THE PRODUCTION PLANNING PROBLEMS OF FLEXIBLE MANUFACTURING SYSTEMS WITH HIGH TOOL VARIETY

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Dedicated to
my parents who guided me to work in an academic environment
and to
my wife Kamala who inspirits me to continue it.

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ABSTRACT

This research is concerned with certain production planning problems associated with flexible manufacturing systems (FMS) with high tool variety. In this environment of FMS, the tool requirements at workstations exceed the respective tool magazine capacities. During an extensive survey of related literature, it appeared that the problems associated with this type of FMS have been overlooked by the FMS research community.

The operational problems of FMS are discussed with special reference to the constraints imposed by tooling. The characteristics of the selected FMS type are clearly defined. This discussion is supplemented with a detailed description of a real FMS which resembles the operations of the selected type of FMS.

Having identified certain drawbacks of some existing simulation software, the development of a comprehensive FMS simulator which uses a novel hybrid modelling technique is discussed. The use of a graphical post-processor which can be used to enhance the system logic of the FMS is also described

A number of parameters associated with the tool management system are identified and the methods are described to evaluate these parameters. The importance of evaluating these parameters in design and operation of an FMS is stressed.

The development of a tool post-processor which can assist in identifying the scale of the tooling problem and in evaluating tool management parameters is presented.

A variety of tool availability strategies which reduce the tool exchange rates are suggested and evaluated. Finally, the part selection (for immediate processing) problem

is solved using a novel technique which takes the advantage of the availability of real time data in FMS.

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CHAPTER 1

FLEXIBLE MANUFACTURING SYSTEMS AND ASSOCIATED OPERATIONAL PROBLEMS

1.1 INTRODUCTION

For decades, manufacturing resources have been used as stand alone facilities with little or no integration between them. In recent years however, the extensive development and use of computer assisted systems within the manufacturing industry has led to a proliferation of *system designs* [Cook 1978].

In early 1970's the concept of *flexible manufacture* was introduced by linking production equipment under the control of one or more computers. It is expected that these flexible manufacturing systems would achieve the flexibility of job shops while approaching the higher productivity of transfer lines. In this research work, some problems pertinent to FMS are discussed and solved.

Prior to a detailed discussion of associated problems and proposed solution strategies, a brief introduction to FMS and their major operational problems is presented.

1.2 EVOLUTION OF FLEXIBLE MANUFACTURING SYSTEMS

A major breakthrough in manufacturing technology was realized when the first numerically control machine tool was invented [Hatvany 1983]. Since then in parallel to the rapid development of computer technology, this concept of numerical control has been continuously enhanced. Although the first few generations of NC machines were operated by their own control system, in late 60's a group of NC machines were linked together and operated under the control of a central computer. This is known as DNC (Direct Numerical Control) system.

At this level of automation, however integration was limited to machine tools, but it was soon realized that further improvements can be achieved if parts were delivered to workstation automatically. In mid 60's D T Williamson, then Director of Research

& Development, Molins Company (UK), conceived the idea of automated part handling system for a cluster of workstations [Williamson 1965]. It is generally recognized as the exposition of the FMS concept [Kochan 1985(a)]. Having recognized the importance of this philosophy, since then the manufacturing industry has been implementing FMSs.

1.3 REALIZATION OF FLEXIBLE MANUFACTURING IN THE UNITED KINGDOM

The United Kingdom probably has a stronger claim than any other nation in terms of creating the concept of flexible manufacture. Sadly there is considerable evidence to indicate that FMS is yet another example of an excellent concept originating in Britain, where initial advantage has been lost through industry's failure to apply it on any significant scale and exploit its benefits.

In early 80's the British Government launched the FMS support scheme which accelerated implementation of FMSs and by 1985, 33 FMS installations were reported [Kochan 1985(b)].

The UK industry accounts for wide variety of FMSs, from small systems to large scale systems. The British Aerospace, JCB Transmission Ltd and Anderson Strathclyde Plc claim some of the most impressive FMSs in UK. An exhaustive review of UK FMS installations can be found in [Bessant and Hayward 1986].

Nearly ten system were visited during this research work, and the following general observations were made.

- **a.** Production planning and control is a major operational problem. None of the companies used any decision support systems to solve these problems.
- **b.** Although some companies used simulation at the design stage to evaluate vendor's proposal, most of the companies do not use simulation to solve day to day operational problems.

c. There are few systems in which tool management has been given proper consideration. Most companies believe that tool management is a major problem.

d. Except in very few systems , the processing characteristics of parts are not very complex and require not more than 2 or 3 operations to finish the parts. In most systems all operations can be carried out in a single fixture setup.

e. In many systems, the debugging of software has taken very long time (4-5 years).

