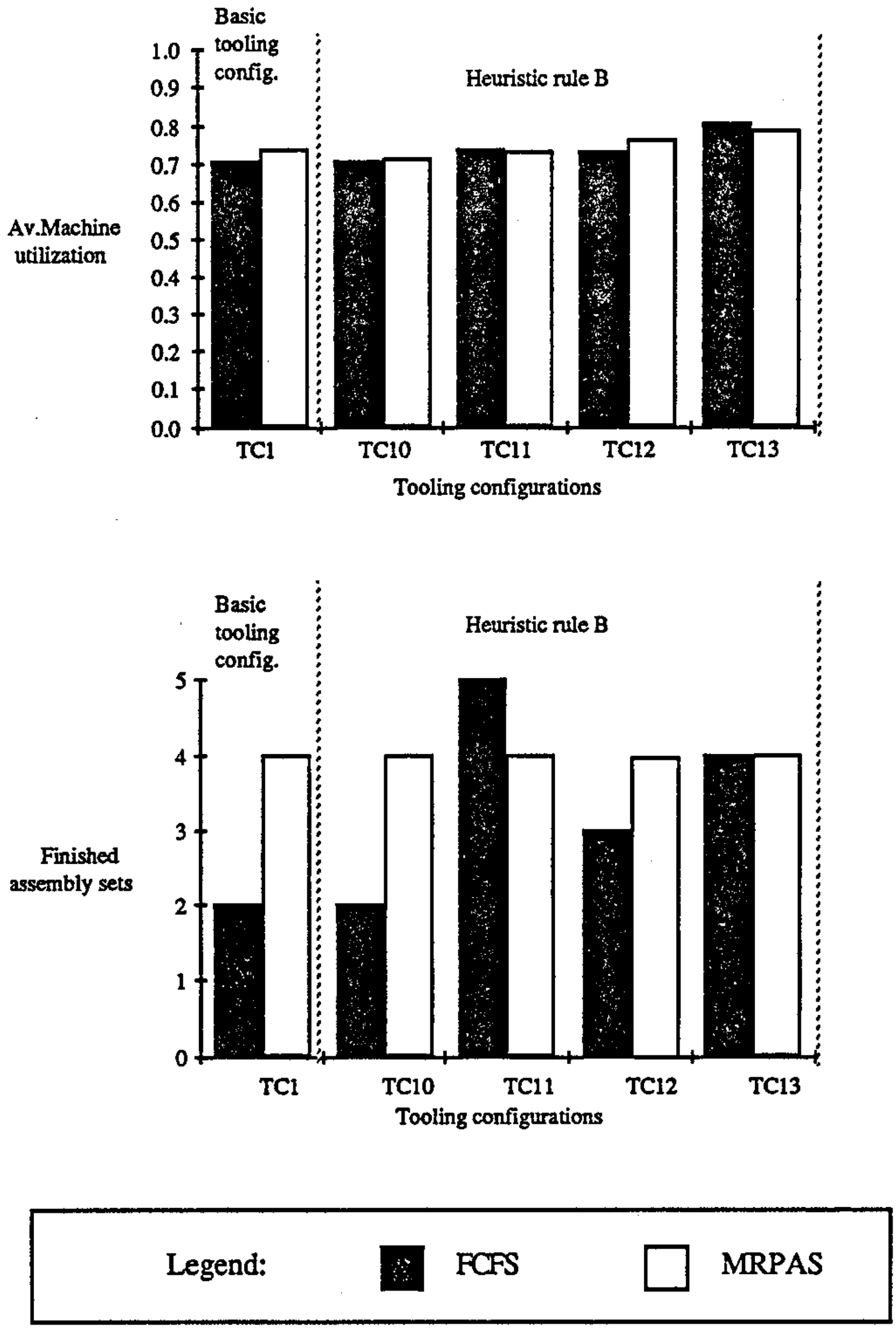


Fig. 10.9.3	Performance of the limited purpose machining centres FMS under both FCFS and MRPAS scheduling rules for tooling configurations generated under MRPAS using tool combination heuristic B.

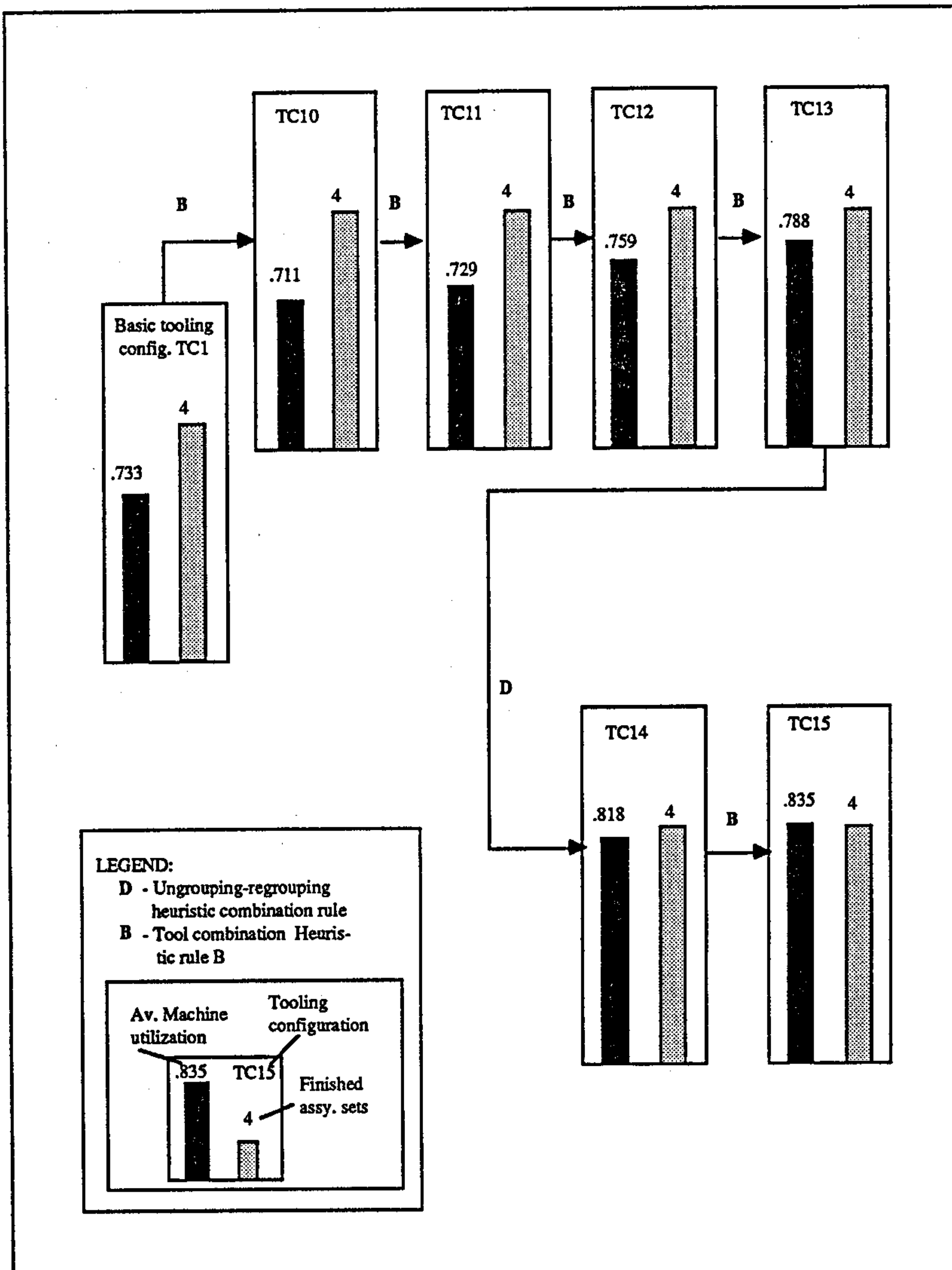


Fig. 10.9.4	FMS performance improvement and sequence development of tooling configurations through the use of the ungrouping--regrouping tool combination heuristic rule, Rule D.

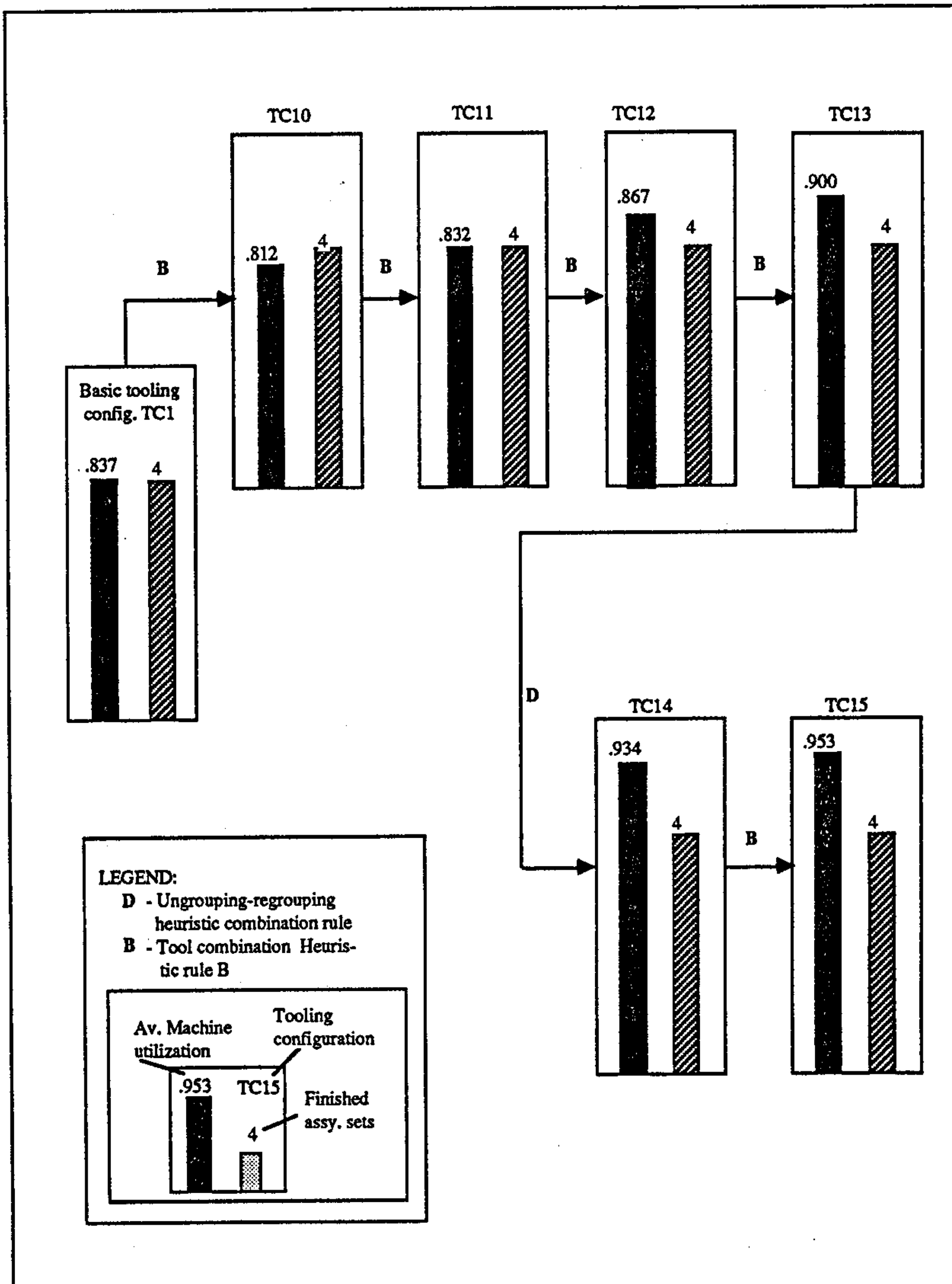


Fig. 10.9.5	Improved FMS performance through the use of the ungrouping-regrouping tool combination heuristic rule--Normalized Utilization view

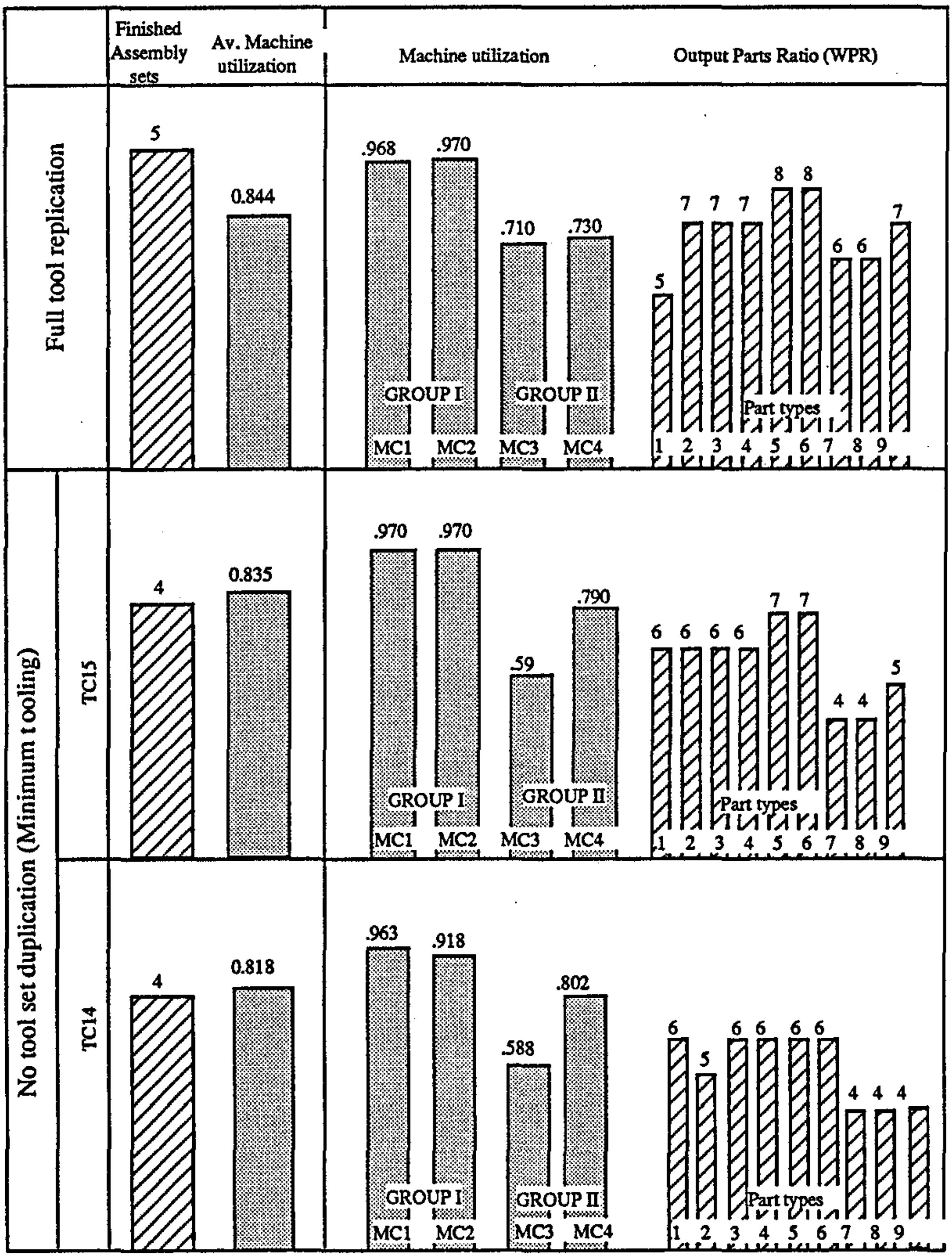
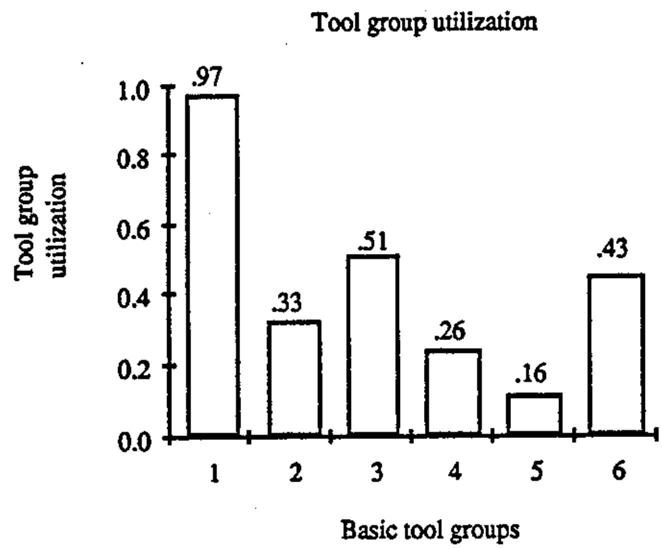


Fig. 10.10.1

Comparison of the performance of the limited purpose machining centres configured FMS for the full tool replication tooling configuration and tooling configurations under no tool set duplication.

Average Machine Utilization = 0.672
Finished Assembly Sets = 4



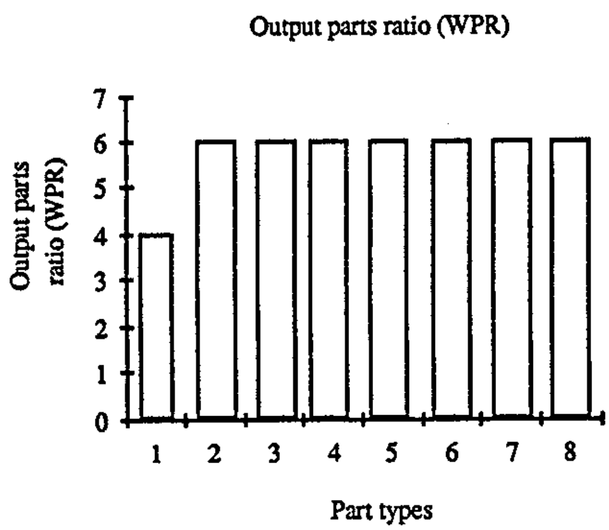
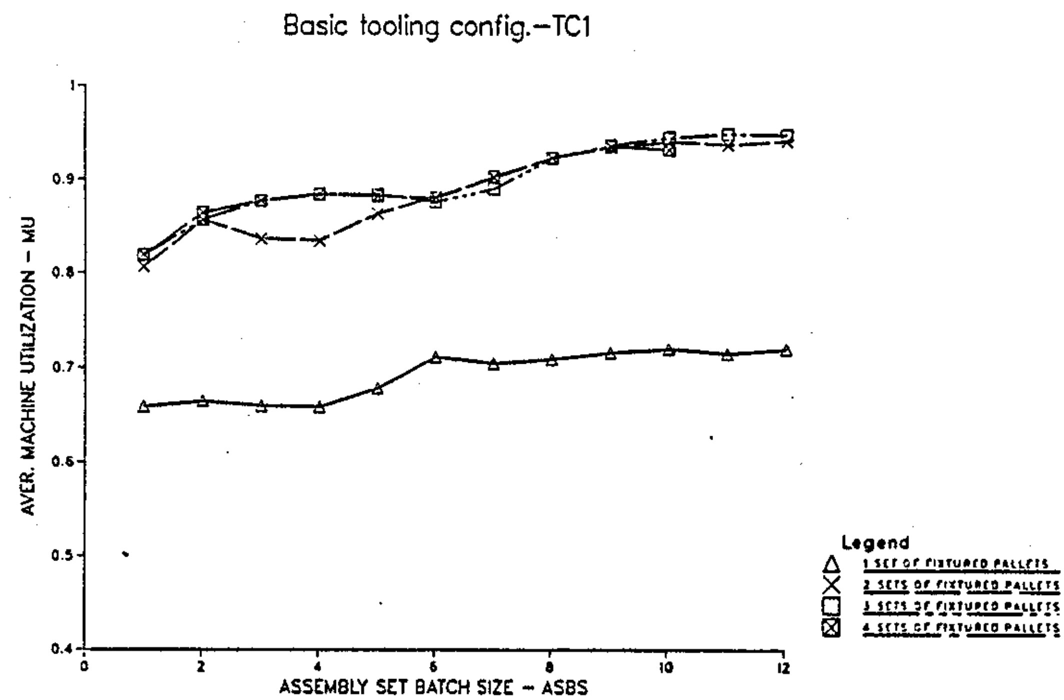