At present the rate of implementation of large scale FMSs is declining while modular implementation of FMSs is increasing. The idea is that a simple system can be expanded to a fully fledged FMS by adding various production modules in a sequential manner.

1.4 DEFINITION FOR FLEXIBLE MANUFACTURING SYSTEMS

Flexible manufacturing system is a phrase which is open to wide interpretation and various definitions have been suggested in literature [Wood 1982, Kusiak 1985]. However when attempting to solve problems pertinent to these systems a conceptual definition of FMS is necessary. The International Institute of Production Engineering Research (CIRP) recently completed a set of definitions for automated manufacturing systems of which FMS is a part. First it provides a definition for an automated system [Kochan 1985(a)].

> *An automated manufacturing system is an unit within a manufacturing system consisting of an integrated assembly or machines and/or associated equipment to carry out production with a minimum of manual attention together with the means for transferring components automatically through the system; all operating under fully programmable control.*

In engineering manufacture an automated production system usually encompasses machine tools for processing and other workstations such as washing, inspection etc..

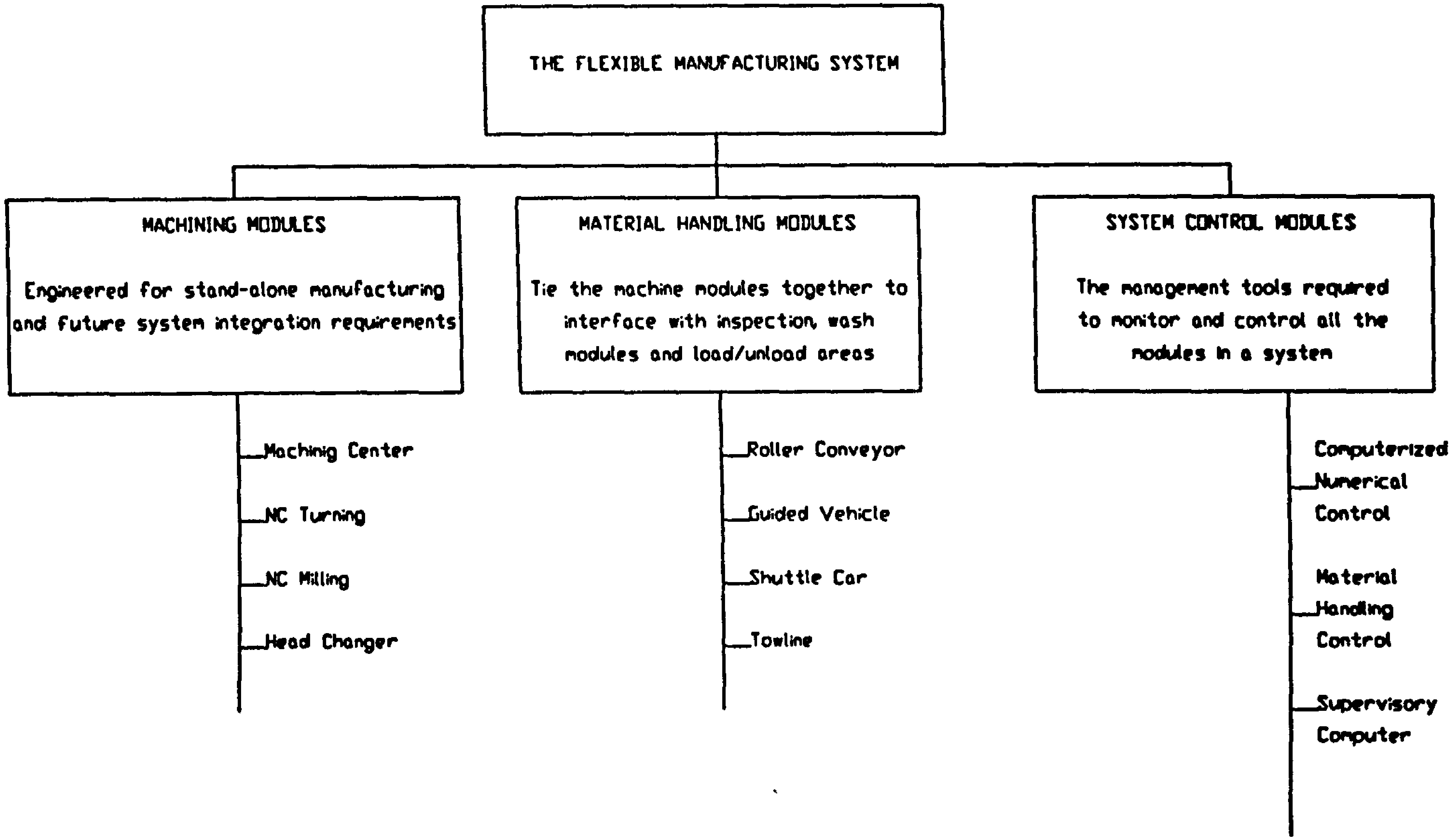


Figure 1.1 The Fundamental Building Blocks of FMS

Within the framework of automated manufacturing system, CIRP define FMS as [Kochan 1985(b)];

> *A flexible manufacturing system is an automated system which is capable, with minimum of manual intervention of producing any of a range or family of products. The flexibility is usually restricted to family of products for which the system is designed.*

This broad definition covers wide variety of FMSs, therefore various attempts have been made to identify possible variants of FMSs [Stecke and Browne 1984]. Basically these approaches classify systems based upon the number of machining modules involved and/or type of material handling system used.

1.5 DESCRIPTION OF FLEXIBLE MANUFACTURING SYSTEMS

Any FMS consists of number of hardware and software modules. While hardware modules provide various processing and supporting facilities such as machining, material handling etc., software modules assure the proper control over the system and management reporting etc. Major hardware and software modules are shown in Figure 1.1. In the following some of the keywords used in this work are defined.

A FMS is generally capable of producing several different *part types* which are members of one or more *part families* which are formed on the basis of similarities of characteristics (e.g. geometrical, material etc.). An individual representative of a given part type is called a workpiece.

Fixtures hold the workpieces in different orientation for machining on different faces. It may be possible that a given fixture can be shared by different part types. Fixtured workpieces are mounted on *pallets* which are the interface to the *material handling system (MHS)* which moves workpieces within the system.

Each workpiece is manufactured via a sequence of *routes*. A route is a trip through the system, after which the workpiece is removed from the system. After a workpiece completes its first route, it will be re-entered and sent on its second route, and so on, until all routes are completed. The reason for separate routes is usually a need for a separate fixtures.

On a given route a workpiece will visit a given sequence of *machine groups.* A machine group can contain several machines and any machine in the group can process a workpiece that is destined for that group. The machine groups can overlap that is the same machine can participate in two or more machine groups.

Typically FMS machine groups do metal cutting. But there are various FMS support functions. Inspection tasks are handled by a special *inspection machine groups* and the tasks of fixturing/loading and defixturing/unloading of parts entering and leaving the system are handled by a special *load/unload workstation group.*

Once a workpiece is released to the system human intervention is kept at lowest possible level by controlling the activities of the system through a system of computer hardware and software.

1.6 OPERATIONAL PROBLEMS OF FLEXIBLE MANUFACTURING SYSTEMS

Although flexible manufacturing systems are computer controlled automated systems they do not relieve the burden of the planning and control aspects of the system. These aspects have been recognized as major operational problems pertinent to these systems. The following is the comprehensive discussion of typical production planning problems encountered in FMS environment;

The life cycle of operational procedure begins when production orders (what to make, how many and when to be completed) are received by the system. For a variety of reasons, the simultaneous processing of all required workpieces may not be possible. Prime among these reasons are the tool capacity constraints and limited number of fixtures and pallets. Therefore it is necessary to *select a subset of part types for immediate processing.* Once the part types have been selected, some aggregate information can be obtained concerning the total processing requirements, tool requirements etc..

Since the system processes different part types in different planning periods, it may not be suitable to maintain a fixed machine group configuration. Different product mixes generate different patterns of work load distribution and demand different combinations of tools. Thus having selected part types for immediate processing, machines can be *partitioned to form logical machine groups.* Each member in a given machine group is identically tooled to perform the same set of operations .

Some FMSs produce parts that are required in certain relative ratios. For example the system may produce many part types and components for later assembly. It may desirable also to produce in certain ratio to maximize some system performance indexes. Therefore it may be necessary to determine *the production ratio for selected part types.*

In most of the systems, production ancillaries such as fixtures, pallets etc. are limited. Some fixtures may be shared by different part types. Thus when these limited resources constrain the way system is operated it is necessary to *allocate the limited number of pallets and fixtures among the selected part types.*

When production rates of the selected part types are determined, production requirements of individual part types can be fragmented into operation modules. Then it is necessary to *allocate operations and associated cutting tools of the selected part types among the groups of machines.*

In most of the systems, the development of operational strategies has been left to the user. It should be borne in the mind that no universal strategy can be developed due to variations in several factors associated with these systems. When these FMS planning problems are solved, the system is ready to accept parts for processing. The next major task is the control of part flow through the system.

Since an FMS is capable of processing different part types simultaneously, it is possible to release parts to the system in different sequences. However random releasing of part types may not be wise as it contributes to the system performance. In some systems, it may be necessary to control the input sequence to avoid constraints imposed by limited resources. Therefore it is required to determine the *optimal sequence in which the selected part types are released into the system.*

Once the parts are released to the system further control over the part flow is necessary. When alternative routes are possible, parts should be selected in a logical manner to improve the system performance. Thus appropriate *scheduling methods preferably real-time, on-line techniques* need to be developed.