Fig. 10.11.1	Summarized FMS performance under the basic tooling configuration for part mix A - Limited Purpose Machines case



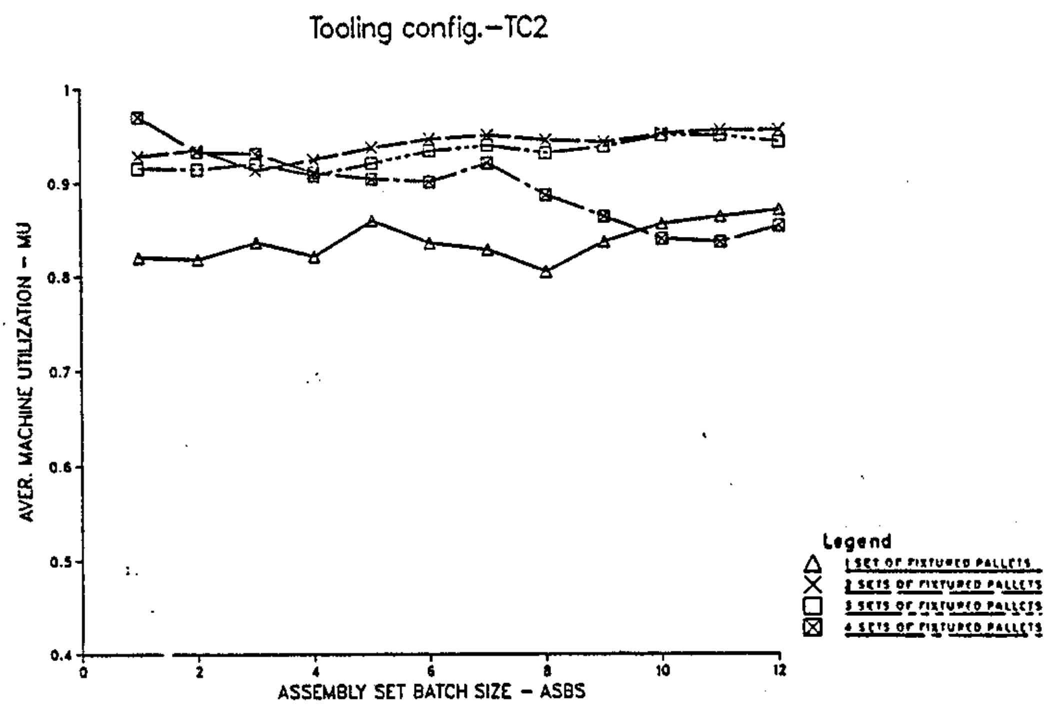


Fig. 10.12.1	Behaviour of machine utilization with ASBS for two different tooling configurations under the same available minimum tools and for different pallet levels

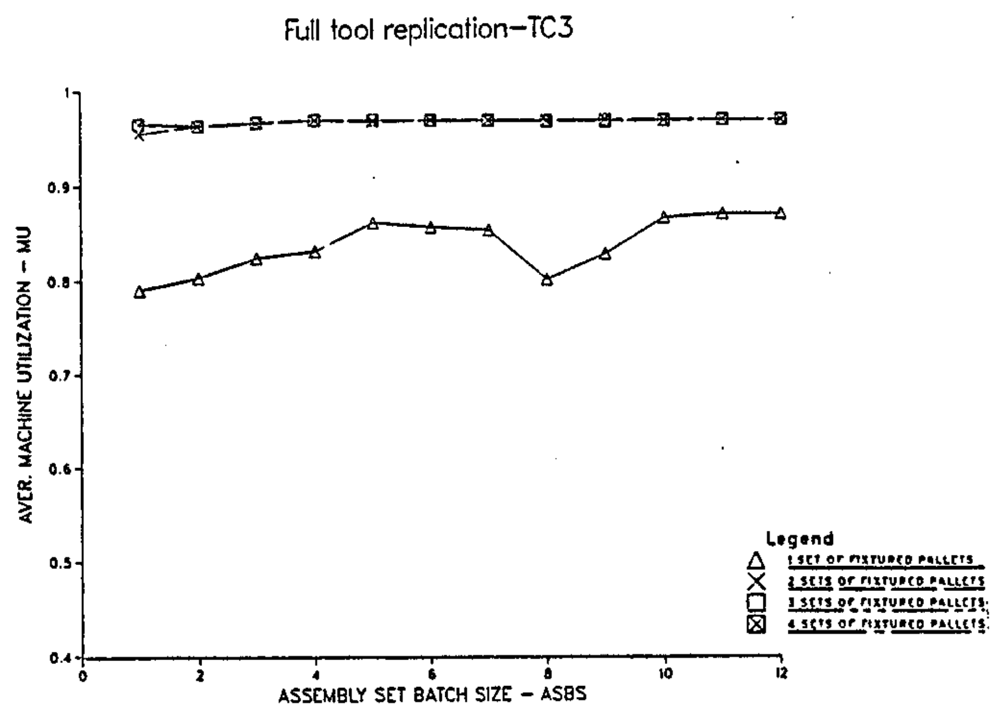
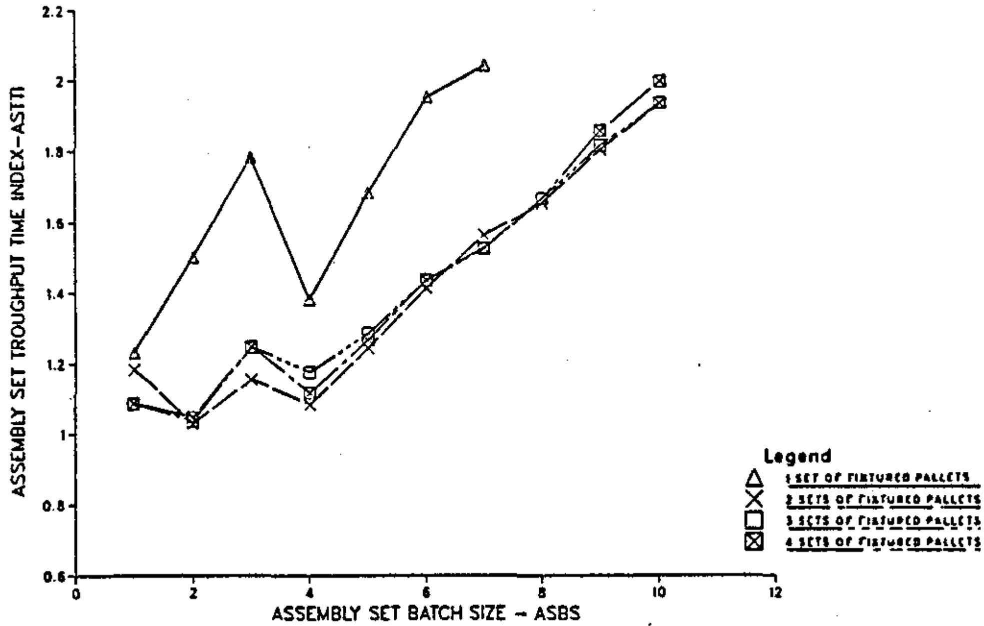


Fig. 10.12.2	Machine utilization for different pallet levels under full tool replication in every machining centre of the FMS

Basic tooling config.TC1



Tooling config. TC2

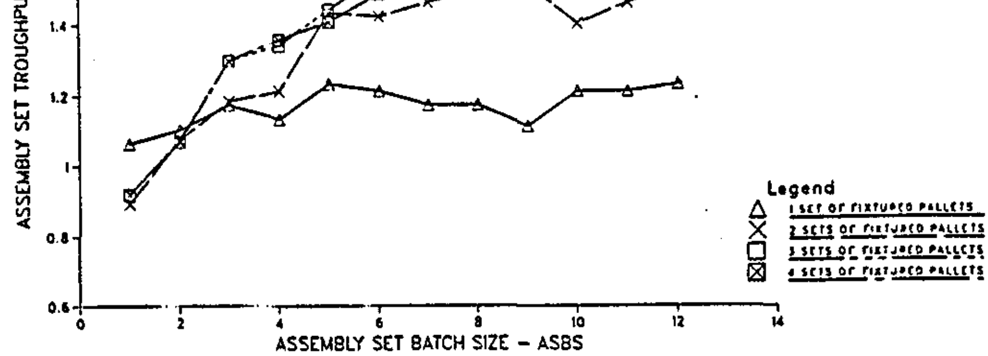


Fig. 10.12.3	Assembly Set Throughput Time Index under two tooling configurations combining the same number of tools for different pallet levels.

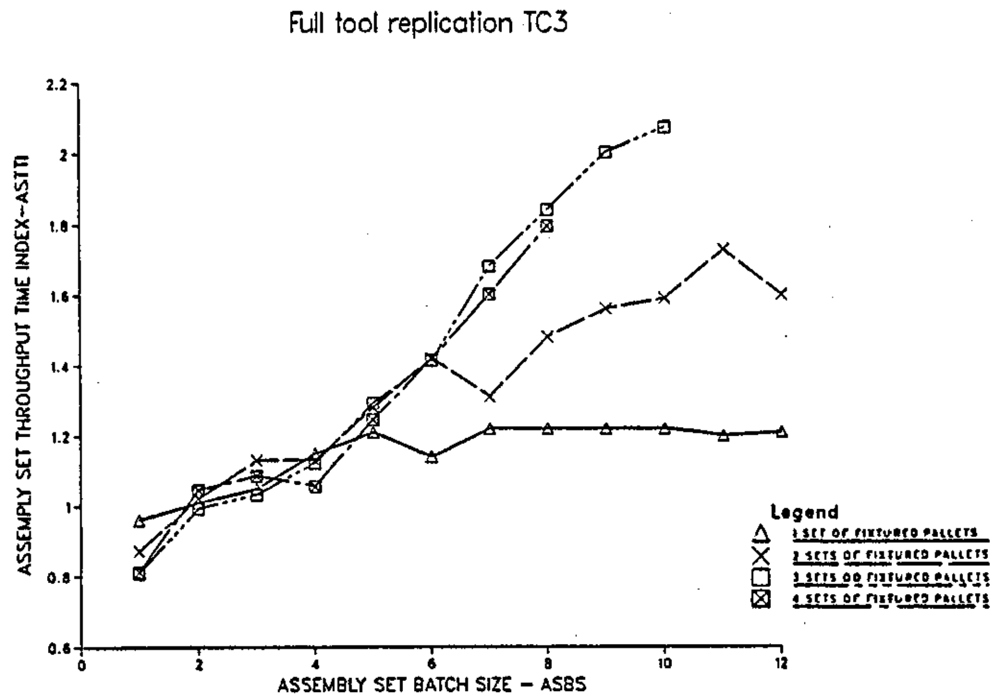


Fig. 10.12.4	Assembly Set Throughput Time Index for four pallet levels under full tool replication in every machining centre

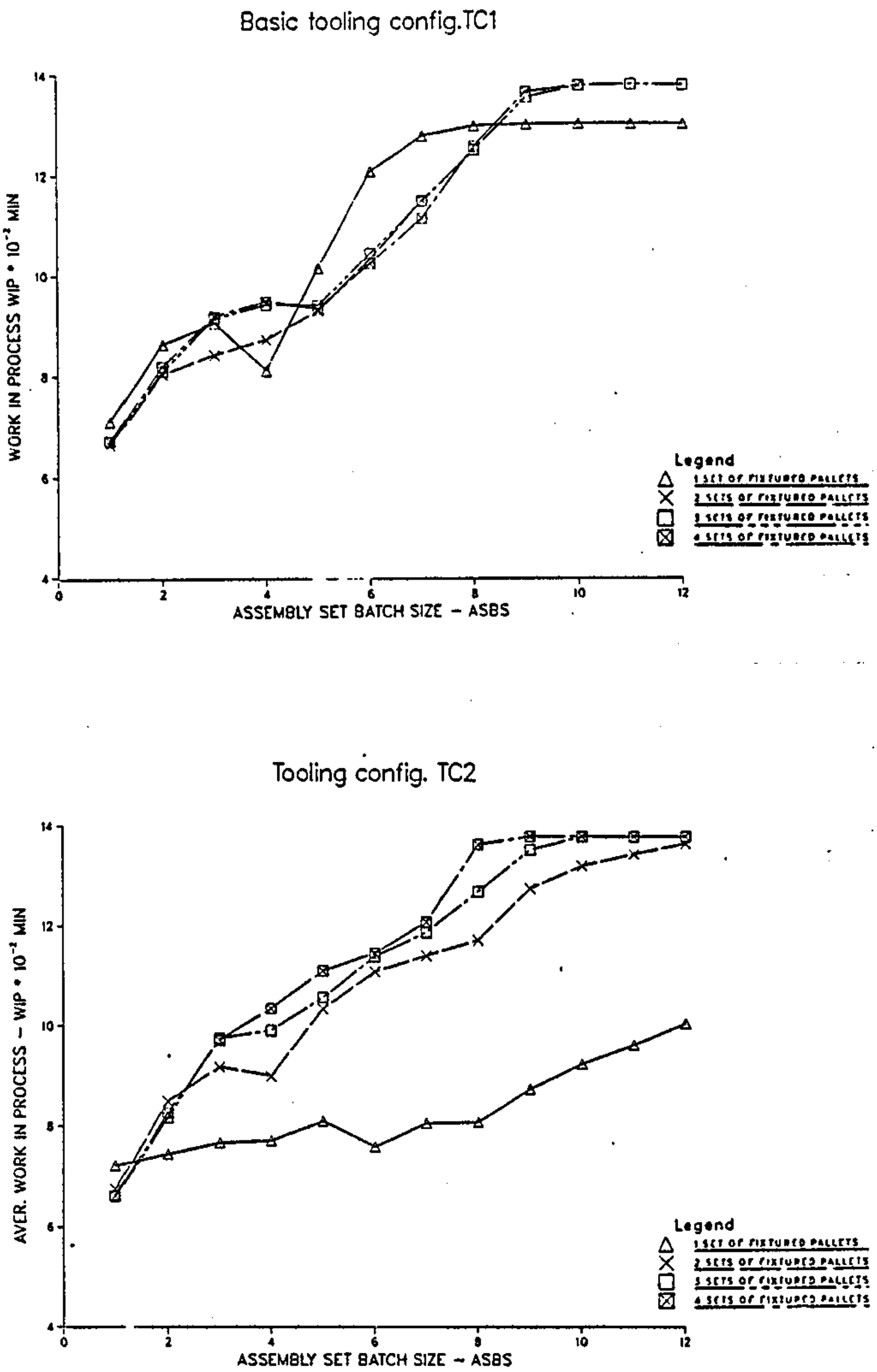


Fig. 10.12.5	Work in process under two tooling configurations combining the same minimum number of tools for different pallet levels.

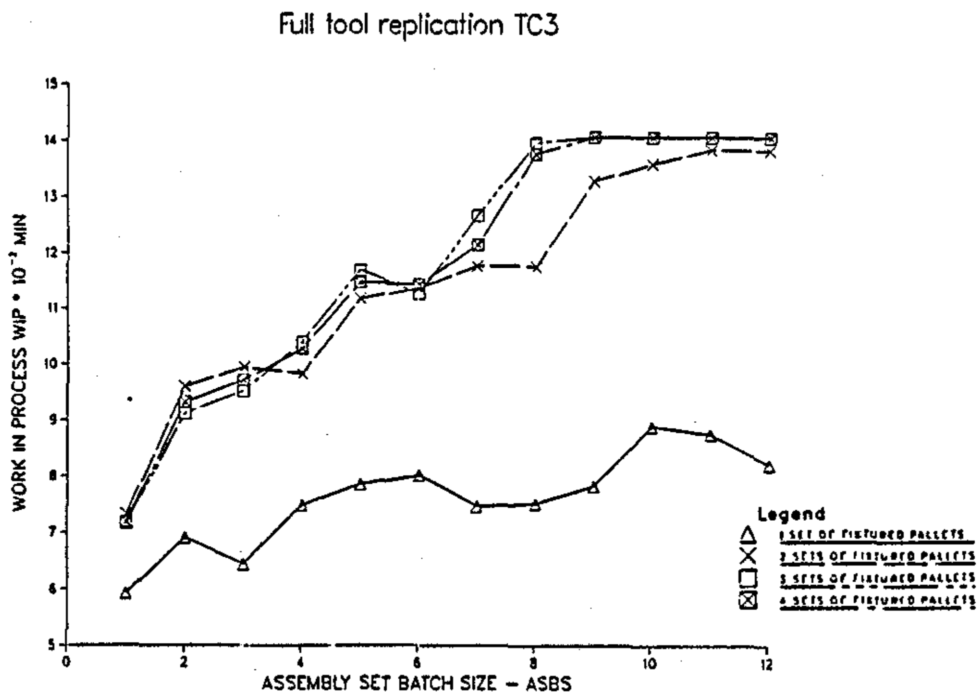


Fig. 10.12.6	Work in process for different pallet levels under full tool replication in every machining centre of the FMS

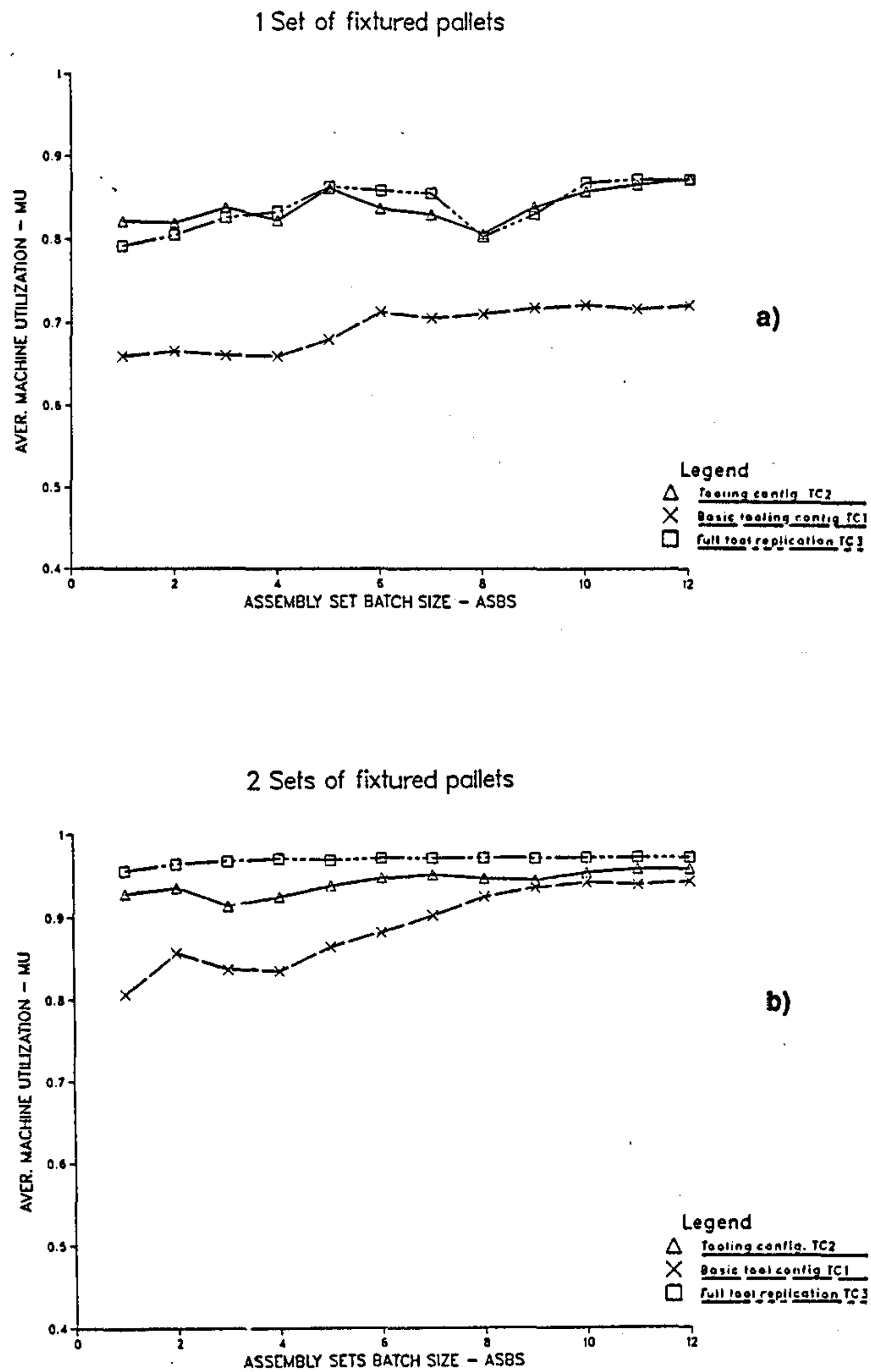
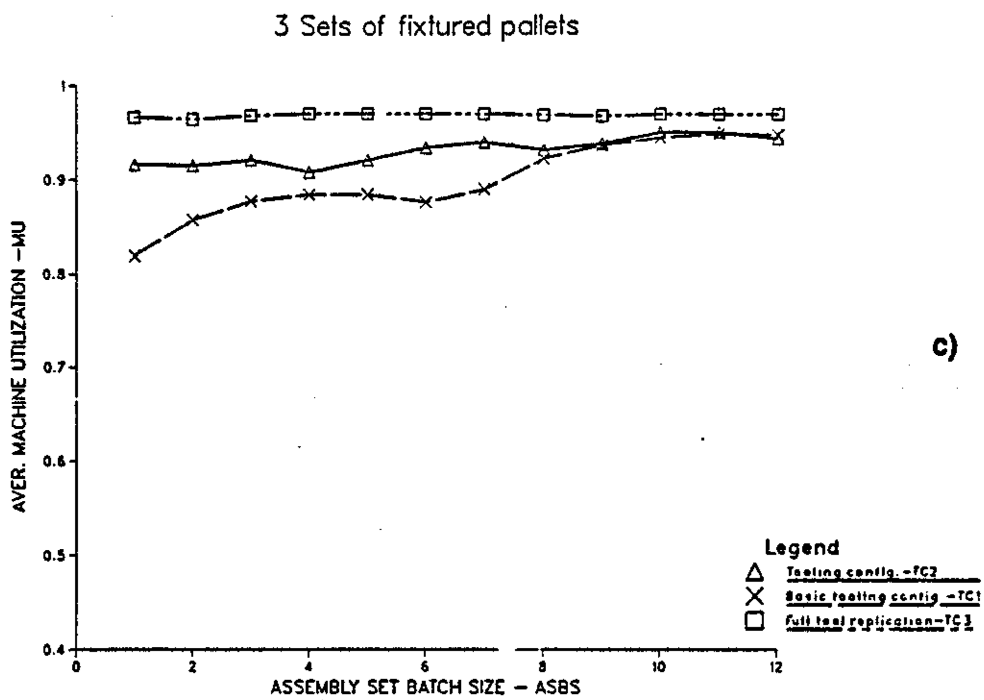