Furthermore operational strategies should be developed, in order to respond to system disturbances such as machine breakages, tool breakages etc.

1.7 TOOLING CONSTRAINTS AND TOOL FLOW CONTROL

In the first generation of FMS, tooling aspects were largely ignored and all efforts were concentrated on controlling the part flow. However, it has now been recognized that tool management aspects are major obstacles in achieving the expected performance. In general, two types of problems exist.

Firstly, it is necessary to develop an overall strategy for tool management in FMS. This includes, tool inventory control, tool requirement planning, tool tracking and monitoring and tool delivery system. Apart from these inter-system tooling related activities, the strategy should be extended to communicate with the design, the process planning system etc. Except in a few systems, the level of automation associated with tool management is very rudimentary. So far, no integrated tool management system has been reported.

Secondly, tools can impose severe constraints on the production planning and control problems discussed above. The complexity of these constraints mainly depends on the aggregate tool requirements and tool magazine capacity. In some systems aggregate tool requirements are low and the magazine capacity is large enough to hold all necessary cutting tools. This type of system would require the simplest tool management system and operational problems may not be constrained by tooling. But at the other extreme, aggregate tool requirements exceed the tool magazine capacity and almost all production planning control problems are severely constrained by tooling. Furthermore, a more comprehensive tool management system is essential.

When FMSs are designed, one or more part families are taken as the basis. However it is almost impossible to maintain the same set of part families throughout the life cycle of an FMS. New product types may be introduced to obtain the advantages of flexible manufacture and the part family spectrum expanded. Thus even a simple FMS may gradually turn into a complex system. One of the adverse effects of this development is the expansion of the tool population.

1.8 FOCUS OF THIS RESEARCH

It is conspicuous from the above discussion, that when aggregate tooling requirements exceed the tool magazine capacity, most of the production planning and control problems are constrained by tooling. This research is an investigation of production planning problems of FMS in the high tool variety environment. It also addresses the tool management aspects of FMS and modelling of tool flow within a FMS, which are essential pre-requisites. In particular, the part selection problem in the high tool variety environment is solved. Such a problem of FMS apparently has not previously been discussed in the literature.

As stated above, in general tool management aspects have been overlooked. Therefore it is necessary to identify major aspects of tool management system and their interactions with production planning and control of FMS.

In the quest for solution strategies for these operational problems, the availability of a model of the system would be invaluable. As a consequence of the negligence of tooling aspects, modelling of FMS is confined to part flow. Thus appropriate modelling techniques have to be developed to understand the scale of the tooling problem and to augment the generation of solution strategies.

CHAPTER 2

PROBLEM STATEMENT

2.1 INTRODUCTION

This chapter sets out the problem statement of the research programme. The problem was captured through accumulation of knowledge about the planning and control problems of a real FMS and the constraints imposed by tooling and tool management in general. The appropriateness of the selected research area is further strengthened by the findings of a literature survey which reveal gradual perception of the importance of tooling aspects in the industry.

There are many variants of FMS configuration. Different systems operate at different level of complexity. Thus it is essential to identify the major characteristics of the selected type of FMS.

The factors which influence the selection of the type of the FMS are discussed and the problem area is clearly defined. Pre-requisites of the research program are identified and the major steps are outlined.

2.2 FLEXIBILITY OF FLEXIBLE MANUFACTURING SYSTEMS

The term flexible manufacturing system is used in the industry to describe a variety of automated systems and to some extent it has become a misnomer. The ambiguity arises due to the phrase *flexibility*, because to different people flexibility means different things. However attempts have been made to identify flexibilities pertinent to automated manufacturing systems. Most comprehensive set of definitions is proposed by Browne and others [1984] who gives the following list;

> *Machine Flexibility* measures the ease of making the changes required to produce a given set of parts.

Product Flexibility represents the ability to changeover to produce a new set of products economically and quickly.

Process Flexibility measures the ability to produce a given set of part types in several ways.

Operation Flexibility measures the ability to interchange the ordering of certain operations for each part type.

Routing Flexibility measures the ability to handle breakdowns while continuing to produce the desired set of part types.

Volume Flexibility measures the ability to operate a FMS profitably at different production volumes.

Expansion Flexibility represents the capability of expanding a FMS as needed, easily and modularly.

Production Flexibility represents the universe of part types that the FMS can produce.