Fig. 10.12.7	Machine utilization under different levels of fixtured pallets for three tooling configurations



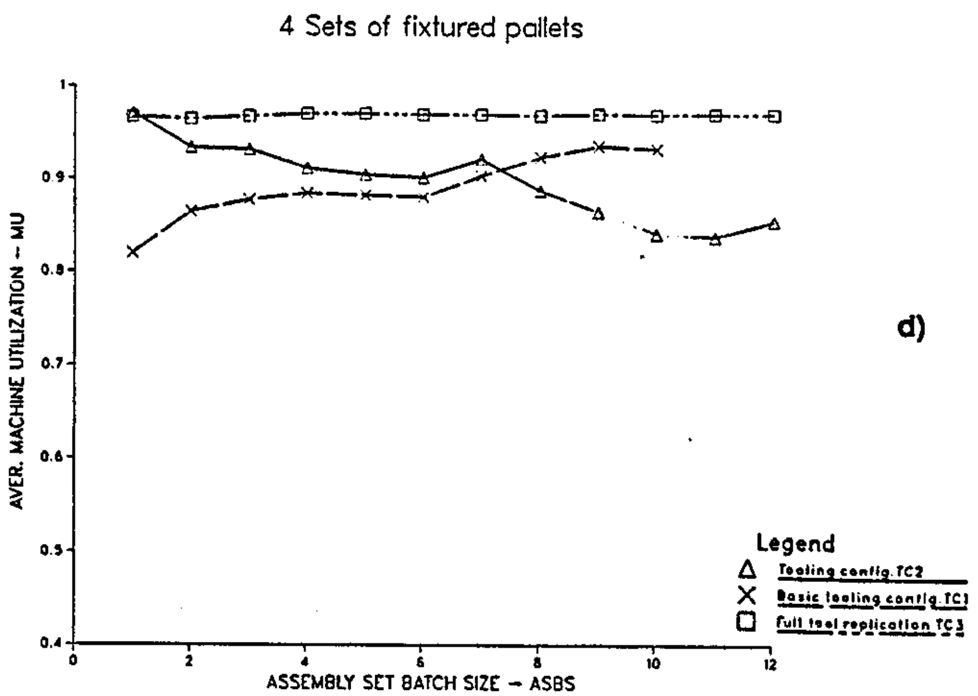


Fig. 10.12.7 (Cont'd)	Machine utilization under different levels of fixtured pallets for the three tooling configurations

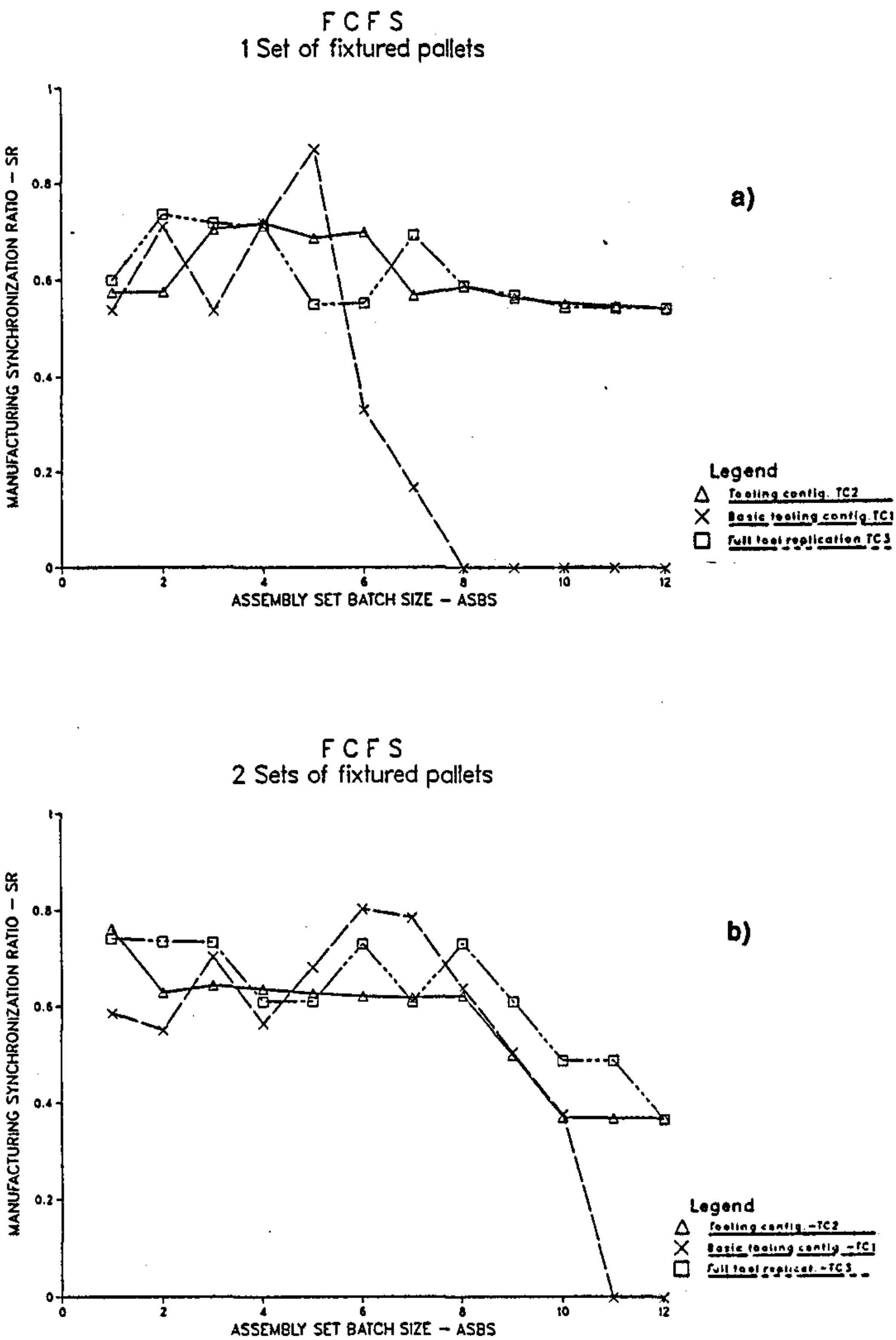
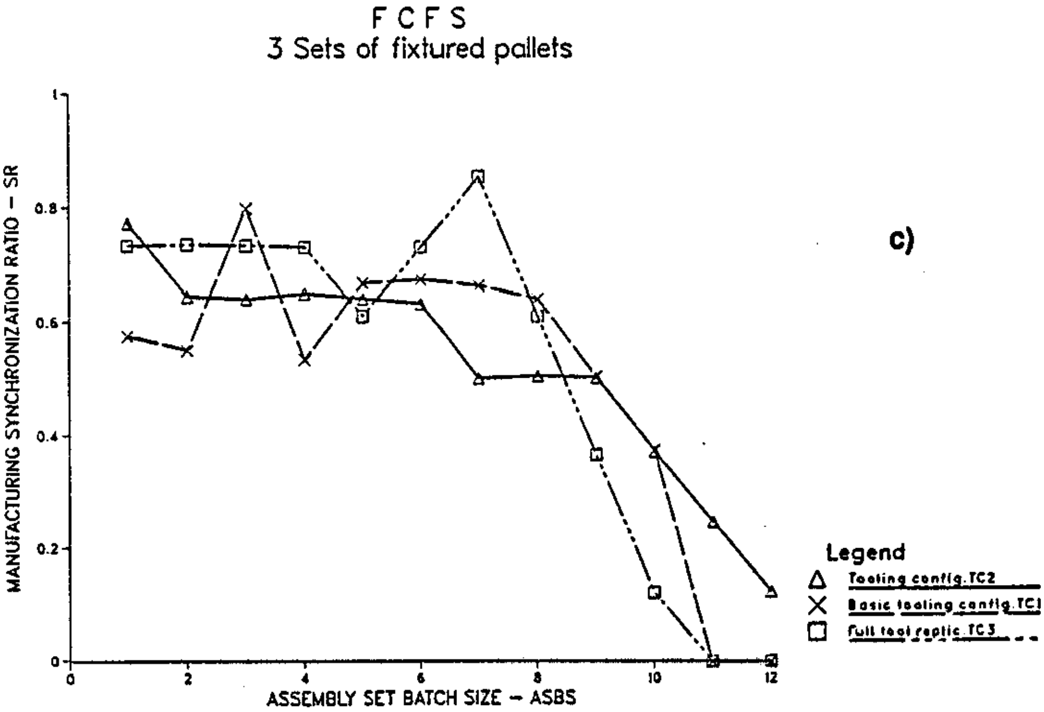


Fig. 10.12.8	Manufacturing Synchronization Ratio for the three tooling configurations under different number of pallets



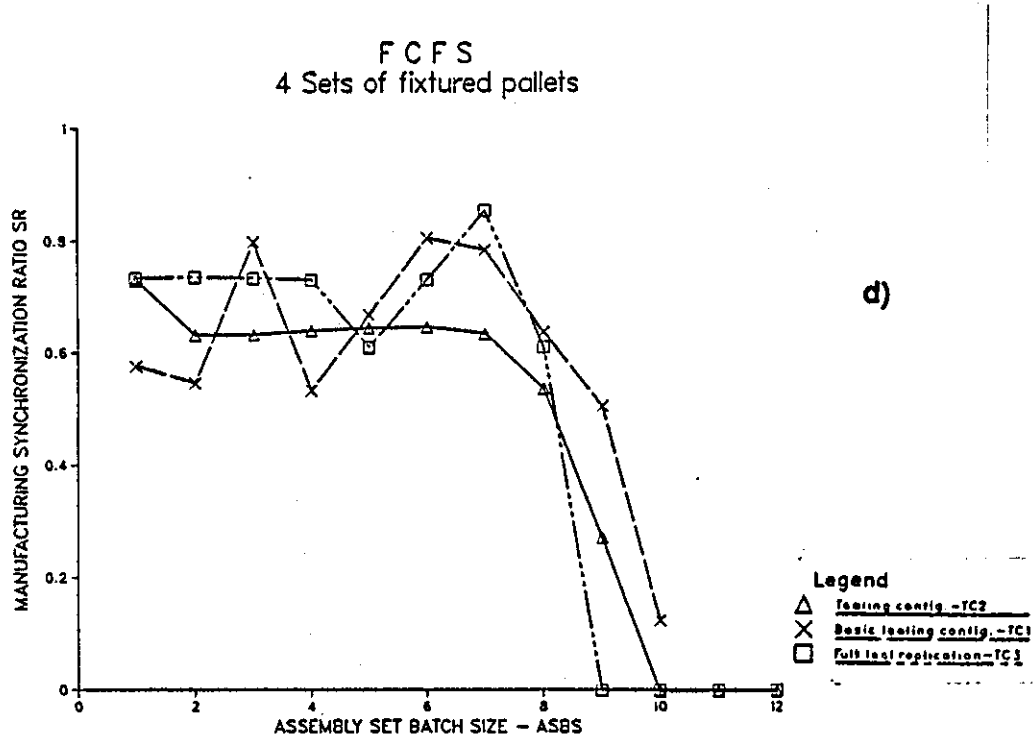


Fig. 10.12.8 (Cont'd)	Manufacturing Synchronization Ratio for the three tooling configurations under different number of pallets

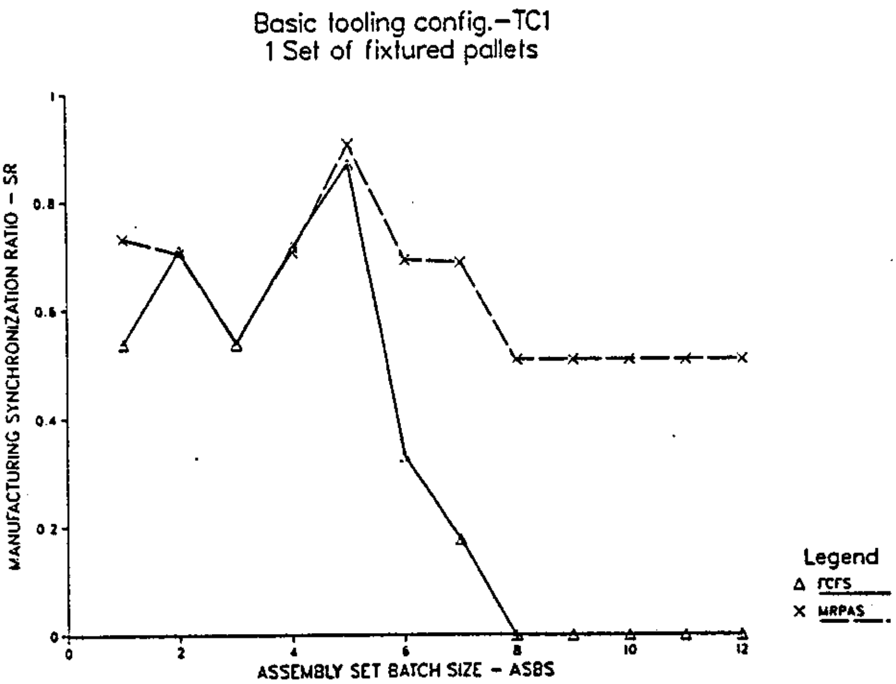


Fig. 10.12.9

Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with a single set of fixtured pallets and the basic tooling configuration

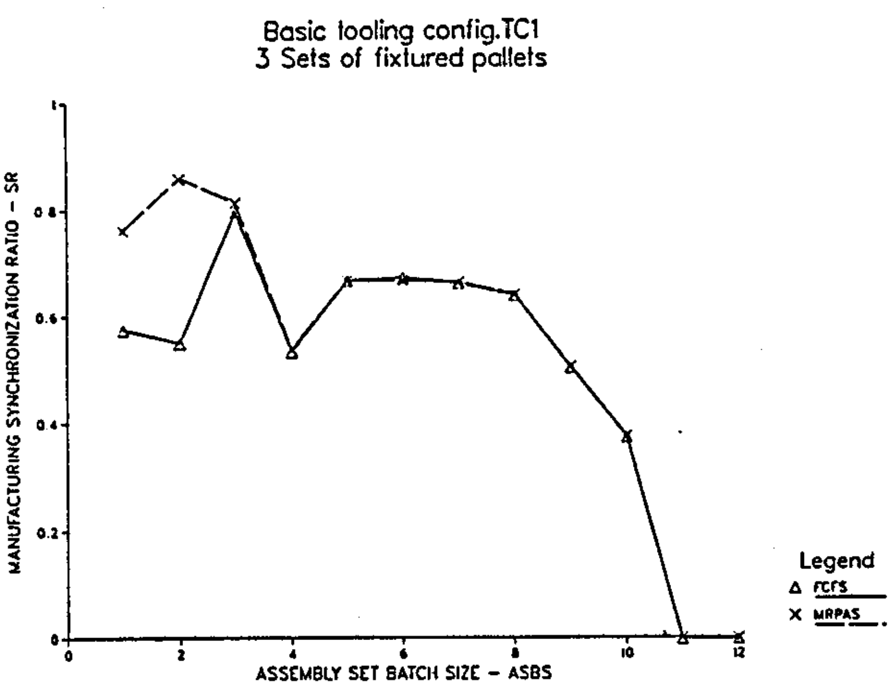


Fig. 10.12.10

Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with three sets of fixtured pallets and the basic tooling configuration

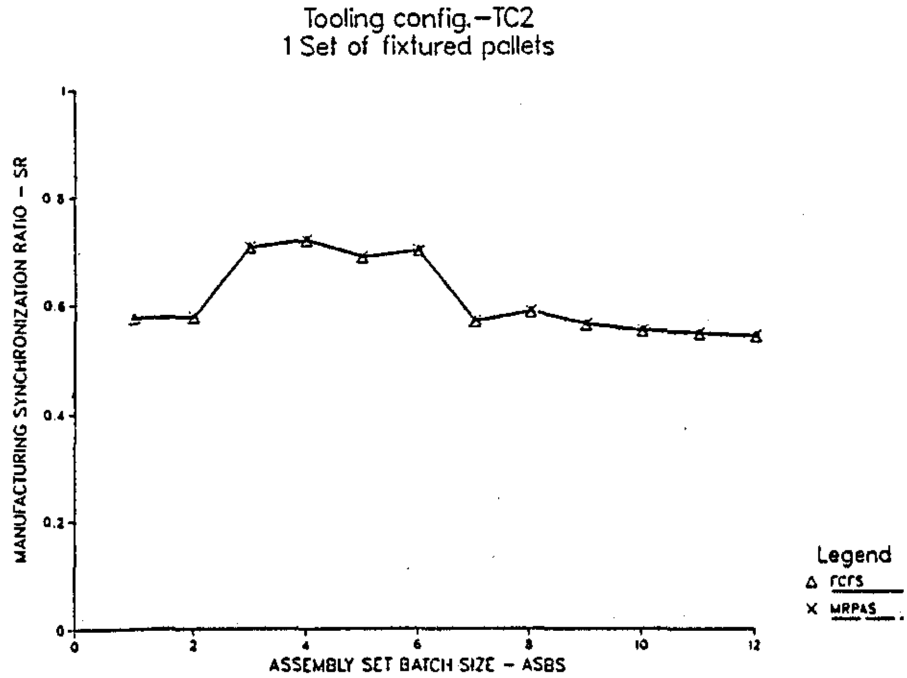


Fig. 10.12.11	Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with a single set of fixtured pallets and the well performing tooling configuration TC2

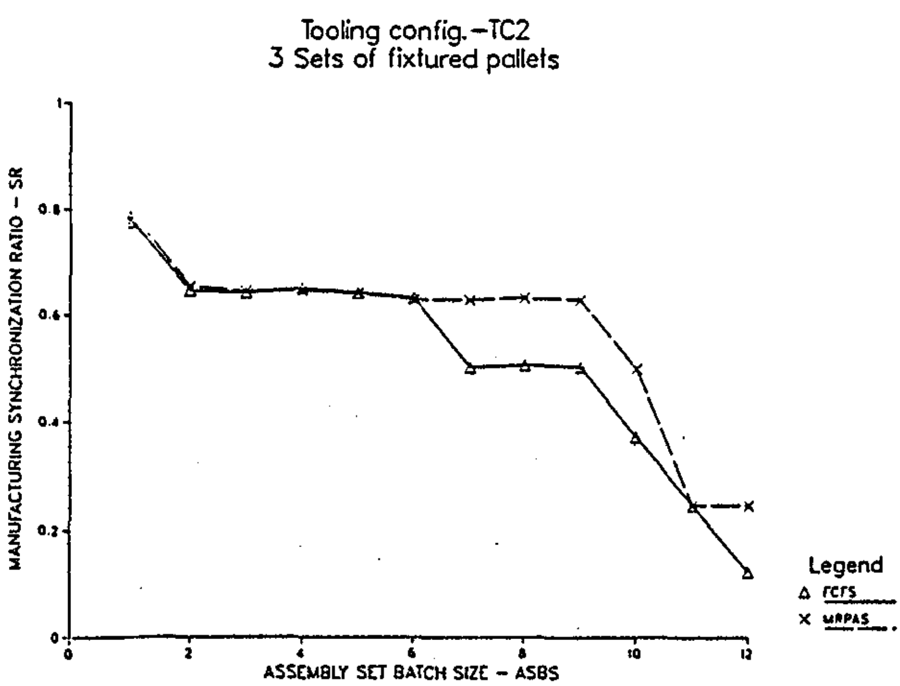


Fig. 10.12.12	Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with three set of fixtured pallets and the well performing tooling configuration TC2

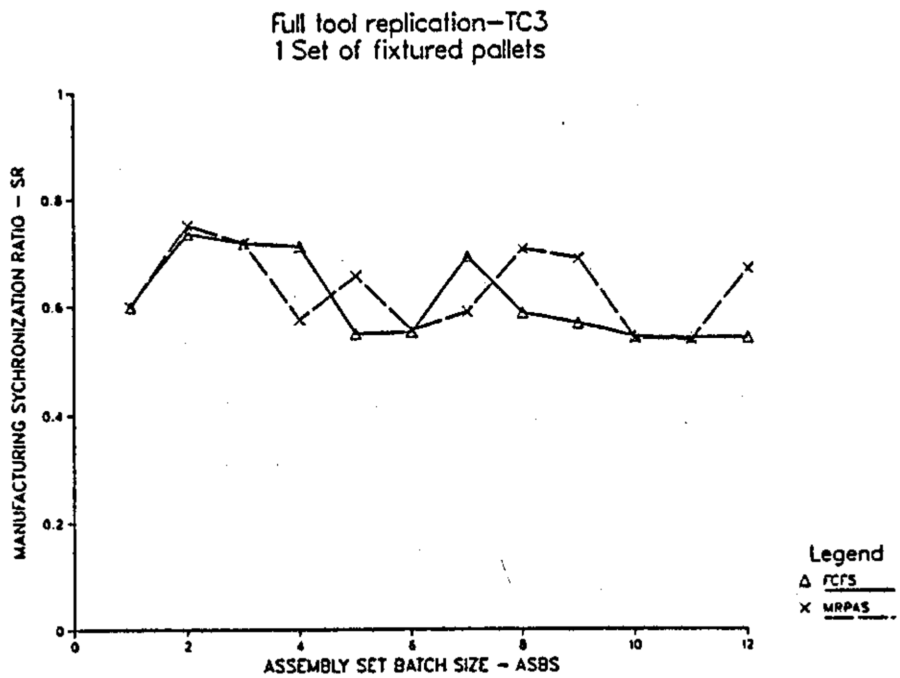


Fig. 10.12.13	Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with a single set of fixtured pallets and full replication in every machining centre of the FMS.

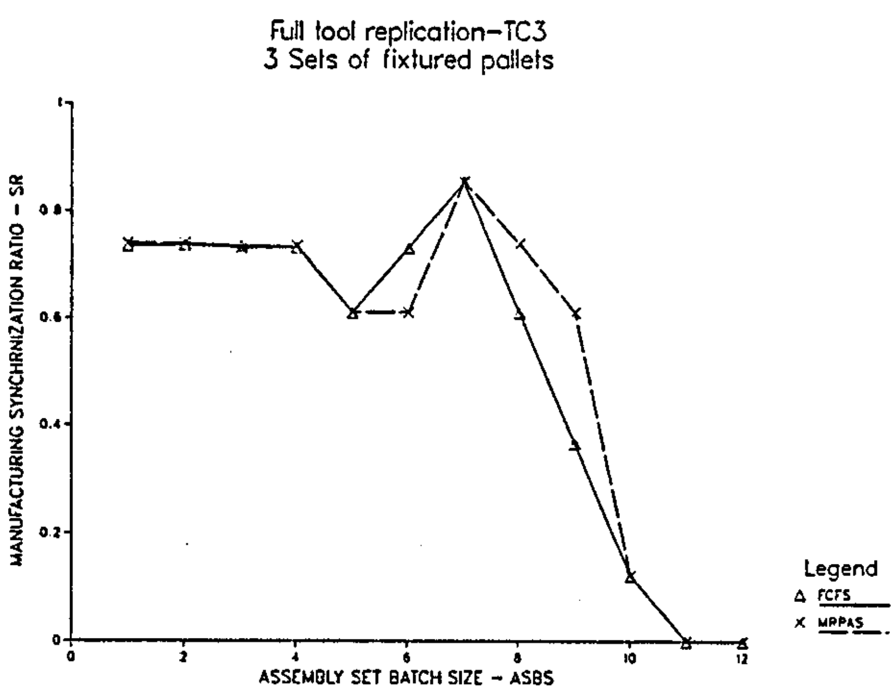


Fig. 10.12.14	Comparison of the behaviour of the two scheduling rules FCFS and MRPAS for a system set-up with three set of fixtured pallets and full replication in every machining centre of the FMS.

TABLE S

Table 3.1: A summary of the characteristics of simulation models developed for studying FMS design and operation (a)

DATE	NAME	DESCRIPTION/PURPOSE	LANGUAGE	GRAPH. CAPABS.	GENERALITY	DETAIL/ COMPLEXITY	ORIGEN Res.Institution	ORIGEN Country	TOOLING SYTEM MODELLING	TYPE	PRACTICAL FMS APPLICATIONS	BIBLIOG SOURCES (b)	OBSERVATIONS
1971	K&T Sim.	Study a large variety of FMS physical configurations and MHSs	SIMSCRIPT	N	High	High	K & Trecker	USA	N	M	Several	3	Run in a UNIVAC 1108
1973	-	Generalized Model of FMS	SIMSCRIPT 1,5	N	High	Medium	Wisconsin Univ.	USA	N	M	Allis Chalmers FMS	38;18	Emphasis on MHS with carts Run in a UNIVAC 1108
1976	MUZIK	"Modular Simulation for Flexible linked Manufacturing Systems	FORTRAN (GPSS)	U	High	Medium	IPA-Stuttgart	WG	N	M	Several	5;35	Requires specialist knowlede.
1976	CATLINE	Simulation of control and operational issues of the Caterpilar Line	CASP IV	N	Very Low	High	Purdue Univ.	USA	N	M	Caterpilar Line	31	Specific to Caterpilar line
1977	GCMS	"General Computerized Manufacturing System Simulator"	GASP IV FORTRAN	I/O	High	Medium	Purdue Univ.	USA	N	M	Rockwell FTL	21;20;32	Emphasis on MHS;1 GASP and 1 FORTRAN version.
1977	PSWZ	Prog. zur Simulat. der Verkzeugflusse	BASIC FORTRAN		Medium	High	Achen Univ.	WG	Y	M	Mess.B.B. FMS - WG	36	
1977	CMHASS	Complex Manuf.Handling and Assy. System Simulator	BASIC	N	U	U	MIT	USA	N	M	U	2	
1977	COSMOS	FMS simulation with CRT display for evaluating the feasibility of CMS		A	High	Low	MIT	USA	N	M	U	7;30	Post-processed animation in a CRT display; Simulation is only part of COSMOS
1977	-	Simulation Of FMS for Rot.Parts	SIMULA	N	Medium	Medium	Berlin Univ.	WG	N	M	Pilot FMS for Rot. Parts at Berlin Univ.	5	Supervision of SPUR,G. Run in a DEC-10/20 and
1977	GEMS	General. Manufacturing Simulator	Q-GERT	I	High	Medium	Texas A&M Univ.	USA	U	G	U	27;30	
1978	-	Simulation for evaluation of organizational measures in Manuf. Systems	U	N	High	Low	Aachen Univ.	WG	N	M	U	11	

Table 3.1: A summary of the characteristics of simulation models developed for studying FMS design and operation (cont.)

DATE	NAME	DESCRIPTION/PURPOSE	LANGUAGE	GRAPH. CAPABS.	GENERALITY	DETAIL/ COMPLEXITY	ORIGIN		TOOLING SYTEM MODELLING	TYPE	PRACTICAL FMS APPLICATIONS	BIBLIOG SOURCES	OBSERVATIONS
							Res.Institution	Country					
1978	IRHMC	Study part mix selection, work flow and process selection in CMS	Q-GERT	I	Low	U	Purdue Univ.	USA	N	M	Ingersoll Rand Line	14	
1979	CAMSAM	First stage Design of FMS	U	N	Medium	Very Low	Purdue Univ.	USA	N	M	Rockwell FTL; Caterpilar Line; Ingersoll Rand Line	14	
1979	HABMS	"Advanced Batch Manufacturing Systems Model"	ECSL	N	Very High	Very Low	Wisconsin Univ.	USA	N	M	U	33	Hihly simplified modelling assumptions.
1979	VMSM	Model to study the Variable Mission sytems from Cincinatti Milacron	FORTRAN IV Plus	U	High	U	Cincinatti Milac.	USA	N	M	Variable Mission Systs.	14;3	Can run in the control computer of the VM Systs.
1980	Q-CAN-Q	Simulates CAN-Q Math. Model	Q-GERT	I	High	Very Low	Purdue Univ.	USA	N	M	Caterpilar Line	14	Relies on the simplified assumptions of CAN-Q
1981	COL	Carts On Line	ECSL	U	Low	Low	Draper Lab.	USA	N	M	U	3	
1981	GEMS	"General Flexible Manufacturing Systems Simulator"	FORTRAN 77 GASP IV	U	High	Medium	Draper Lab.	USA	N	M	U	3	
1982	SIKTAS	Simulation for Complex Technical Elementes and Systems	FORTRAN PASCAL	I/O/A	High	High	Stuttgart Univ.	WG	Y	G	FMSs at Stutt.Univ. and Burkhart &Webber	6	Two language based models are available
1982	FIST	Flexible Integrated Simulation Tool	FORTRAN	N	Low	Low	Illionis Inst.Tech.	USA	N	M	U	33	
1982	SPEED	FMS Modelling	FORTRAN 66	U	Medium	Medium	Horizon Sw. Inc.	USA	N	M	U	3	Emphasis on cart MHSs. Inter.Model Generat. availab.
1983	MAP/1	Modelling Analysis Prog./1 - Simulation of any Batch Manuf. System	SLAM	N	Very High	Medium-Low	Pritsker & Asso.	USA	N	G	An FMS for transmission cases	27;28	

Table 3.1: A summary of the characteristics of simulation models developed for studying FMS design and operation (cont.)

DATE	NAME	DESCRIPTION/PURPOSE	LANGUAGE	GRAPH. CAPABS.	GENERALITY	DETAIL/ COMPLEXITY	ORIGEN Res.Institution	ORIGEN Country	TOOLING SYTEM MODELLING	TYPE	PRACTICAL FMS APPLICATIONS	BIBLIOG. SOURCES	OBSERVATIONS
1983	-	Simulation model to evaluate control policies in FMSs for Rot. Parts.	BCSL	N	Medium	Low	Loughborough Univ.	GB	N	M	U	4	
1983	FMSSIM	FMS Simulator	FORTRAN	I/O/A	High	Medium	McMaster Univ.	Canada	N	M	U	33;9	Emphasis on MHS; Separated SW for animation
1983	REFLEX	Renault FMS Simulator	FORTRAN	A	Medium	High	Renault	France	Y	M	Renault FMS	15	Emphasis on MHS; Uses a separated system to visualize the simulation in a CRT
1983		Simulation of the AGV's network for the COMAU FMS	U	U	U	U	COMAU	Italy	U	M	COMAU FMS	15	
1983	GPDEMS	"General Discrete Event Manufacturi Simulator"	FORTRAN77 (GASP IV)	I/O/A	High	High	Univs.:Nagoya Osaca and Kobe	Japan	Y	G	U	19	Implem. in a Mini-comp. DG MV6000
1983		Sim.Model for study scheduling problems in FMS	SLAM II FORTRAN	N	Low	Medium	Texas Univ. and Harris Corporat.	USA	Y	M	Proposed Aircraft Ind. FMS	1	323 lines of SLAM code and 1731 lines of FORTRAN code
1984	MAST	Manufacturing Automated Systems Design Tool	FORTRAN	I/O/A	High	U	CMS Res. Inc.	USA	U	M	Many	22;3	Animation through the BEAM program
1985	PATHSIM	Modular Simulation Model for Automatic Tool Handling	SLAM	N	Medium	Medium	Purdue Univ.,G.E. and Ingersoll Eng.	USA,GB	Y	M	U	8;27	Emphasis on Physical Conf. of Tooling Systems of FMS.
1985	KOSMO	A simulator for FMSs	PASCAL	I/O/A	Medium	Medium	Tokyo Univ.	Japan	N	M	FMS for Escavators-Jap.	34	Data input by icons
1985	UOSGFMS	"User Oriented Simulator Generator do Design and Control FMS"	BASIC /SIMAN	I/O	Low	Low	Rensselaer Instit.	NY-USA	N	G	U	17	Coded of the generated model obtained in SIMAN
1985	FASTSIM	Design and Perform.Evaluation of FMS through Simulation	FORTRAN77	N	Medium	Low	Mectron	Italy	N	M	U	24	Runs in VAX750 and DEC350 Similarities with Q-CAN-Q

Table 3.1: A summary of the characteristics of simulation models developed for studying FMS design and operation (cont.)

DATE	NAME	DESCRIPTION/PURPOSE	LANGUAGE	GRAPH. CAPABS.	GENERALITY	DETAIL/ COMPLEXITY	ORIGEN Res.Institution	ORIGEN Country	TOOLING SYTEM MODELLING	TYPE	PRACTICAL FMS APPLICATIONS	BIBLIOG SOURCES	OBSERVATIONS
1985	MODEL MASTER	A simulation Program for Manufacturing Systems Study	U	I/O/A	High	Medium	General Electric	USA	U	G	Israel Airgraft Industry FMS	26;13	
1985		Simulation of the Maxino Max FMS					Cranfield	GB	Y	M	Makino MAX FMS	25	
1985	TOLSIM	Simulation of Tool System Requirems. in a FMS with Tool Carts	FORTRAN IV GASP	O/A	Low	High	McMaster Univ.	Canada	Y	M	U	10	Animation on a colour refresh Display or VT-100 terminal
1986	GISA	Graphical Interative Simulation and Animation	SLAM	I/O/A	High	High	Aachen Univ.	WG	Y	D	U	4	Modelling by Icons
1986	PLUSS/TSS	General Manufacturing Simulator	U	I	High	High	Syst.Res.Labs.of Nipon Electric	Japan	U	M	FMS for telephone equipment	13	Interactive Simulation of various flow structures
1986	SCHED/SIM	Scheduling through simulation	U	I/O/A	High	Low	Factrol Inc.	USA	N	M	Several	16	
1986	XMAS	Expert Syst.for Manuf.Simulation.	PROLOG	U	U	U	Technical Univ.	Denmark	U	G	U	37	Modell building takes only a few hours
1987	FMS-SET	Simulation of an FMS for Turbine Blades	FORTRAN77	N	Medium	High	Ansaldo and Automata	Italy	Y	M	Ansaldo Componenti FMS	29	Runs in VAX II/Miccro VMC

Symbols:

FMS	Flexible Manufacturing System	I	Input
FTL	Flexible Transfer Line	O	Output
CMS	Computerized Manufacturin System	A	Animation
MHS	Material Handling System	I/O/A	Input/Output/Animation
IPA	Institute for Production Automation	M	Model
FHG	Frunhofer Institute for Production	G	Model generator
		U	Unknown
		Y	Yes
		N	No

(a) - Based on available references

(b) - See Bibligraphy on page 212

Table 8.1 - Number of Tooling Configurations G_n^t with n tool groups formed from t basic tool sets

n \ t	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2		1	3	7	15	31	63	127	255	511	1023
3			1	6	25	90	301	966	3025	9330	28501
4				1	10	65	350	1701	7770	34105	145750
5					1	15	140	1050	6951	42525	246730
6						1	21	266	2646	22827	179487
7							1	28	462	4494	54285
8								1	36	750	10494
9									1	45	1155
10										1	54
11											1
G_t	1	2	5	15	52	203	877	4140	21147	114589	667481

LEGEND:

$$G_t = \sum_{n=1}^{t} G_n^t \qquad G_n^t = G_{t-1}^{n-1} + n \cdot G_{t-1}^{n}$$

t - Number of Basic Tool Sets

n - Number of Tool Groups in a Particular Tooling Configuration

G_n^t - Number of Tooling Configurations with n Tool Groups each

Table 8.2 - Maximum number G_{mt} of Tooling Configurations which can be generated from a number of t Basic Tool Sets to run FMS's with a number m of Machining Centres.

m \ t	1	2	3	4	5	6	7	8	9	10	11
1	1	2	5	15	52	203	877	4140	21147	114589	667481
2		1	4	14	51	202	876	4139	21146	114588	667480
3			1	7	36	171	813	4012	20891	114077	666457
4				1	11	81	512	3046	17866	104747	637956
5					1	16	162	1345	10096	70642	492206
6						1	22	295	3145	28117	245476
7							1	29	499	5290	65989
8								1	37	796	11704
9									1	46	1210
10										1	55
11											1

LEGEND:

$$G_{mt} = \sum_{n=m}^{t} G_n^t \qquad \text{or} \qquad G_{mt} = G_{m-1}^{t-1} + \sum_{n=m+1}^{t} n \cdot G_{n-1}^{t-1}$$

G_{mt} - Maximum number of Tooling Configurations

m - Number of Machining Centres in an FMS

t - Number of Basic Tool Sets Corresponding to as many NC global part-operations

G_n^t - Number of Tooling Configurations with n tool groups generated from t Basic Tool Sets

Table 10.2.1 : Typical Part mix

Part type	1	2	3	4	5	6	7	8	9
Number of parts per Assy. Set	2	1	1	1	1	1	1	1	1

Table 10.2.2 : Part-Operation times of the selected part mix

Part type	Operation Times (min)		
	1st Opn.	2nd Opn	3rd Opn
1	47	43	40
2	52	67	-
3	53	27	20
4	53	27	20
5	15	-	-
6	15	-	-
7	9	9	10
8	9	9	10
9	7	11	-

Table 10.3.1: Alternative combinations for studying the influence of tooling levels and tooling configurations on FMS performance.