It is anticipated that a good FMS would possess all of these flexibilities. However it may not be financially viable or appropriate to have all flexibilities in one system. Therefore system designers would decide a sub-set of flexibilities to build into the system, based upon user requirements. The operational complexity of FMS is partly attributed to the type of flexibilities embedded into the system. Generally, higher system flexibility demands greater planning and control effort. As an example when routing flexibility is added to the system, more comprehensive scheduling logic needs to be developed.

2.3 FLEXIBILITY AND SYSTEM CONSTRAINTS

A set of part families suitable for flexible manufacture is the centre piece of the FMS design process. The characteristics of these parts and their production requirements set the major features of the system such as the number of workstations and their type, material handling system and the number of pallets etc. Once the system is operational, it may be necessary to make products whose characteristics are different to those of the original set of parts. However, there are certain system constraints which limit the expansion of part families. They can be categorized as follows;

2.3.1 Constraints Imposed by Production Equipment

The production equipment basically includes, workstations, material handling system and inspection stations etc. This hardware subsystem sets the higher level constraints. For example, a machining centre sets the maximum working envelope (it is logically possible to process any part which lies within the working envelope) and the maximum weight of the part. The material handling system also limits the size and weight of the parts being delivered. The tool magazine capacity is an another higher level constraint. Alteration of these constraints (such as adding a new workstation) requires high investment and they are done on long term basis, in responds to changes in production environment.

2.3.2 Constraints Imposed by Production Ancillaries

Production ancillaries such as fixtures and tools limit the types of parts that the system can process. Within the limits imposed by higher level constraints, it may possible to expand the FMS product spectrum by adding more tools and fixtures. Generally, these do not demand high investment. Thus the system flexibility can be improved in this way to meet short term requirements.

2.3.3 Constraints Imposed by Software System

The system software sets overall operational strategies for the system. Thus any changes in operational tactics must be reflected in system software. The complexity of modifying software, however, depends on the way that it has been implemented. If modular structure has been used, it may be relatively easy to make changes. The cost of these changes depend on the degree of enhancement.

From the above discussion it is clear that by altering constraints imposed by production ancillaries, the product and volume flexibilites of the system can be improved on a short term basis. In the case of cutting tools, an interesting problem arises, as it interacts with a higher level constraint, tool magazine capacity.

2.4 CLASSES OF FLEXIBLE MANUFACTURING SYSTEMS

Apart from the flexibility diversity, different systems have different types of architecture due to alternative combinations of production equipment. These variations have been classified, based on two main factors, the number of workstations involved and the type of material handling system used [Dupont 1982, Stecke and Browne 1984];

Type I FMS : Flexible Manufacturing Cell (FMC)

A FMC consists of a single CNC machine tool with automatic tool changing and automated loading and unloading of parts from an associated buffer.

Type II FMS : Flexible Machining System (FMS)

It consists of several FMCs of possibly different types. Being the most general type of FMS, there are also several kinds of automated MHSs (eg. AGV, rail guided car etc.) that can be used with this system to provide subcategories of this type II.

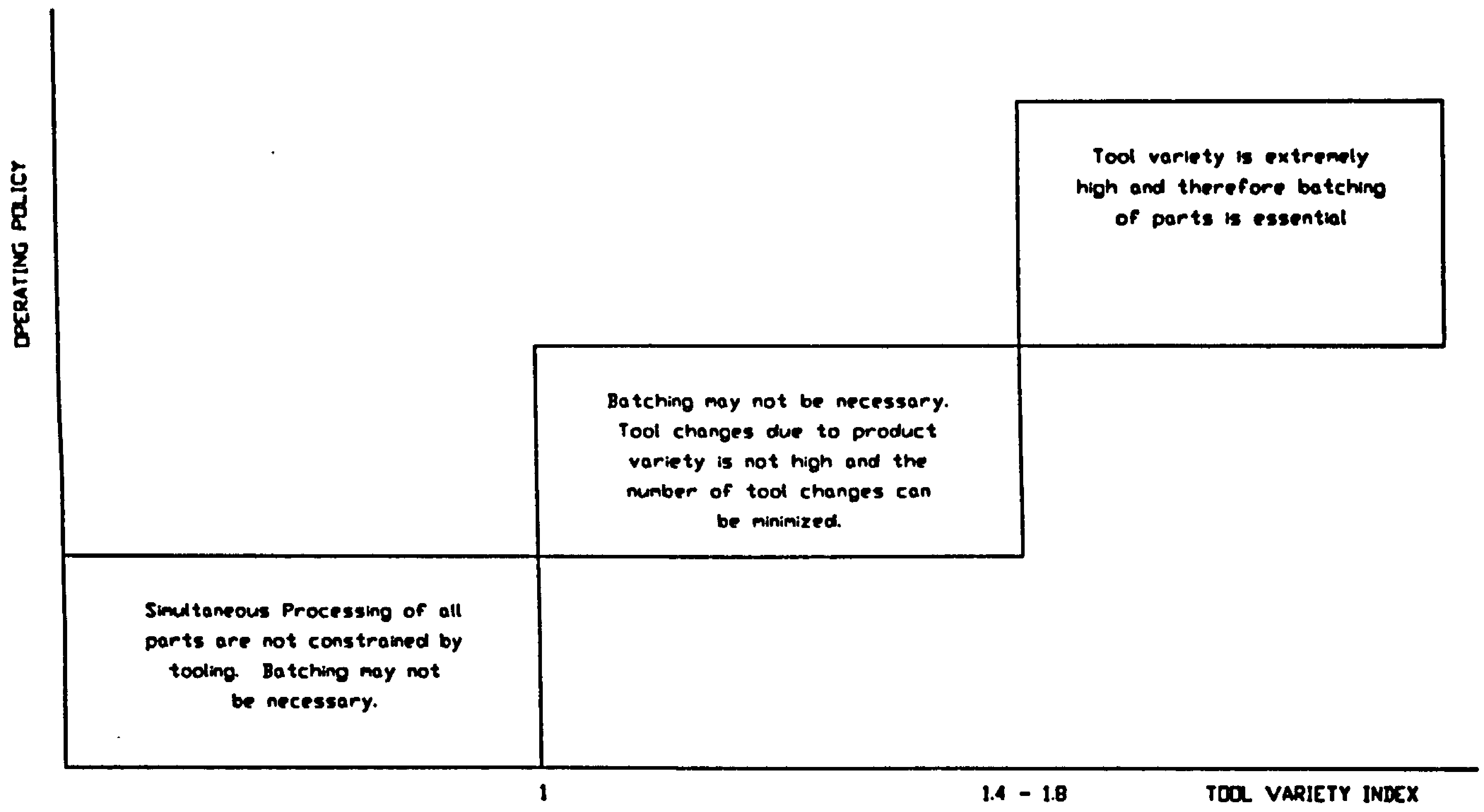


Figure 2.1 The Different Operating Strategies Due to Varying Tool Requirements

Type III FMS : Flexible Transfer Line (FTL)

A FTL requires that each part has a fixed route through the system.

Further classification of FMSs are possible based on major operational features. Remarkable difference in operating policies can exist due to constraints imposed by various production ancillaries, such as fixtures, pallets and tools. Among these tools can decisively set the way the system is operated and it would depend on the ratio between aggregate tool requirements and the tool magazine capacity.

When operations are assigned to workstations, aggregate tool requirements at each workstation can be estimated. A new parameter *tool variety index* has been defined based on these values (chapter 7). The system may operate at different levels of complexity based on the value of system tool variety index [Fig. 2.1]

Further categories of FMSs can be defined according to processing characteristics of parts and batch sizes. Among various processing characteristics, the processing time is an important factor and it may used when operational strategies are developed. Most of the developed methods are however limited to systems with short processing times and larger batch sizes. In this environment production requirements are split into batches, and are released to the system one after another with re- configuration of tools after each batch. But when batch sizes are small and processing times are longer, this conventional a batch-after-another strategy may not be appropriate. One of the important facts in this environment is that *the system may not reach a steady state.*

Variations in the above factors are taken into account when the type of FMS is selected. In the context of this work, the selected FMS type would include the following characteristics.

a. All major flexibilities

b. FMS/AGV type

c. High tool variety environment

d. Small batch sizes and long processing times (highly dynamic environment)

2.5 PROBLEMS ASSOCIATED WITH THE SELECTED FMS TYPE

The above mentioned characteristics of the system would set out different dimensions to production planning and control problems. In general, these features increase the complexity of operational strategies.

2.5.1 All Major Flexibilities

As mentioned before, higher system flexibility leads to a large number of candidate decisions for a given problem and it may be necessary to test these options to find a good candidate decision. The level of flexibility may change from time to time, and this dynamism may bring additional operational problems. For example, production flexibility can be improved by adding more tools to the system but at the same time more comprehensive logic is required to control the part releasing sequence.

2.5.2 FMS/AGV Type

FMS/AGV type of flexible manufacturing system is regarded as the most complex type among the variants. Although this type of addressable material handling system is more effective, they bring additional control problems. For example, system logic must be able to avoid possible collision of vehicles and more effective transporter assignment strategies are required to improve the utilization of the material handling system.