Number of alternative tooling situations	Flexibility of the machining stations	Level of tool duplication
1	Multipurpose machining stations	NONE Minimum tooling
2		RESTRICTED Restricted and controlled tool duplication
3		MAXIMUM Full tool replication in every machine
4	Limited purpose machining stations	NONE Minimum tooling
5		RESTRICTED Restricted and controlled tool duplication
6		MAXIMUM Full tool replication in every machine

Table 10.4.1 : Basic tooling configuration, tool sets and corresponding part-operations

Basic tool groups	Number of tools	Basic Tool sets	Part Operations
1	18	1 2	1.1 1.2
2	22	3	1.3
3	18	4	2.1
4	24	5	2.2
5	7	6 7	3.1 4.1
6	6	8 9	3.2 4.2
7	7	10 11	3.3 4.3
8	22	12 13 14 15 16 17 18 19 20 21	5.1 6.1 7.1 8.1 7.2 8.2 7.3 8.3 9.1 9.2

Table 10.4.2 - Generation of tooling configurations from the basic one using randomly chosen pairs of tool sets to be combined for the FMS running under FCFS scheduling rule

Tooling confi-gurations Tool groups	Initial basic tooling configurat. TC1 (Tool Sets)	Randomly generated tooling configurations																								COMMENTS		
		TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15	TC16	TC17	TC18	TC19	TC20	TC21	TC22	TC23	TC24	TC25			
1	1,2	1,2	1,2 12to21	1,2 6.7 12to21	1 to 3 6 to 9 12to21	•	•	•	•	1,2	1,2 8,9	1,2 8,9	•	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	•	•	•	•	FMS running period: Three eight hour shifts		
2	3	3,8,9	3,8,9	3,8,9	•	1,2,3	1,2,3	1,2,3 12to21	10,11 1,2,3 12to21	3	3	3	1 to 3 8,9	3	•	•	•	3	3,6,7	3,6,7	3,6,7	3	1,2 3,5	1,2 3,5	1,2 3,5			
3	4	4	4	4	4	4	4	4	4	4	4	4,6,7	4,6,7	4	4	4	4	•	•	•	•	4	4	4 12to21	4 12to21			
4	5	5	5	5	5	5	5,8,9	5,8,9	5,8,9	5 12to21	5 12to21	5 12to21	5 12to21	5,6,7	3,5,6,7	•	•	5	5	5 10,11	5 10,11	5,1,2	•	•	•			
5	6,7	6,7	6,7	•	•	6,7	6,7	6,7	6,7	6,7	6,7	•	•	•	•	•	•	6,7	•	•	•	6,7	6,7	6,7	•			
6	8,9	•	•	•	•	8,9	•	•	•	8,9	•	•	•	8,9	8,9	8,9	8,9	8,9	8,9	8,9	4,8,9 12to21	8,9	8,9	8,9	8,9			
7	10,11	10,11	10,11	10,11	10,11	10,11	10,11	10,11	•	10,11	10,11	10,11	10,11	10,11	10,11	10,11	10,11	10,11	10,11	•	•	10,11	10,11	10,11	10,11 6,7	FMS performance		
8	12 to 21	12to21	•	•	•	12to21	12to21	•	•	•	•	•	•	12to21	12to21	12to21 3,5to7	12to21 3 to 7	12to21 4	12to21 4	12to21 4	•	12to21	12to21	•	•	Total Av.	Max.	Min.
Av.Mach.Util	0.809	0.837	0.685	0.427	0.362	0.785	0.784	0.61	0.535	0.85	0.763	0.773	0.679	0.814	0.769	0.532	0.465	0.834	0.877	0.895	0.835	0.743	0.666	0.672	0.692	0.704	0.895	0.362
Finish Assy.Sets	4	4	3	1	0	3	3	2	2	4	4	5	3	5	4	3	2	4	5	5	5	4	2	2	2	3.21	5	0

Table 10.4.3 - Generation of tooling configurations from the basic one using four heuristic tool set combination rules under the FCFS scheduling rule.

Tooling configurations / Tool groups	Initial basic tooling configuration TC1 (Tool Sets)	Heuristic generated tooling configurations (Scheduling rule: FCFS)														COMMENTS		
		Heuristic rule A				Heuristic rule B				Heuristic rule C				Heur.rule D				
		TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14	TC15			
1	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	FMS Running period: Three eight hour shifts		
2	3	3	3	3,4 8,9	3,4 8,9	3	3	3 6,7	3 6,7	3	3	3 12to21	3 12to21	3 6,7	3 6,7			
3	4	4	*	*	*	4	*	*	*	4	4	4	4,5	*				
4	5	*	*	*	*	*	*	*	*	5	5	5	*	*	*			
5	6,7	6,7	6,7	6,7	6,7	6,7	6,7	*	*	6,7	*	*	*	*	*			
6	8,9	8,9	4 8.9	*	*	8,9	4 8,9	4 8,9	4 8,9	*	*	*	*	4 8 to 11	4,5 8,9			
7	10,11	5 10,11	5 10,11	5 10,11	5,12to21 10,11	5 10,11	5 10,11	5 10,11	10to21 5	8 to 11	6 to 11	6 to 11	6 to 11	5 12to21	10to21	FMS performance		
8	12 to 21	12 to 21	12 to 21	12 to 21	*	12 to 21	12to21	12to21	*	12 to 21	12 to 21	*	*	*	*	Total av. (Heuristic rules)	Max	Min
Av.Mach.Util	0.808	0.807	0.795	0.846	0.873	0.807	0.795	0.8	0.872	0.827	0.813	0.887	0.896	0.93	0.918			
Heur.Average		0.830				0.819				0.856				0.924		0.857	0.93	0.795
Finish.Assy.Sets	4	4	4	4	4	4	4	5	4	4	4	6	4	6	6			
Heur.Average		4				4.25				4.5				6		4.69	6	4

LEGEND: FCFS - First Come First Served

Table 10.4.4 - Generation of tooling configurations from the basic one using heuristic tool set combination rules under the MRPAS scheduling rule.

Tooling configurations / Tool groups	Initial basic configuration TC1 (Tool Sets)	Heuristic generated tooling configurations													COMMENTS		
		Heuristic rule A				Heuristic rule B				Heuristic rule C				Heur.rule D			
		TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	TC14			
1	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	FMS running period: three eight hour shifts		
2	3	3	3	3,4 10,11	3,4 10,11	3 12to21	3 12to21	3 12to21	3 12to21	3	3	3,4,5	3,4,5	3,4,10,11			
3	4	*	*	*	*	4	4	4,8,9 10,11	4,8,9 10,11	4	4,5	*	*	*			
4	5	5	*	*	*	5	5	5	5,6,7	5	*	*	*	*			
5	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	*	6,7	6,7	6,7	6,7	6,7,8,9			
6	8,9	8,9	5,8,9	5,8,9		8,9	*	*	*	8,9	8,9	8,9	8,9 10to21	*			
7	10,11	4,10,11	4,10,11	*	*	10,11	8,9 10,11	*	*	10to21	10to21	10to21	*	*	FMS Performance		
8	12 to 21	12 to 21	12 to 21	12 to 21	12 to 21 5,8,9	*	*	*	*	*	*	*	*	12 to 21 5	Total av	Max	Min
Av.Mach.Util	0.800	0.802	0.830	0.844	0.818	0.876	0.889	0.906	0.912	0.815	0.826	0.892	0.875	0.929	0.863	0.929	0.802
Heur.Average		0.824				0.896				0.852							
Finish Assy.Sets	4	5	5	5	4	6	6	6	6	5	5	6	6	6	5.462	6	4
Heur.Average		4.75				6				5.5							

Scheduling rule: MRPAS - Minimum Remaining Parts in the Assembly Set

Table 10.5.1: FMS Average Machine Utilization and Finished Assembly Sets for 12 tooling configurations with MRPAS and FCFS scheduling rules under randomized AS pasts release and deterministic ordered part release.

TOOLING CONFIGURATIONS	AVERAGE MACHINE UTILIZATION				ASSEMBLY SETS OUTPUT			
	MRPAS		FCFS		MRPAS		FCFS	
	Random U1r	Ordered U1o	Random U2r	Ordered U1o	Random AS1r	Ordered AS1o	Random AS2r	Ordered AS2o
TC1	0.852	0.876	0.856	0.892	5	6	6	5
TC2	0.852	0.889	0.870	0.888	6	6	5	5
TC3	0.873	0.906	0.877	0.894	6	6	6	6
TC4	0.900	0.912	0.903	0.907	6	6	6	6
TC5	0.828	0.815	0.844	0.828	5	5	6	5
TC6	0.826	0.826	0.821	0.794	5	5	5	4
TC7	0.889	0.892	0.879	0.898	6	5	6	6
TC8	0.869	0.875	0.873	0.875	5	6	5	4
TC9	0.820	0.789	0.789	0.827	5	5	4	4
TC10	0.835	0.822	0.799	0.813	5	4	4	4
TC11	0.867	0.882	0.872	0.887	5	6	5	6
TC12	0.870	0.890	0.871	0.896	5	6	6	4

Table 10.5.2 : Variations in FMS Utilization and Assembly Set(as) Output between the randomized AS part release and the deterministic ordered AS part release under MRPAS and FCFS

Tooling Configurations	Variation in Machine Utilization		Variation in AS Output	
	MRPAS (x1i)	FCFS (x2i)	MRPAS (x3i)	FCFS (x4i)
TC1	-0.024	-0.036	-1	1
TC2	-0.031	-0.018	0	0
TC3	-0.033	-0.017	0	0
TC4	-0.012	-0.004	0	0
TC5	0.013	0.016	0	1
TC6	0	0.027	0	1
TC7	-0.003	-0.019	1	0
TC8	-0.006	-0.002	-1	1
TC9	0.031	-0.038	0	0
TC10	0.013	-0.014	1	0
TC11	-0.015	-0.015	-1	-1
TC12	-0.02	-0.025	-1	2
SUM	-0.087	-0.145	-2	5
Average (Xj)	-7.25E-03	-1.21E-02	-1/6	5/12
St.Dev.Estimate	1.93E-02	1.91E-02	0.75878	0.79296
ItoI variate	1.3	2.19	0.761	1.82
t(0.025,11) : t test at 5% significance			t = 2.201	

Legend:

x1i = U1r - U1o ; x2i = U2r - U2o (see table 10.5.1)
x3i = AS1r - AS1o ; x4i = AS2r - AS2o (see table 10.5.1)

Table 10.8.1 : Part mix A

Part type	1	2	3	4	5	6	7	8
Number of parts per assembly set	3	1	1	1	1	1	1	1

Table 10.8.2 : Part-Operation times of part mix A

Part type	Operation Times (min)		
	1st Opn.	2nd Opn	3rd Opn
1	47	43	40
2	53	27	20
3	53	27	20
4	15	-	-
5	15	-	-
6	9	9	10
7	9	9	10
8	7	11	-

Table 10.8.3 : Basic tooling configuration, tool sets and corresponding part-operations of part mix A

Basic tool groups	Tool sets	Part Operations
1	1 2	1.1 1.2
2	3	1.3
3	6 7	2.1 3.1
4	8 9	2.2 3.2
5	10 11	2.2 3.3
6	12 13 14 15 16 17 18 19 20 21	4.1 5.1 6.1 7.1 6.2 7.2 6.3 7.3 8.1 8.2

Table 10.8.4 - Generation of improved tooling configurations through controlled and restricted tool set duplication for part mix A - Configurations and FMS performance.

Tooling configurations / Tool groups	Initial basic configuration TC1	Heuristic generated tooling configurations under restricted tool duplication								COMMENTS	
		Tool dupl.rule	Heuristic rule A			Heuristic rule D					
	(Tool Sets)	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9		
1	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	FMS running period is three eight hour shifts	
2	3	3	3	3	6,7,3	6,7,3	6,7,3	3	3,10,11		
3	6,7	6,7	6,7	6,7	*	*	*	6,7	6,7		
4	8,9	8,9	*	*	*	*	*	*	*		
5	10,11	10,11	8,9,10,11	*	*	*	*	*	*		
6	12 to 21	12 to 21	12 to 21	12 to 21	12 to 21	12 to 21 10,11	12 to 21 8,9,10,11	12 to 21 8,9,10,11	12 to 21 8,9		
7	*	1,2	1,2	8,9,10,11 1,2	8,9,10,11 1,2	8,9 1,2	1,2	1,2	1,2	FMS performance	
										Minimum	Best
Av.Mach.Util	0.672	0.8	0.791	0.809	0.873	0.879	0.872	0.929	0.924	0.672	0.924
Finish Assy.Sets	3	5	5	5	5	5	5	5	6	3	6

Scheduling rule used: MRPAS (Minimum Remaining Parts in the Assembly Set)

Table 10.9.1 - Generation of tooling configurations from the basic one using two heuristic tool set combination rules under the FCFS and MRPAS scheduling rules-Limited purpose FMS machines case

Tooling configurations / Tool groups	Initial basic tooling configuration TC1 (Tool sets)	FCFS								MRPAS				COMMENTS
		Heuristic rule B				Heuristic rule C				Heuristic rule B				
		TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12	TC13	
1	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	1,2	*	*	*	FMS Running period: Three eight hour shifts
2	3	3	3	3	3,6,7	3	3	3	3	*	*	*	*	
3	4	4	12 to 21 4	12 to 21 4,8,9	12 to 21 4,8,9	4	4	4	4,8,9 12 to 21	4	4	4	12 to 21 4	
4	5	*	*	*	*	5	5	5,6,7 10,11	5,6,7 10,11	5	5	5,3 10,11	5,3 10,11	
5	6,7	6,7	6,7	6,7	*	6,7	6,7 10,11	*	*	6,7	6,7	6,7	6,7	
6	8,9	8,9	8,9	*	*	8,9 12 to 21	8,9 12 to 21	8,9 12 to 21	*	8,9	1,2,8,9	1,2,8,9	1,2,8,9	
7	10,11	5,10,11	5,10,11	5,10,11	5,10,11	10,11	*	*	*	3,10,11	3,10,11	*	*	
8	12 to 21	12 to 21	*	*	*	*	*	*	*	12 to 21	12 to 21	12 to 21	*	
														Sched.rules
Av.Mach.Util	0.706	0.714	0.780	0.804	0.836	0.789	0.795	0.778	0.812	0.703	0.734	0.721	0.806	F
Heur.Average		0.784				0.794				0.741				C
Finish.Assy.Sets	2	2	1	5	5	2	2	2	5	2	5	3	4	F
Heur.Average		3.25				2.75				3.50				S
Av.Mach.Util	0.733	0.751	0.804	0.798	0.845	0.792	0.82	0.751	0.804	0.711	0.729	0.759	0.788	M
Heur.Average		0.800				0.792				0.747				R
Finish.Assy.Sets	4	5	4	4	4	4	4	4	5	4	4	4	4	P
Heur.Average		4.25				4.25				4.00				A
														S

SCHEDULING RULES LEGEND: FCFS - First Come First Served ;MRPAS - Minimum Remaining Parts in the Assembly Set

Table 10.9.2 - Improved FMS performance through generation of tooling configurations using the Ungroup-Regroup tool combination heuristic rule D-Limited purpose machines FMS case

Tooling configurations / Tool groups	Initial basic tooling configuration	Tooling configurations under minimum tooling			COMMENTS	
	TC1 (Tool sets)	TC13	TC14	TC15		
1	1,2	*	1,2	1,2	FMS Running period: three eight hour shifts	
2	3	*	*	*		
3	4	4,12to21	4,12to21	4,12to21 8,9		
4	5	5,3,10,11	5,3,10,11	5,3,10,11		
5	6,7	6,7	6,7	6,7		
6	8,9	1,2,8,9	8,9	*		
7	10,11	*	*	*	FMS performance	
8	12 to 19	*	*	*	Minimum	Best
Av.Mach.Util	0.733	0.788	0.818	0.835	0.788	0.835
Finish.Assy.Sets	4	4	4	4	4	4

Scheduling rule : MRPAS - Minimum Remaining Parts in the Assembly Set

Table 10.9.3 : Calculation of the degree of balance, UT, of an FMS

Part-operations mix	Machining group where processed	Part processing requirements per Assy Set or part mix (min)	Processing time assignment through the FMS machining groups (min)		Comments
			Group I	Group II	
1,2	I	180	180	*	
3	II	80	*	80	
4	I	52	52	*	
5	II	67	*	67	
6,7	II	106	*	106	
8,9	I	54	54	*	
10,11	II	40	*	40	For each 390 min of load to group I there is only 293 min for group II
12 to 21	I	104	104	*	
Total processing time per group (Ti)			390	293	
Number of machines in the group (Mi)			2	2	
Aver. processing time per machine (Ti/Mi)			195	146.5	
Maximum possible utilization, Ui, of each machine group i			1.0	0.7513 (146.5/195)	
Maximum possible theoretical FMS machine utilization or Degree of Balanceof the FMS UT : g - Number of machine groups		$UT = \frac{\sum_{i=1}^{g} Mi * Ui}{\sum_{i=1}^{g} Mi}$	$UT = \frac{2*1.0+2*0.7513}{2+2}$ $\boxed{UT = 0.876}$		

Table 10.9.4 - Calculation of the Normalized Utilization

	TOOLING CONFIGURATIONS						
	TC1	TC10	TC11	TC12	TC13	TC14	TC15
UTILIZATION (MU)	0.733	0.711	0.729	0.759	0.788	0.818	0.835
NORMALIZED UTILIZATION (NMU=MU/0.876)	0.837	0.812	0.832	0.867	0.9	0.934	0.953
	Basic Tooling Configuration	Not applying the Ungrouping-Regrouping tool combination heuristic rule D				Applying the Ungrouping-Regrouping rule D	

Table 10.11.1 - Generation of tooling configurations using two heuristic tool set combination rules under and MRPAS scheduling rule-Limited purpose FMS machines case - Part Mix A

Tooling configurations Tool groups	Initial basic tooling configuration	Tooling configurations under restricted tool duplication				COMMENTS	
		Tool dupl.rule	Heuristic rule B				
	TC1 (Tool sets)	TC2	TC3	TC4	TC5		
1	1,2	1,2	1,2	1,2	1,2	FMS Running period: Three eight hour shifts	
2	3	3	3	3	3,10,11		
3	6,7	6,7	6,7	6,7	6,7		
4	8,9	8,9	8,9,12to21	8,9,12to21 1,2	8,9,12to21 1,2		
5	10,11	10,11	10,11	10,11	*		
6	12 to 21	12 to 21	*	*	*	FMS performance	
7	*	1,2	1,2	*	*	Minimum	Best
Av.Mach.Util	0.672	0.728	0.706	0.78	0.777	0.672	0.78
Finish.Assy.Sets	4	4	4	5	4	4	5

Scheduling rule : MRPAS - Minimum Remaining Parts in the Assembly Set

Table 10.11.2 : Calculation of the degree of balance, UT, of the FMS of Fig.10.9.1 under part mix A.