2.5.3 High Tool Variety Environment

As discussed earlier (section 1.7) most production planning and control problems are constrained by tool magazine capacity. In the following, additional dimensions added to these problems by tooling aspects are highlighted.

a. Selection of Subset of Parts for Immediate Processing

There may be several criteria for this, such as limited number of fixtures and machine capacity etc. In this environment however, tool magazine capacity may be the prime reason. Therefore, when parts are selected for immediate processing, their *tooling similarities* must be considered. If more unsimiliar (in tooling aspects) parts are selected, it may be necessary to change tools at intermediate stages due to product variety.

b. Machine Grouping

When machines are grouped logically to meet changes in production requirements, it is desirable to form few machine groups with a large number of machines in each group. If tooling requirements exceed the magazine capacity, more machine groups have to be created reducing the routing flexibility of the system.

c. Production Ratio of Selected Part Types

Usually, a certain ratio of part types is maintained, when FMS feeds a downstream manufacturing facility such as assembly line. But tooling aspects may also control the part ratio. It is thought that part types can be grouped according to their rate of consumption of tool life. There may be parts of which operations consume a higher percentage of tool life (to avoid repetitive use of long terms, this types of parts are named as H type). If only H type parts are produced in a certain production period, the number of tool changes could be high and the tool handling system may not be able to cope up with high demand for tools, resulting machine down due to *tool starving*. But this could be controlled by blending H type parts with other part types and maintaining a certain ratio, between these types.

d. Part Releasing Strategy

Parts can be released to the system in different sequences. For example, 5 different part types can have 120 (5!) different sequences. These different part releasing patterns will result in different number of tool exchanges due to product variety. As an example, consider the following example which represent a high tool variety.

Tool Magazine Capacity = 3 pockets

Current magazine content = [t1,t2,t3]

Tool requirements for part types A, B and C are as follows;

A = [t4,t5] B = [t3,t5] C = [t1,t2]

The number of tool changes are estimated below for two different sequences;

Sequence 1: A-B-C

	Initial	type A	type B	type C
Tool Magazine Content	t1 t2 t3	t1 t4 t5	t3 t4 t5	t1 t2 t5
Tools removed		t2 t3	t1	t3 t4
No. of changes		2	1	2

Total number of tool changes due to product variety = 5

Sequence 2: C-B-A

	Initial	type C	type B	type A
Tool	t1	t1	t1	t4
magazine	t2	t2	t5	t5
content	t3	t3	t3	t3
tools removed			t2	t1
No. of changes		0	1	1

Total number of tool changes due to product variety = 2

Therefore, if C-B-A sequence is selected instead of A-B-C, the number of tool changes due to variety can be reduced by nearly 50%. This simple example can also reveal another important aspects in tool changing. In the first sequence (A-B-C), at the second stage (processing type B), instead unloading t1, tool t4 could have been taken out, then the number of tool exchanges at the next stage is reduced. But this require some kind of look-ahead feature in the tool unloading strategy.

2.5.4 Small Batch Sizes and Long Processing Time

As pointed out in above, when batch sizes are small and processing times are long, the system may not reach a steady state. Due to long processing times, transient time could be high but the system cannot reach a steady state as product mix changes constantly due small batch sizes. Therefore in this case, real time data must be used as the system cannot settle down to a certain state.

It is clear from the above discussion, that in this type of FMS, there are many challenging problems to be solved. Operational problems associated with this type of FMS are apparently not discussed in the literature.

2.6 OBJECTIVES OF THE RESEARCH PROGRAM

There are two major objectives of the research programme;

a. To identify and evaluate FMS tool management parameters.

A number of tool management parameters will be defined and procedures will be developed to evaluate them. These tool management parameters can be used to identify the scale of the tooling problem of a given FMS and to generate operating rules for the management of cutting tools.

b. To develop operatinal strategies to reduce the rate of tool exchanges.

As discussed in section 2.5.3, it is required to minimise the rate of tool exchanges in high tool variety environment of FMS. A number of tool availability strategies will be proposed and they will evaluated using data collected from a real FMS. The rate of tool exchanges can also be controlled by selecting the parts (for immediate processing) in a logical manner. A novel technique which uses real time data will be developed to solve the part selection problem.

It is expected that a model of the system which can mimic the tool handling within the system will be useful at various stages of the research programme. Firstly, a comprehensive part flow simulator will be devloped and then it will be enhanced to capture tooling aspects of the system.

Each major stage of the research programme will be supplemented by a comprehensive literature survey.

CHAPTER 3

A FLEXIBLE MANUFACTURING SYSTEM

3.1 INTRODUCTION

The integration of various production sub-systems in modern manufacturing systems has increased the level of complexity of operational aspects. A sound understanding of the interactions between these sub-systems is vital before the associated operational problem can be solved. This can be partly achieved through a detailed study of a real FMS.

Furthermore, data from a real FMS can provide a realistic test bed for strategies developed during the research. It is specially difficult to create a hypothetical database for a tooling system.

An excellent example which portrays the type of FMS being studied, exists within local industry. Major features and operational aspects of this system are presented in this chapter. The data which drives the system are also explained.