Part-operations mix	Machining group where processed	Part processing requirements per Assy Set or part mix (min)	Processing time assignement through the FMS *machining* groups (min)		Comments
			Group I	Group II	
1,2	I	270	270	*	
3	II	120	*	120	
6,7	II	106	*	106	
8,9	I	54	54	*	
10,11	II	40	*	40	
12 to 21	I	104	104	*	For each 428 min of load to group I there is only 266 min for group II
Total processing time per group (Ti)			428	266	
Number of machines in the group (Mi)			2	2	
Aver. processing time per machine (Ti/Mi)			214	133	
Maximum possible utilization, Ui, of each machine group i			1.0	0.62 (133/214)	

Maximum possible theoretical FMS machine utilization or Degree of Balanceof the FMS UT :

g - Number of machine groups

$$\boxed{UT = \frac{\sum_{i=1}^{g} Mi * Ui}{\sum_{i=1}^{g} Mi}}$$

$$UT = \frac{2*1.0+2*0.62}{2+2}$$

$$\boxed{UT = 0.810}$$

Table 10.11.3 - Improved FMS performance through generation of tooling configurations using the Tool Duplication heuristic rule B- - Limited purpose machines FMS-Part Mix B

Tooling configurations / Tool groups	Initial basic tooling configuration TC1 (Tool sets)		Restricted tool duplication			Restricted tool duplication			COMMENTS	
		TC14	TC16	TC17	TC15	TC18	TC19	TC20		
1	1,2	1,2	1,2	1,2	1,2	1,2	1,2,12to21	1,2,14to19	FMS Running period: Three eight hour shifts	
2	3	*	*	*	*	*	*	*		
3	4	4,12to21	4,12to21	4,12to21	4,12to21 8,9	4,12to21 8,9	4,12to21 8,9	4,12to21 8,9		
4	5	5,3,10,11	5,3,10,11	5,3,10,11	5,3,10,11	5,3,10,11	5,3,10,11	5,3,10,11		
5	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7		
6	8,9	8,9	8,9	*	*	*	*	*		
7	10,11	*	*	*	*	*	*	*	FMS performance	
8	12 to 19	*	11 to 21	8,9,11to21	*	12 to 21	*	*	Minimum	Best
Av.Mach.Util	0.733	0.818	0.800	0.814	0.835	0.835	0.824	0.841	0.800	0.841
Finish.Assy.Sets	4	4	4	5	4	4	4	5	4	5

Scheduling rule : MRPAS - Minimum Remaining Parts in the Assembly Set

Table 10.12.1 - Tooling configurations composition

Tool groups	Basic Tooling configuration TC1 (tool sets)	Tooling configuration TC2 (tool sets)	Full tool replicatiom TC3 (tool sets)
1	1 2	1 2	1 to 21
2	3	3,6,7	1 to 21
3	4	4, 8 to 11	1 to 21
4	5	5, 12 to 21	1 to 21
5	6 7	*	*
6	8 9	*	*
7	10 11	*	*
8	12 13 14 15 16 17 18 19 20 21	*	*

APPENDIXES

APPENDIX 1

General Tooling Configuration Structures Generation Process

This appendix is to show the general process of tooling configurations generation, table A1, which was the basis for obtaining the mathematical equations presented in section 8.2.

Table A1 - Tooling configurations generation process

t	n	k	G	G^{t}_{n}	$Gt=\sum G^{t}_{n}$	G Grouping structures	Mathematical expressions for the G values
1	1	1	1	1	1	|x|	1
2	1	1	1	1		|xx|	C(2,2)=1
	2	1	1	1	2	|x| |x|	1
3	1	1	1	1		|xxx|	C(3,3)=1
	2	1	3	3		|x| |xx|	C(3,1)=3
	3	1	1	1	5	|x| |x| |x|	1
4	1	1	1	1		|xxxx|	C(4,4)=1
	2	1	4			|x| |xxx|	C(4,1)=4
		2	3	7		|xx| |xx|	C(4,2)/2=3
	3	1	6	6		|x| |x| |xx|	C(4,2)=6
	4	1	1	1	15	|x| |x| |x| |x|	1
5	1	1	1	1		|xxxxx|	C(5,5)=1
	2	1	5			|x| |xxxx|	C(5,1)=5
		2	10	15		|xx| |xxx|	C(5,2)=10
	3	1	10			|x| |x| |xxx|	C(5,2)=10
		2	15	25		|xx| |xx| |x|	5•C((5-1),2)/2=15
	4	1	10	10		|xx| |x| |xx|	
	5	1	1	1	52	|x||x||x||x||x|	1
6	1	1	1	1		|xxxxxx|	C(6,6)=1
	2	1	6			|x| |xxxxx|	C(6,1)=5
		2	15			|xx| |xxxx|	C(6,2) = 15
		3	10	31		|xxx| |xxx|	C(6,3)/2 = 10
	3	1	15			|x| |x| |xxxx|	5•C((6-2),2)/2=15
		2	15			|xx| |xx| |xx|	
		3	60	90		|x| |xxx| |xx|	E
	4	1	45			|x| |x| |xx| |xx|	
		2	20	65		|x| |x| |x| |xxx|	T
	5	1	15	15		|x| |x| |x| |x| |xx|	
	6	1	1	1	203	|x| |x| |x| |x| |x| |x|	C
7	1	1	1	1		E	
	2	1	7				
		2	21			T	
		3	35	63			
	3	1	21			C	
		2	105				
		3	70				
		4	105	301			
	4	1	35				$C(a,b) = \frac{a!}{(a-b)! \cdot b!}$
		2	210				
		3	105	350			
	5	1	35				
		2	105	140			
	6	1	21	21			
	7	1	1	1	877		
		A N	D S O	O N			

Legend:

t - Number of tool sets

n - Number of tool groups in a Tooling Configuration

k - Number of different grouping structures with the same number of tool groups

G - Number of tooling configurations within the same tool grouping structure

G^{n}_{t} - Number of tooling configurations with the same number of n tool groups formed from t tool sets

$\sum_{n=1}^{t} G^{n}_{t}$ - Total number of tooling configurations formed from t tool sets

APPENDIX 2

Typical Model Input and Results Output files

Fig. A21

```
********************************
*    INPUT DATA AND RUN FILE   *
********************************

*C SITAM1
*EXECUTE 1,50,300 SIMTIM=1440
  DATA TO BE READ:
    MCSYST    4
    NFMC
      2
      2
      2
      2
    TGRSYST 7
    TGRTYP         TSETQTY        TSETKIND       SIZE
       1              2                            39
                                     1
                                     2
       2              1                            37
                                     3
       3              1                            36
                                     4
       5              2                            39
                                     6
                                     7
       6              2                            34
                                     8
                                     9
       7              3                            38
                                     5
                                    10
                                    11
       8             10                            40
                                    12
                                    13
                                    14
                                    15
                                    16
                                    17
                                    18
                                    19
                                    20
                                    21
     *STOP
```

Fig . A.22

```
*************************
*  RESULTS OUTPUT FILE  *
*************************
```

-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-

FMS SYSTEM MAIN VARIALBLES :

```
SIMULATION TIME    =  1440
TULDUPL            =     0
NUMB. OF OPERATORS =     2
NUMB. OF MACHINES  =     4
   MACHINE  1 IS OF TYPE 1
   MACHINE  2 IS OF TYPE 1
   MACHINE  3 IS OF TYPE 2
   MACHINE  4 IS OF TYPE 2
NUMBER OF BUFFERS :
   AT MACHINE   1  =     1
   AT MACHINE   2  =     1
   AT MACHINE   3  =     1
   AT MACHINE   4  =     1
NUMB.OF TOOL GROUPS=     7
NUMB. HAND. DEVICES=     1
GRIPER POSITIONS :
   OF HAND.DEV.  1 =     1
```

RULES FOR SYSTEM OPERATION:

CONTROL RULE	DAY SHIFT	MID SHIFT	NIGHT SHIFT
PARTS RELATED	18	18	18
FIXTS.RELATED	0	0	0
JOB(ASSY SET\BATCH)/ RELEASE RULE	0	0	0

LEGEND

PART RELATED RULES
    RULE 1 = FCFS
    RULE 18= MRPAS

FIXTURED PALLETS RELATED RULE
    FXRULE 0 = HIGHEST PRIOR. PART CLAMP. RULE

JOB (ASSEMBLY SET/BATCH) RELEASED RULE
    RULE 0 = JOBS RELEASED IN A FCFS BASIS

LOADED SETS BY TYPE

CELL	FREQUENCY
1	8********

LOADED PARTS BY TYPE

CELL	FREQUENCY
1	16****************
2	8********
3	8********
4	8********
5	8********
6	8********
7	8********
8	8********
9	8********

FIXTURES IN SYSTEM BY TYPE

CELL	FREQUENCY
1	2**
2	2**
3	2**
4	2**
5	2**
6	2**
7	2**
8	2**

DISTRIBUTION OF PROCESSING TIME PER MACH.OPERATION
==

CELL	FREQUENCY
20	4****
30	4****
40	7*******
50	9*********
60	5*****
70	3***
80	6******
90	6******
100	3***
110	7*******
120	0
130	2**
140	0
150	0
160	0
170	0
180	4****

MEAN PROC.TIME MACH.OPN.-PALLET SET-UP 75.166654
ST.DEV.PROC.TIME PER MACH.OPN 40.352237

```
DISTRIBUTION OF PROCESSING TIME PER OPERATION
OF ALL PARTS LOADED INTO THE FMS SYSTEM.
=============================================

CELL  FREQUENCY
   5     8********
  10    56********************************************************
  15    16****************
  20    16****************
  25    16****************
  30     0
  35     0
  40    16****************
  45    32********************************
  50     8********
  55    16****************
  60     0
  65     8********


MEAN PROC.TIME PER PART OPN. 28.333330
ST.DEV.PROC.TIME PER PART .OPN 18.295403
-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-x-

     FMS PERFORMANCE MEASURES
     ========================

UTILIZATION OF OPERATOR   1 IS .54
            IN TOOLING AREA   .118
            IN CLAMPING AREA  .426
UTILIZATION OF OPERATOR   2 IS .45
            IN TOOLING AREA   .103
            IN CLAMPING AREA  .354

TOTAL AVERAGE OPERATORS UTILIZATION = .501

            IN TOOLING AREA         .111
            IN CLAMPING AREA        .390
```

MACHINE TAPE UTILIZATION OF MC 1= .897
MACHINE TAPE UTILIZATION OF MC 2= .863
MACHINE TAPE UTILIZATION OF MC 3= .608
MACHINE TAPE UTILIZATION OF MC 4= .633

TOTAL MACHINE TAPE UTILIZATION= .7506

UTILIZATION OF TOOLGR 1 = .77
UTILIZATION OF TOOLGR 2 = .27
UTILIZATION OF TOOLGR 3 = .25
UTILIZATION OF TOOLGR 4 = .51
UTILIZATION OF TOOLGR 5 = .26
UTILIZATION OF TOOLGR 6 = .44
UTILIZATION OF TOOLGR 7 = .47

TOTAL TOOL GROUP UTILIZATION = .4289

TOTAL UTILIZATION OF HD. 1 IS / .444
UTILIZATION OF THE HD. 1 IN PARTS HANDLING = .444
UTILIZATION OF THE HD. 1 IN TOOLS HANDLING = .000

TOTAL AVERAGE UTILIZATION OF HANDLING DEVICES = .444
IN PARTS HANDLING .444
IN TOOLS HANDLING .000

TIME UTILIZATION OF THE FMS

MACHINES	PROCESSING	CHANGING TOOLS/WPS	WAITING	TOTAL	UTILIZ.
1	1293	101	46	1440	.89791
2	1243	68	129	1440	.86319
3	876	34	530	1440	.60833
4	912	85	443	1440	.63333
4	4324	288	1148	5760	.75069
HDEVICES					
1		640	800	1440	.44444
1		640	800	1440	.44444

MANUFACTURING OUTPUT

PROCESSED WORKPIECES

TYPE	QUANTITY FINISHED	QUANTITY IN PROCESS
1	10	6
2	6	2
3	5	3
4	5	3
5	7	1
6	7	1
7	6	2
8	6	2
9	6	2
TOTAL...	58	22

PROCESSED WORKPIECE SETS

TYPE	QUANTITY FINISHED	QUANTITY IN PROCESS
1	5	3
TOTAL...	5	3

THROUGHPUT TIMES

HIST OF SET THROUGHPUT TIMES

CELL	FREQUENCY
750	3***
850	0
950	1*
1050	1*

HIST OF WPS THROUGHPUT TIMES

```
CELL  FREQUENCY
  50      2**
 150      9*********
 250     10**********
 350      9*********
 450     10**********
 550      4****
 650      4****
 750      6******
 850      0
 950      4****
```

MEAN OF WP THROUGHPUT TIMES= 425.86201

HIST.ASSY.SETS THRUPUT TIME INDEX(ASTTI)

```
CELL  FREQUENCY
  10      1*
  12      2**
  14      2**
```

MEAN ASSY. SET THROUGHPUT TIME INDEX= 12.399999

W O R K   I N   P R O G R E S S

HIST OF WIP OF PARTS QUANTITY

```
CELL  FREQUENCY
  10     50**********
  14     30******
  18    413********************************************************************************************
  22    482*********************************************************************************************************
  26    406*******************************************************************************************
  30     59***********
```

MEAN WIP OF PARTS QTY= 21.724998   PARTS

```
HIST. OF THE TOTAL TIME WIP

CELL  FREQUENCY
 300   172*******************************************
 400     5*
 500    31*******
 600   154**************************************
 700   321********************************************************************************
 800   332***********************************************************************************
 900   245*************************************************************
1000   180*********************************************

MEAN TOTAL TIME WIP = 730.76379  MIN
```

```
AVERAGE WP PRODUCTION RATE= 2.4166667 WORKPIECES PER HOUR
```

```
DISTRIB OF TRANSPORT TIMES OF PALLETS TO AND FROM MACHINES
CELL  FREQUENCY
   2      6***
   4    124**************************************************************
   6     37******************
   8      3*

AV PALLET TRANSPORT TIMES        = 4.4
STAND.DEVIATION TRANSPORT TIMES = 1.0
```

```
CLAMPING    WAS STARTED          170 TIMES
UNCLAMPING WAS STARTED           150 TIMES
MACHINES WERE UNLOADED            58 TIMES
MACHINES WERE LOADED              64 TIMES
MACHINING WAS STARTED             60 TIMES
CHANGTOOLS WAS SUCCESSFUL         17TIMES
POOLMCS WAS SUCCESSFUL             0TIMES
UNPOOL WAS SUCCESSFUL              0TIMES
UNLDMAGAZ WAS SUCCESSFUL          13TIMES
LOADMAG WAS SUCCESSFUL            17TIMES
```

APPENDIX 3

Computer Simulation Experiments - Detailed Representation of the Tooling Configurations Generated

This appendix is a detailed representation of the genration process and tooling configurations presented in chapter 10 on computer simulation experiments.

Table A3.1 - Generation process for tooling configurations of the table 10.4.3

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC RULE: A

FMS with similar Multi-purpose Machines: M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.	TC2	TG Util.	TC3	TG Util.	TC4	TG Util.	TC5	TG Util.
1	1,2	0.94	1,2	0.93	1,2	0.94	1,2	0.96	1,2	0.96
2	3	0.33	3	0.33	3	0.31	3,4,8,9	0.81	3,4,8,9	0.93
3	4	0.26	4	0.27	*	*	*	*	*	*
4	5	0.24	*	*	*	*	*	*	*	*
5	6,7	0.51	6,7	0.51	6,7	0.50	6,7	0.61	6,7	0.63
6	8,9	0.26	8,9	0.26	4,8,9	0.40	*	*	*	*
7	10,11	0.19	5,10,11	0.40	5,10,11	0.43	5,10,11	0.39	5,10,11 12to21	0.94
8	12 to 2	0.45	12 to 21	0.49	12 to 21	0.57	12 to 21	0.59	*	*
	Av.Mach.Util = 0.608 Finished ASs = 4		Av.Mach.Util = 0.607 Finished ASs = 4		Av.Mach.Util = 0.795 Finished ASs = 4		Av.Mach.Util = 0.646 Finished ASs = 4		Av.Mach.Util = 0.873 Finished ASs = 4	

TC1	TC2	TC3	TC4	TC5
7, 4, 6, 3, 2, 8, 5, 1 -> Combine 4 and 7	6, 3, 2, 7, 8, 5, 1 -> Combine 3 and 6	2, 6, 7, 5, 8, 1 -> Combine 6 and 2	7, 8, 5, 2, 1 Combine 8 and 7	1,2 / 6,7 / 3,4,8,9 / 5,10,11 12 to 21

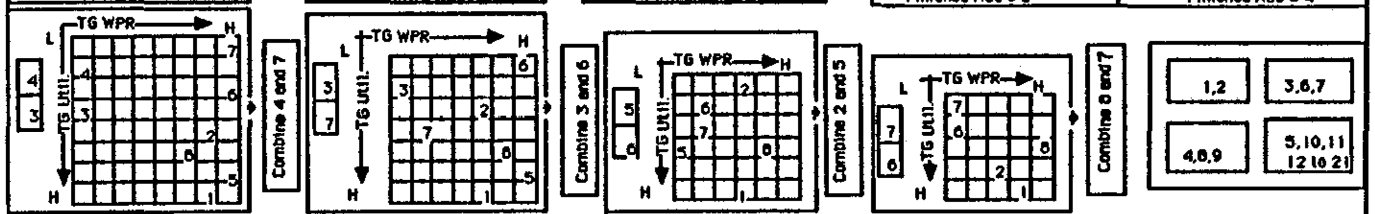
Opns 1	2	3	WPs	TC1 (WPR)	TC2 (WPR)	TC3 (WPR)	TC4 (WPR)	TC5 (WPR)
1	2	3	1	6	6	5	6	6
4	5	•	2	4	4	7	6	6
6	8	10	3	7	7	4	4	6
7	9	11	4	7	7	4	4	6
12	•	•	5	7	7	8	8	6
13	•	•	6	7	7	8	8	6
14	16	18	7	5	6	7	8	4
15	17	19	8	5	6	7	8	4
20	21	•	9	5	6	8	8	6
			Total WPs	59/21 Fin/wip	62/18 Fin/wip	63/17 Fin/wip	66/24 Fin/wip	60/30 Fin/wip

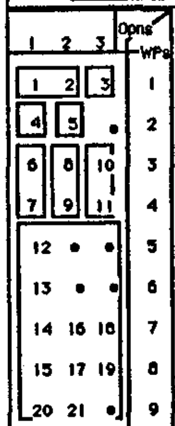
Table A3.1 (cont.) - Generation process for tooling configurations of the table 10.4.3

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC RULE: B

FMS with similar Multi-purpose Machines: M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.	TC6	TG Util.	TC7	TG Util.	TC8	TG Util.	TC9	TG Util.
1	1,2	0.94	1,2	0.93	1,2	0.94	1,2	0.965	1,2	0.965
2	3	0.33	3	0.33	3	0.31	3,6,7	0.956	3,6,7	0.956
3	4	0.28	4	0.27	*	*	*	*	*	*
4	5	0.24	*	*	*	*	*	*	*	*
5	6,7	0.51	6,7	0.51	6,7	0.50	*	*	*	*
6	8,9	0.26	8,9	0.26	4,8,9	0.40	4,8,9	0.38	4,8,9	0.62
7	10,11	0.19	5,10,11	0.40	5,10,11	0.43	5,10,11	0.37	5,10,11 12to21	0.948
8	12 to 21	0.45	12 to 21	0.49	12 to 21	0.57	12to21	0.56	*	*
	Av.Mach.Util = 0.808 Finished ASs = 4		Av.Mach.Util = 0.807 Finished ASs = 4		Av.Mach.Util = 0.795 Finished ASs = 4		Av.Mach.Util = 0.799 Finished ASs = 5		Av.Mach.Util = 0.872 Finished ASs = 4	





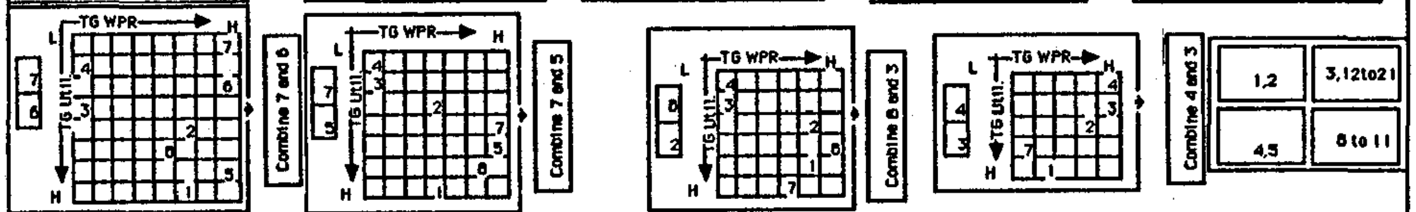
WPs	TC1 (WPR)	TC6 (WPR)	TC7 (WPR)	TC8 (WPR)	TC9 (WPR)
1	6	6	5	6	6
2	4	4	7	6	6
3	7	7	4	4	6
4	7	7	4	4	6
5	7	7	8	8	8
6	7	7	8	8	8
7	5	6	7	8	4
8	5	6	7	8	4
9	5	6	8	8	6
Total WPs	59/21 Fin/wip	62/18 Fin/wip	63/17 Fin/wip	66/24 Fin/wip	60/30 Fin/wip

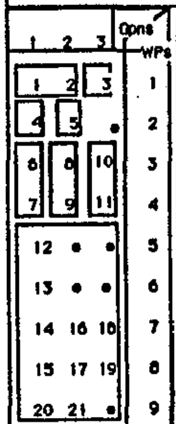
Table A3.1 (cont.) - Generation process for tooling configurations of the table 10.4.3

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC RULE: C

FMS with similar Multi-purpose Machines: M1 M2 M3 M4

TG No.	TC1 Tool set	TG Util.	TC10	TG Util.	TC11	TG Util.	TC12	TG Util.	TC13	TG Util.
1	1,2	0.94	1,2	0.94	1,2	0.93	1,2	0.965	1,2	0.965
2	3	0.33	3	0.33	3	0.33	3,12to21	0.927	3,12to21	0.925
3	4	0.28	4	0.28	4	0.30	4	0.32	4,5	0.738
4	5	0.24	5	0.25	5	0.18	5	0.37	*	*
5	6,7	0.51	6,7	0.51	*	*	*	*	*	*
6	8,9	0.26	*	*	*	*	*	*	*	*
7	10,11	0.19	8 to 11	0.45	6 to 11	0.95	6 to 11	0.956	6 to 11	0.956
8	12 to 21	0.45	12 to 21	0.52	12 to 21	0.53	*	*	*	*
	Av.Mach.Util = 0.808 Finished ASs = 4		Av.Mach.Util = 0.827 Finished ASs = 4		Av.Mach.Util = 0.6133 Finished ASs = 4		Av.Mach.Util = 0.887 Finished ASs = 6		Av.Mach.Util = 0.896 Finished ASs = 4	





WPs	TC1 (WPR)	TC10 (WPR)	TC11 (WPR)	TC12 (WPR)	TC13 (WPR)
1	6	6	6	6	6
2	4	4	4	8	8
3	7	7	6	6	4
4	7	7	6	6	4
5	7	7	8	8	8
6	7	7	8	8	8
7	5	6	6	7	7
8	5	6	6	7	7
9	5	6	7	8	8
Total WPs.	59/21 Fin/wip	62/26 Fin/wip	63/25 Fin/wip	70/20 Fin/wip	66/24 Fin/wip

Table A3.1 (cont.) - Generation process for tooling configurations of the table 10.4.3

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC
RULE: D

FMS similar Multi-purpose Machs.
M1 M2 M3 M4

TG No.	TC9	TG Util.
1	1,2	0.965
2	3,6,7	0.956
3	*	*
4	*	*
5	*	*
6	4,8,9	0.62
7	5,10,11 12to21	0.948
8	*	*

Av.Mach.Util = 0.872
Finished ASs = 4

TG No.	TC14	TG Util.
1	1,2	0.96
2	3,6,7	0.95
3	*	*
4	*	*
5	*	*
6	4,8to11	0.84
7	5,12to21	0.94
8	*	*

Av.Mach.Util = 0.93
Finished ASs = 6

	TC15	TG Util.
1	1,2	0.80
2	3,6,7	0.965
3	*	*
4	*	*
5	*	*
6	4,5,8,9	0.943
7	10 to 21	0.956
8	*	*

Av.Mach.Util = 0.918
Finished ASs = 6

Heuristic Rule D :

Ungroup TG No.7 and group basicTG No.7 to TG No.6 →

1,2	3,6,7
4,8 to 11	5,12 to 21

Ungroup TG No.7 and group basicTG No.4 toTG No.6 →

1,2	3,6,7
4,5,8,9	10 to 21

WPs	TC9 (WPR)
1	6
2	6
3	6
4	6
5	8
6	8
7	4
8	4
9	6
Total WPs	60/30 Fin/wip

WPs	TC14 (WPR)
1	6
2	8
3	8
4	7
5	8
6	8
7	6
8	6
9	7
Total WPs	70/20 Fin/wip

WPs	TC15 (WPR)
1	6
2	7
3	7
4	7
5	9
6	9
7	7
8	7
9	8
Total WPs	73/17 Fin/wip

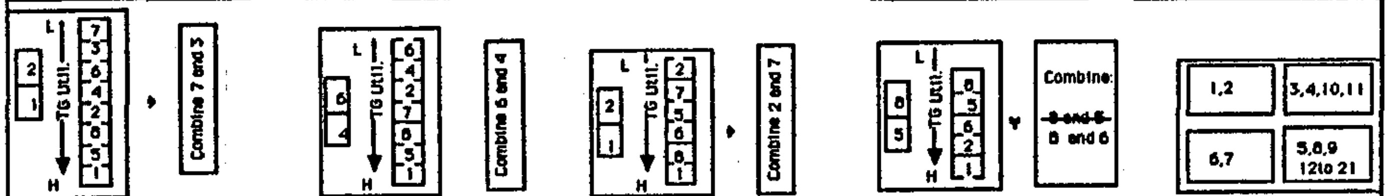
Table A3.2 - Generation process for tooling configurations of the table 10.4.4

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: A

FMS similar Multi-purpose Machs.

M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.	TC2	TG Util.	TC3	TG Util.	TC4	TG Util.	TC5	TG Util.
1	1,2	0.90	6,2	0.91	1,2	0.93	1,2	0.96	1,2	0.945
2	3	0.33	3	0.33	3	0.33	3,4 10,11	0.77	3,4 10,11	0.786
3	4	0.25	*	*	*	*	*	*	*	*
4	5	0.28	5	0.27	*	*	*	*	*	*
5	6,7	0.51	6,7	0.58	6,7	0.53	6,7	0.55	6,7	0.591
6	8,9	0.26	8,9	0.18	8,9,5	0.53	5,8,9	0.57	*	*
7	10,11	0.17	4,10,11	0.39	4,10,11	0.44	*	*	*	*
8	12 to 2	0.47	12 to 21	0.51	12 to 21	0.54	12 to 21	0.50	5,8,9 12to 21	0.948
	Av.Mech.Util = 0.800 Finished ASs = 5		Av.Mech.Util = 0.802 Finished ASs = 5		Av.Mech.Util = 0.830 Finished ASs = 5		Av.Mech.Util = 0.844 Finished ASs = 5		Av.Mech.Util = 0.818 Finished ASs = 4	



Opns 1	Opns 2	Opns 3	WPs	TC1 (WPR)	TC2 (WPR)	TC3 (WPR)	TC4 (WPR)	TC5 (WPR)
1	2	3	1	5	5	6	6	6
4	5	•	2	5	5	6	7	6
6	8	10	3	5	5	5	5	6
7	9	11	4	5	5	5	5	5
12	•	•	5	7	8	8	7	7
13	•	•	6	7	8	8	7	6
14	16	18	7	6	5	7	7	4
15	17	19	8	6	5	7	7	4
20	21	•	9	6	6	7	7	6
			Fin/wip	57/23	57/26	65/25	64/26	56/27

Table A3.2 (cont) - Generation process for tooling configurations of the table 10.4.4

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: B

FMS with similar Multi-purpose Machines: M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.
1	1,2	0.90
2	3	0.33
3	4	0.25
4	5	0.28
5	6,7	0.51
6	8,9	0.26
7	10,11	0.17
8	12 to 21	0.47

Av.Mach.Util = 0.600
Finished ASs = 5

TG No.	TC6	TG Util.
1	1,2	0.96
2	3,12to21	0.92
3	4	0.28
4	5	0.30
5	6,7	0.62
6	8,9	0.22
7	10,11	0.16
8	*	*

Av.Mach.Util = 0.676
Finished ASs = 6

TG No.	TC7	TG Util.
1	1,2	0.96
2	3,12to21	0.92
3	4	0.25
4	5	0.32
5	6,7	0.63
6		*
7	8,9 10,11	0.44
8	*	*

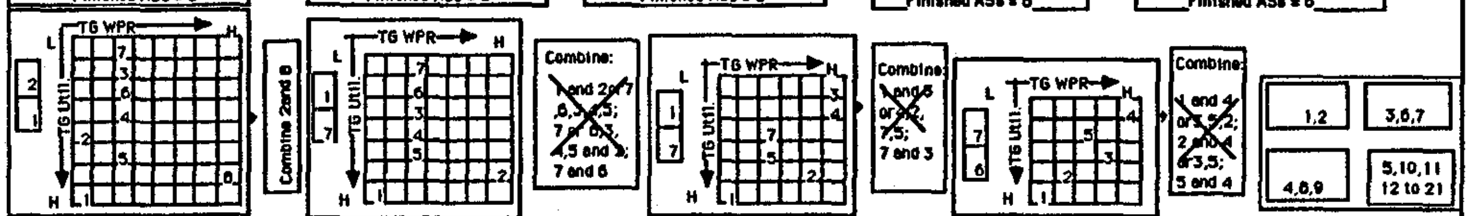
Av.Mach.Util = 0.689
Finished ASs = 6

TG No.	TC8	TG Util.
1	1,2	0.96
2	3,12to21	0.92
3	4,8to11	0.78
4	5	0.41
5	6,7	0.54
6	*	*
7	*	*
8	*	*

Av.Mach.Util = 0.906
Finished ASs = 6

TG No.	TC9	TG Util.
1	1,2	0.92
2	3,12to21	0.97
3	4,8to11	0.81
4	5,6,7	0.96
5	*	*
6	*	*
7	*	*
8	*	*

Av.Mach.Util = 0.912
Finished ASs = 6



Opns 1	2	3
1	2	3
4	5	•
6 7	8 9	10 11
12	•	•
13	•	•
14	16	18
15	17	19
20	21	•

WPs	TC1 (WPR)	TC6 (WPR)	TC7 (WPR)	TC8 (WPR)	TC9 (WPR)
1	5	6	6	6	6
2	5	6	7	8	7
3	5	6	6	7	7
4	5	6	6	7	7
5	7	8	8	9	8
6	7	8	8	9	7
7	6	7	7	6	7
8	6	7	7	6	7
9	6	8	8	7	7
Total wps	57/23 Fin/wip	68/22 Fin/wip	69/21 Fin/wip	71/19 Fin/wip	70/20 Fin/wip

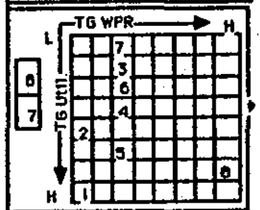
Table A3.2 (cont) - Generation process for tooling configurations of the table 10.4.4

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: C

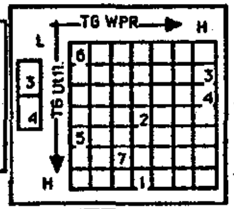
FMS with similar Multi-purpose Machines

M1	M2	M3	M4

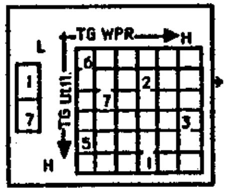
TG No.	TC1 Tool sets	TG Util.	TC10	TG Util.	TC11	TG Util.	TC12	TG Util.	TC13	TG Util.
1	1,2	0.90	1,2	0.94	1,2	0.84	1,2	0.96	1,2	0.96
2	3	0.33	3	0.33	3	0.33	3,4,5	0.94	3,4,5	0.94
3	4	0.25	4	0.25	4,5	0.67	*	*	*	*
4	5	0.28	5	0.32	*	*	*	*	*	*
5	6,7	0.51	6,7	0.54	6,7	0.66	6,7	0.66	6,7	0.65
6	8,9	0.26	8,9	0.22	8,9	0.24	8,9	0.22	8to21	0.94
7	10,11	0.17	10to21	0.63	10to21	0.62	10to21	0.77	*	*
8	12 to 21	0.47	*	*	*	*	*	*	*	*
	Av.Mach.Util = 0.800 Finished ASs = 5		Av.Mach.Util = 0.815 Finished ASs = 6		Av.Mach.Util = 0.826 Finished ASs = 6		Av.Mach.Util = 0.892 Finished ASs = 6		Av.Mach.Util = 0.876 Finished ASs = 6	



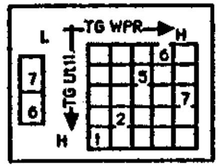
Combine 8 and 7



Combine 3 and 4



Combine 3 and 2



Combine 7 and 6

1,2	3,4,5
6,7	8 to 21

Opns 1	Opns 2	Opns 3	WPs	TC1 (WPR)	TC10 (WPR)	TC11 (WPR)	TC12 (WPR)	TC13 (WPR)
1	2	3	1	5	6	6	6	6
4	5	*	2	5	7	8	6	7
6	8	10	3	5	5	5	6	7
7	9	11	4	5	5	5	6	6
12	*	*	5	7	7	7	6	7
13	*	*	6	7	7	7	8	6
14	16	18	7	6	5	5	7	6
15	17	19	8	6	5	5	7	6
20	21	*	9	6	5	6	8	6
			Total WPs.	57/23 Fin/wip	68/25 Fin/wip	60/25 Fin/wip	68/22 Fin/wip	64/26 Fin/wip

Table A3.2 (cont.) - Generation process for tooling configurations of the table 10.4.4

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: D

FMS similar Multi-purpose Machs.

M1 M2 M3 M4

TG No.	TC5	TG Util.
1	1,2	0.945
2	3,4 10,11	0.786
3	•	•
4	•	•
5	6,7	0.591
6	•	•
7	•	•
8	5,8,9 12to 21	0.948

Av.Mach.Util = 0.818
Finished ASs = 4

TG No.	TC5	TG Util.
1	1,2	0.965
2	3,4 10,11	0.852
3	•	•
4	•	•
5	6,7,8,9	0.950
6	•	•
7	•	•
8	5 12to 21	0.948

Av.Mach.Util = 0.929
Finished ASs = 6

Heuristic Rule D :

Ungroup TG No.8 and group basicTG No.6 to TG No.5 →

1,2	3,4 10,11
6,7,8,9	12 to 21 5

WPs	TC5 (WPR)
1	6
2	6
3	6
4	5
5	7
6	6
7	4
8	4
9	6
Total WPs	56/27 Fin/wip

WPs	TC5 (WPR)
1	6
2	8
3	7
4	7
5	8
6	8
7	6
8	6
9	7
Total WPs	69/31 Fin/wip

Table A3.3 - Generation process for tooling configurations in table 10.8.4

PART MIX A
SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: E,A

FMS with similar Multi-purpose Machines

M1	M2	M3	M4

TG No.	TC1 Tool sets	TG Util.
1	1,2	0.97
2	3	0.29
3	6,7	0.51
4	8,9	0.22
5	10,11	0.16
6	12TO21	0.50
7	•	•

Av.Mach.Util = 0.672
Finished ASs = 3

TG No.	TC2	TG Util.
1	1,2	0.53
2	3	0.41
3	6,7	0.58
4	8,9	0.26
5	10,11	0.16
6	12to21	0.54
7	1,2	0.66

Av.Mach.Util = 0.800
Finished ASs = 5

TG No.	TC3	TG Util.
1	1,2	0.92
2	3	0.45
3	6,7	0.58
4	•	•
5	8 to 11	0.39
6	12to21	0.52
7	1,2	0.25

Finished ASs =5 .0.791

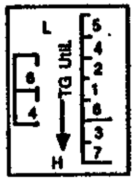
TG No.	TC4	TG Util.
1	1,2	0.71
2	3	0.47
3	6,7	0.51
4	•	•
5	•	•
6	12to21	0.57
7	1,2 8 to 11	0.95

Av.Mach.Util = 0.809
Finished ASs = 5

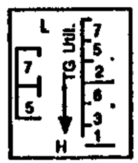
TG No.	TC5	TG Util.
1	1,2	0.963
2	3,6,7	0.983
3	•	•
4	•	•
5	•	•
6	12to21	0.61
7	1,2 8 to 11	0.954

Av.Mach.Util = 0.873
Finished ASs = 5

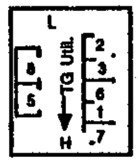
Heuristic E (Tool Duplication rule): -> Duplicate: TG No. 1



-> Combine 5 and 4



-> Combine 7 and 5



-> Combine 2 and 3

1,2	1,2 8 to 11
3,6,7	12 to 21

Opns 1	Opns 2	Opns 3	WPs	TC1 (WPR)
1	2	3	1	3
6	8	10	2	6
7	9	11	3	6
12	•	•	4	7
13	•	•	5	7
14	16	18	6	7
15	17	19	7	7
20	21	•	8	7
			Total WPs	56/14 Fin/wip

WPs	TC2 (WPR)
1	5
2	6
3	6
4	8
5	8
6	7
7	7
8	7
Total WPs	64/16 Fin/wip

WPs	TC3 (WPR)
1	5
2	6
3	6
4	7
5	7
6	6
7	6
8	6
Total WPs	59/21 Fin/wip

WPs	TC4 (WPR)
1	5.6
2	6
3	6
4	8
5	8
6	7
7	7
8	8
Total WPs	67/12 Fin/wip

WPs	TC5 (WPR)
1	5
2	6
3	6
4	8
5	8
6	8
7	8
8	8
	67/23 Fin/wip

Table A3.3 (cont) - Generation process for tooling configurations in table 10.8.4

SCHEDULING RULE: MRPAS ; PART MIX A
TOOL COMBINATION HEURISTIC RULE: D

FMS with similar Multi-purpose Machines

M1 M2 M3 M4

TG No.	TC5	TG Util.
1	1,2	0.963
2	3,6,7	0.963
3	.	.
4	.	.
5	.	.
6	12to21	0.81
7	1,2 8 to 11	0.954

Av.Mach.Util = 0.873
Finished ASs = 5

Heuristic D:

Ungroup TG no.7 and group basic TG No.5 to TG No.6 ->

TG No.	TC6	TG Util.
1	1,2	0.90
2	3,6,7	0.96
3	.	.
4	.	.
5	.	.
6	12to21 10,11	0.76
7	1,2 8 to 9	0.88

Av.Mach.Util = 0.879
Finished ASs = 5

Heuristic D:

Ungroup TG No.7 and group basic TG No.4 to TG No.6 ->

TG No.	TC7	TG Util.
1	1,2	0.78
2	3,6,7	0.96
3	.	.
4	.	.
5	.	.
6	12to21 8 to 11	0.94
7	1,2	0.79

Av.Mach.Util = 0.872
Finished ASs = 5

Heuristic D:

Ungroup TG No.2 into basic TG No.2 and basic TG No.3 ->

TG No.	TC8	TG Util.
1	1,2	0.84
2	3	0.52
3	6,7	0.66
4	.	.
5	.	.
6	12to21 8 to 11	0.94
7	1,2	0.94

Av.Mach.Util = 0.9293
Finished ASs = 5

Heuristic D:

Ungroup TG No.6 and group basic TG No.5 to TG No.2 ->

TG No.	TC9	TG Util.
1	1,2	0.44
2	3,10,11	0.74
3	6,7	0.66
4	.	.
5	.	.
6	12 to 21 8,9	0.87
7	1,2	0.97

Av.Mach.Util = 0.924
Finished ASs = 6

1,2	1,2
3,10,11	12 to 21 8,9

Opns 1	Opns 2	Opns 3	WPs	TC5 (WPR)
1	2	3	1	5
6	8	10	2	6
7	9	11	3	6
12	.	.	4	8
13	.	.	5	8
14	16	18	6	8
15	17	19	7	8
20	21	.	8	8
			Total WPs	67/23 Fin/wip

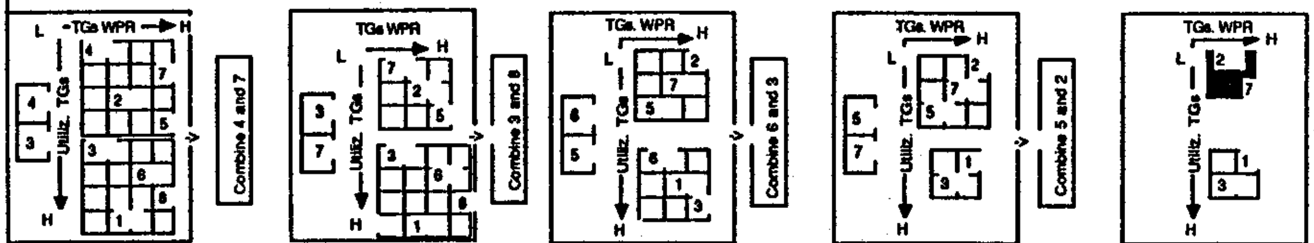
WPs	TC6 (WPR)	TC7 (WPR)	TC8 (WPR)	TC9 (WPR)
1	5.3	5.3	8	6.7
2	6	6	5	6
3	6	6	5	6
4	8	8	8	8
5	8	8	8	8
6	8	6	6	7
7	8	6	6	7
8	8	8	7	7
Total WPs	68/20 Fin/wip	64/24 Fin/wip	63/27 Fin/wip	69/21 Fin/wip

Table A3.4 - Generation process for tooling configurations in table 10.9.1

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC RULE: B

FMS with Limited Purpose Machines: M1, M2, M3, M4

TG No.	TC1 Tool sets	TG Util.	TC2	TG Util.	TC3	TG Util.	TC4	TG Util.	TC5	TG Util.
1	1,2	0.81	1,2	0.81	1,2	0.81	1,2	0.94	1,2	0.94
2	3	0.33	3	0.33	3	0.33	3	0.33	3,6,7	0.95
3	4	0.17	4	0.17	4,12to21	0.63	4,8,9 12to21	0.97	4,8,9 12to21	0.97
4	5	0.09	•	•	•	•	•	•	•	•
5	6,7	0.53	6,7	0.53	6,7	0.58	6,7	0.60	•	•
6	8,9	0.22	8,9	0.22	8,9	0.14	•	•	•	•
7	10,11	0.16	5,10,11	0.27	5,10,11	0.41	5,10,11	0.46	5,10,11	0.45
8	12 to 21	0.49	12 to 21	0.49	•	•	•	•	•	•
	Av.Mach.Util = 0.706 Finished ASs = 2		Av.Mach.Util = 0.714 Finished ASs = 2		Av.Mach.Util = 0.780 Finished ASs = 1		Av.Mach.Util = 0.804 Finished ASs = 5		Av.Mach.Util = 0.836 Finished ASs = 5	



Opns 1	Opns 2	Opns 3	WPs
1	2	3	1
4	5	•	2
6	8	10	3
7	9	11	4
12	•	•	5
13	•	•	6
14	16	18	7
15	17	19	8
20	21	•	9

WPs	TC1 (WPR)	TC2 (WPR)	TC3 (WPR)	TC4 (WPR)	TC5 (WPR)
1	6	6	6	6	6
2	2	2	4	7	6
3	6	6	1	5	7
4	6	6	1	5	6
5	7	7	8	8	8
6	7	7	8	8	8
7	6	6	7	5	5
8	6	6	7	5	5
9	7	7	7	6	6
Total Wps	59/20 Fin/wip	59/21 Fin/wip	59/21 Fin/wip	59/21 Fin/wip	63/17 Fin/wip

Table A3.4 (cont.) - Generation process for tooling configurations in table 10.9.1

SCHEDULING RULE: FCFS
TOOL COMBINATION HEURISTIC RULE: C

FMS with Limited Purpose Machines: M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.
1	1,2	0.81
2	3	0.33
3	4	0.17
4	5	0.09
5	6,7	0.53
6	8,9	0.22
7	10,11	0.16
8	12 to 21	0.49

Av.Mach.Util = 0.706
Finished ASs = 2

TG No.	TC6	TG Util.
1	1,2	0.81
2	3	0.33
3	4	0.22
4	5	0.13
5	6,7	0.58
6	8,9 12to21	0.86
7	10,11	0.19
8	•	•

Av.Mach.Util = 0.789
Finished ASs = 2

TG No.	TC7	TG Util.
1	1,2	0.81
2	3	0.33
3	4	0.22
4	5	0.14
5	6,7 10,11	0.79
6	8,9 12to21	0.86
7	•	•
8	•	•

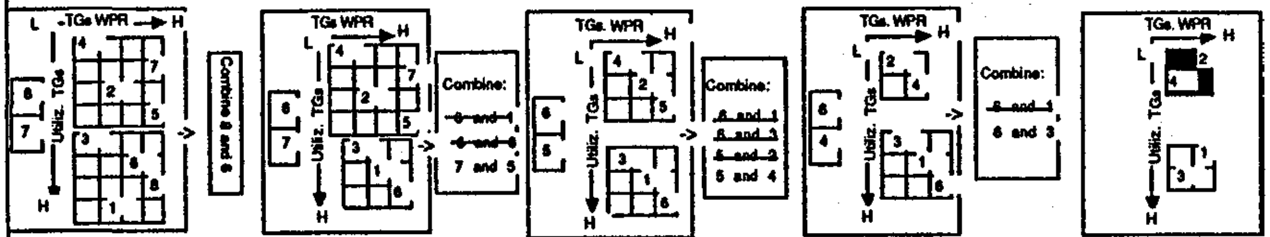
Av.Mach.Util = 0.795
Finished ASs = 2

TG No.	TC8	TG Util.
1	1,2	0.81
2	3	0.33
3	4	0.22
4	5,6,7 10,11	0.91
5	•	•
6	8,9 12to21	0.86
7	•	•
8	•	•

Av.Mach.Util = 0.778
Finished ASs = 2

TG No.	TC9	TG Util.
1	1,2	0.96
2	3	0.34
3	4,8,9 12to21	0.97
4	5,6,7 10,11	0.91
5	•	•
6	•	•
7	•	•
8	•	•

Av.Mach.Util = 0.812
Finished ASs = 5



Opns 1	Opns 2	Opns 3	WPs	TC1 (WPR)	TC6 (WPR)	TC7 (WPR)	TC8 (WPR)	TC9 (WPR)
1	2	3	1	6	6	6	6	6
4	5	•	2	2	2	2	2	6
6	8	10	3	6	7	7	7	6
7	9	11	4	6	7	7	6	5
12	•	•	5	7	6	8	6	7
13	•	•	6	7	8	8	8	7
14	16	18	7	6	7	7	8	5
15	17	19	8	6	7	7	6	5
20	21	•	9	7	8	8	6	6
			Total WPs	59/23 Fin/wip	66/14 Fin/wip	68/14 Fin/wip	62/18 Fin/wip	59/23 Fin/wip

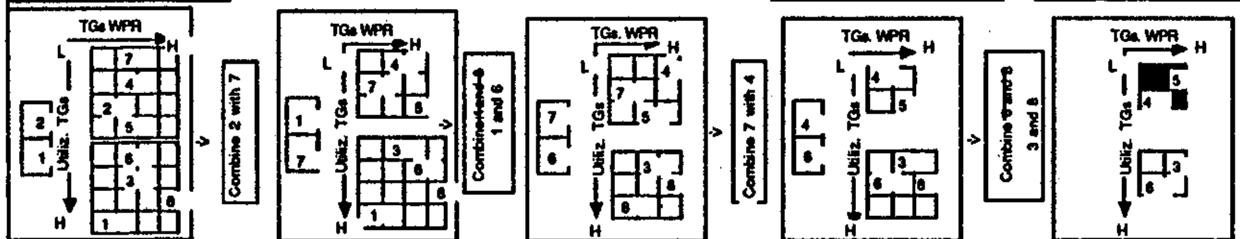
Table A3.4 (cont.) - Generation process for tooling configurations in table 10.9.1

FMS with Limited Purpose Machines

M1 M2 M3 M4

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: B

TG No.	TC1 Tool sets	TG Util.	TC10	TG Util.	TC11	TG Util.	TC12	TG Util.	TC13	TG Util.
1	1,2	0.77	1,2	0.73	•	•	•	•	•	•
2	3	0.26	•	•	•	•	•	•	•	•
3	4	0.23	4	0.25	4	0.27	4	0.21	4,12to21	0.84
4	5	0.23	5	0.26	5	0.27	5,3,10,11	0.70	5,3,10,11	0.74
5	6,7	0.58	6,7	0.51	6,7	0.51	6,7	0.58	6,7	0.58
6	8,9	0.18	8,9	0.25	1,2,8,9	0.97	1,2,8,9	0.97	1,2,8,9	0.97
7	10,11	0.13	3,10,11	0.39	3,10,11	0.36	•	•	•	•
8	12 to 2	0.50	12 to 21	0.43	12 to 21	0.50	4,12 to 21	0.54	•	•
	Av.Mach.Util = 0.733 Finished ASs = 4		Av.Mach.Util = 0.711 Finished ASs = 4		Av.Mach.Util = 0.729 Finished ASs = 4		Av.Mach.Util = 0.759 Finished ASs = 4		Av.Mach.Util = 0.788 Finished ASs = 4	



Opns 1	2	3
1	2	3
4	5	•
6	8	10
7	9	11
12	•	•
13	•	•
14	16	18
15	17	19
20	21	•

WPs	TC1 (WPR)	TC10 (WPR)	TC11 (WPR)	TC12 (WPR)	TC13 (WPR)
1	4	4	4	4	4
2	5	5	6	6	6
3	5	6	5	6	5
4	5	5	5	6	5
5	7	6	7	6	6
6	7	6	7	6	6
7	7	6	7	7	7
8	7	6	7	7	7
9	7	6	7	7	7
Total Wps.	58/22 Fin/wip	54/26 Fin/wip	59/21 Fin/wip	65/23 Fin/wip	63/17 Fin/wip

Table A3.5 - Generation process for tooling configurations in table 10.9.2

SCHEDULING RULE: MRPAS
TOOL COMBINATION HEURISTIC RULE: D

FMS with Limited Purpose Machs.
M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.
1	1,2	0.77
2	3	0.26
3	4	0.23
4	5	0.23
5	6,7	0.56
6	8,9	0.18
7	10,11	0.13
8	12 to 21	0.50

Av.Mach.Util = 0.733
Finished ASs = 4

(Heur.rule B) ...

TG No.	TC13	TG Util.
1	•	•
2	•	•
3	4,12to21	0.84
4	5,3,10,11	0.74
5	6,7	0.58
6	1,2,8,9	0.97
7	•	•
8	•	•

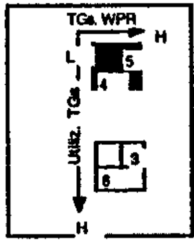
Av.Mach.Util = 0.786
Finished ASs = 4

TG No.	TC14	TG Util.
1	1,2	0.96
2	•	•
3	4,12to21	0.69
4	5,3,10,11	0.80
5	6,7	0.56
6	8,9	0.22
7	•	•
8	•	•

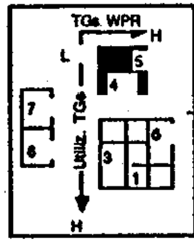
Av.Mach.Util = 0.818
Finished ASs = 4

TG No.	TC15	TG Util.
1	1,2	0.97
2	•	•
3	4,8,9 12to21	0.97
4	5,3,10,11	0.59
5	6,7	0.79
6	•	•
7	•	•
8	•	•

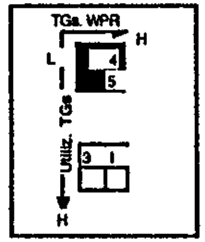
Av.Mach.Util = 0.835
Finished ASs = 4



Heuristic rule D:
Ungroup TG No. 6
in the BTGs 1 and 6



Heuristic rule B:
Combine 3 and 6



Opns 1	Opns 2	Opns 3	WPs	TC1 (WPR)
1	2	3	1	4
4	5	•	2	5
6	8	10	3	5
7	9	11	4	5
12	•	•	5	7
13	•	•	6	7
14	16	18	7	7
15	17	19	8	7
20	21	•	9	7
			Total Wps.	58/22 Fin/wip

WPs	TC13 (WPR)
1	4
2	8
3	5
4	5
5	8
6	8
7	7
8	7
9	7
Total WPs	63/17 Fin/wip

WPs	TC14 (WPR)
1	6
2	5
3	6
4	6
5	8
6	6
7	4
8	4
9	4
Total WPs	53/22 Fin/wip

WPs	TC15 (WPR)
1	6
2	6
3	6
4	6
5	7
6	7
7	4
8	4
9	5
Total WPs	57/23 Fin/wip

Table A3.6 - Generation process for tooling configurations in table 10.11.1

SCHEDULING RULE: MRPAS ; PART MIX A
TOOL COMBINATION HEURISTIC RULE: E and B

FMS with limited-purpose Machines

M1 M2 M3 M4

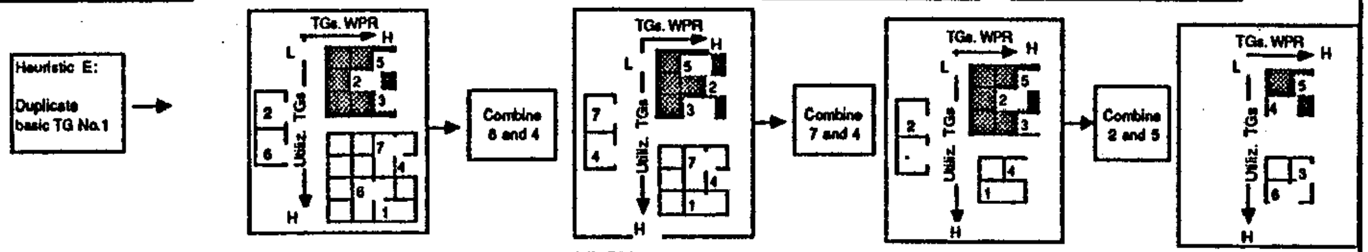
TG No.	TC1	TG Util.
1	1,2	0.97
2	3	0.33
3	6,7	0.51
4	8,9	0.26
5	10,11	0.16
6	12to21	0.43
7	•	•
Av.Mach.Util = 0.672 Finished ASs = 4		

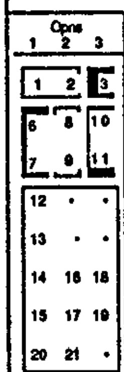
TG No.	TC2	TG Util.
1	1,2	0.97
2	3	0.47
3	6,7	0.46
4	8,9	0.22
5	10,11	0.16
6	12to21	0.39
7	1,2	0.21
Av.Mach.Util = 0.728 Finished ASs = 4		

TG No.	TC3	TG Util.
1	1,2	0.97
2	3	0.33
3	6,7	0.52
4	8,9 12 to 21	0.65
5	10,11	0.16
6	•	•
7	1,2	0.15
Av.Mach.Util = 0.708 Finished ASs = 4		

TG No.	TC4	TG Util.
1	1,2	0.96
2	3	0.42
3	6,7	0.58
4	8,9,1,2 12 to 21	0.97
5	10,11	0.16
6	•	•
7	•	•
Av.Mach.Util = 78 Finished ASs = 5		

TG No.	TC5	TG Util.
1	1,2	0.96
2	3,10,11	0.58
3	6,7	0.57
4	8,9,1,2	0.97
5	•	•
6	•	•
7	•	•
Av.Mach.Util = 0.777 Finished ASs = 5		





WPs	TC5 (WPR)
1	4
2	6
3	6
4	6
5	6
6	6
7	6
8	6
Total WPs	54/16 Fin/wip

WPs	TC2 (WPR)
1	5.7
2	6
3	6
4	6
5	6
6	4
7	4
8	4
Total WPs	53/24 Fin/wip

WPs	TC3 (WPR)
1	4
2	6
3	6
4	6
5	6
6	6
7	6
8	6
Total WPs	54/26 Fin/wip

WPs	TC4 (WPR)
1	5
2	6
3	6
4	7
5	7
6	5
7	5
8	5
Total WPs	56/24 Fin/wip

WPs	TC5 (WPR)
1	4.7
2	6
3	6
4	7
5	7
6	5
7	5
8	6
Total WPs	56/24 Fin/wip

Table A3.7 - Generation process for tooling configurations in table 10.11.3

SCHEDULING RULE: MRPAS ; Part Mix B
TOOL COMBINATION HEURISTIC RULE: E and B

FMS with Limited Purpose Machs.
M1 M2 M3 M4

TG No.	TC1 Tool sets	TG Util.
1	1,2	0.77
2	3	0.26
3	4	0.23
4	5	0.23
5	6,7	0.66
6	8,9	0.18
7	10,11	0.13
8	12 to 21	0.50
Av.Mach.Util = 0.733 Finished ASs = 4		

(Heur. rule B) ... →

TG No.	TC14	TG Util.
1	1,2	0.96
2	•	•
3	4,12to21	0.69
4	5,3,10,11	0.60
5	6,7	0.66
6	8,9	0.22
7	•	•
8	•	•
Av.Mach.Util = 0.818 Finished ASs = 4		

TG No.	TC16	TG Util.
1	1,2	0.96
2	•	•
3	4,12to21	0.43
4	5,3,10,11	0.74
5	6,7	0.58
6	8,9	0.22
7	•	•
8	11 to 21	0.24
Av.Mach.Util = 0.800 Finished ASs = 4		

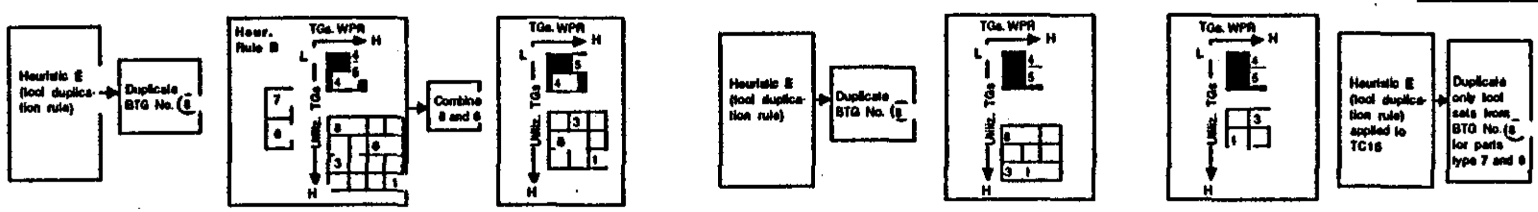
TG No.	TC17	TG Util.
1	1,2	0.96
2	•	•
3	4,12to21	0.43
4	5,3,10,11	0.74
5	6,7	0.58
6	•	•
7	•	•
8	8,9,11to21	0.24
Av.Mach.Util = 0.814 Finished ASs = 6		

TG No.	TC15	TG Util.
1	1,2	0.97
2	•	•
3	4,8,9 12to21	0.97
4	5,3,10,11	0.59
5	6,7	0.79
6	•	•
7	•	•
8	•	•
Av.Mach.Util = 0.836 Finished ASs = 4		

TG No.	TC18	TG Util.
1	1,2	0.97
2	•	•
3	4,8,9 12to21	0.97
4	5,3,10,11	0.59
5	6,7	0.79
6	•	•
7	•	•
8	12to21	0.0
Av.Mach.Util = 0.836 Finished ASs = 4		

TG No.	TC19	TG Util.
1	1,2,12to21	0.97
2	•	•
3	4,8,9 12to21	0.93
4	5,3,10,11	0.58
5	6,7	0.79
6	•	•
7	•	•
8	•	•
Av.Mach.Util = 0.824 Finished ASs = 4		

TG No.	TC20	TG Util.
1	1,2,14to19	0.97
2	•	•
3	4,8,9 12to21	0.97
4	5,3,10,11	0.61
5	6,7	0.80
6	•	•
7	•	•
8	12to21	•
Av.Mach.Util = 0.841 Finished ASs = 5		



1 2 3	Opns / WPs	TC1 (WPR)
1 2 3	1	4
4 5 •	2	5
6 8 10	3	6
7 9 11	4	5
12 • •	5	7
13 • •	6	7
14 16 18	7	7
15 17 19	8	7
20 21 •	9	7
	Total Wps.	58/22 Fin/wip

WPs	TC14 (WPR)	TC16 (WPR)	TC17 (WPR)	TC15 (WPR)	TC18 (WPR)	TC19 (WPR)	TC20 (WPR)
1	8	6	6	6	6	4	6
2	5	5	5	6	6	7	6
3	6	6	6	6	6	7	7
4	6	6	6	6	6	7	7
5	8	7	6	7	7	8	7
6	6	7	8	7	7	8	7
7	4	4	5	4	4	5	5
8	4	4	5	4	4	5	6
9	4	6	6	6	5	7	6
Total WPs	63/22 Fin/wip	57/28 Fin/wip	61/24 Fin/wip	57/23 Fin/wip	57/23 Fin/wip	62/26 Fin/wip	59/31 Fin/wip

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