3.2 THE COMPANY AND THE PRODUCTS

The group of companies involved is one of the largest manufacturer of mining machines in Western Europe, supplying equipment to most of coal producing countries of the world. The five companies and thirteen factories are spread over four continents [Anderson Strathclyde Plc 1986]. The Scottish based company produces coal cutting machines [Fig. 3.1] and employs more than 700 on a 21 acre site with 35,000 sq. ft. of buildings. This factory has a high investment in machine tools and modern manufacturing facilities.

The coal cutters, the main product, are produced in a variety of sizes and configurations to suit different mining conditions. They are driven by electric motors of up to 1 Megawatt installed power and weigh 40 tonnes. The machine consists of a series of

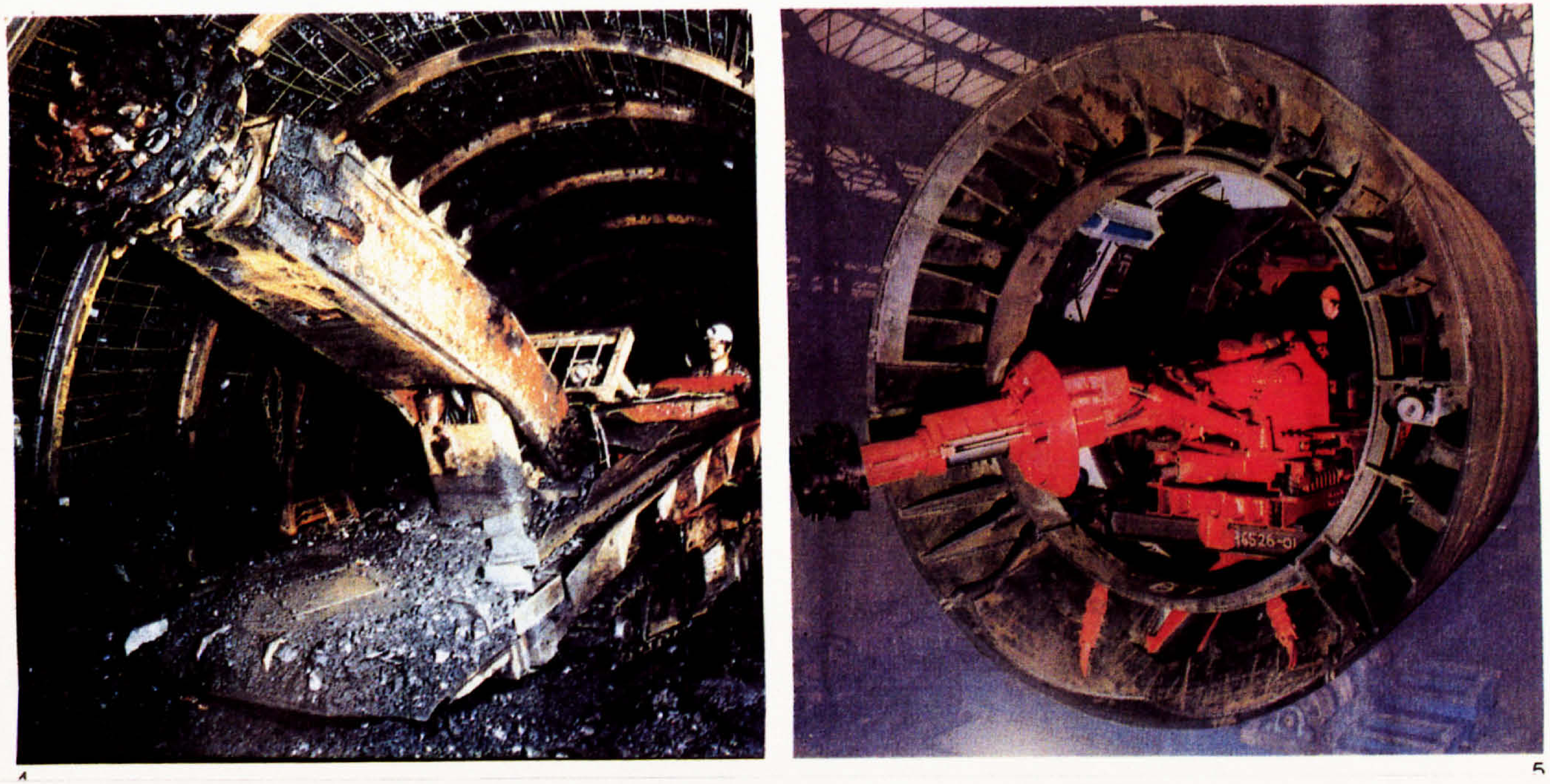


Figure 3.1 The Coal Cutters (Courtesy of Anderson Strathclyde Plc.)

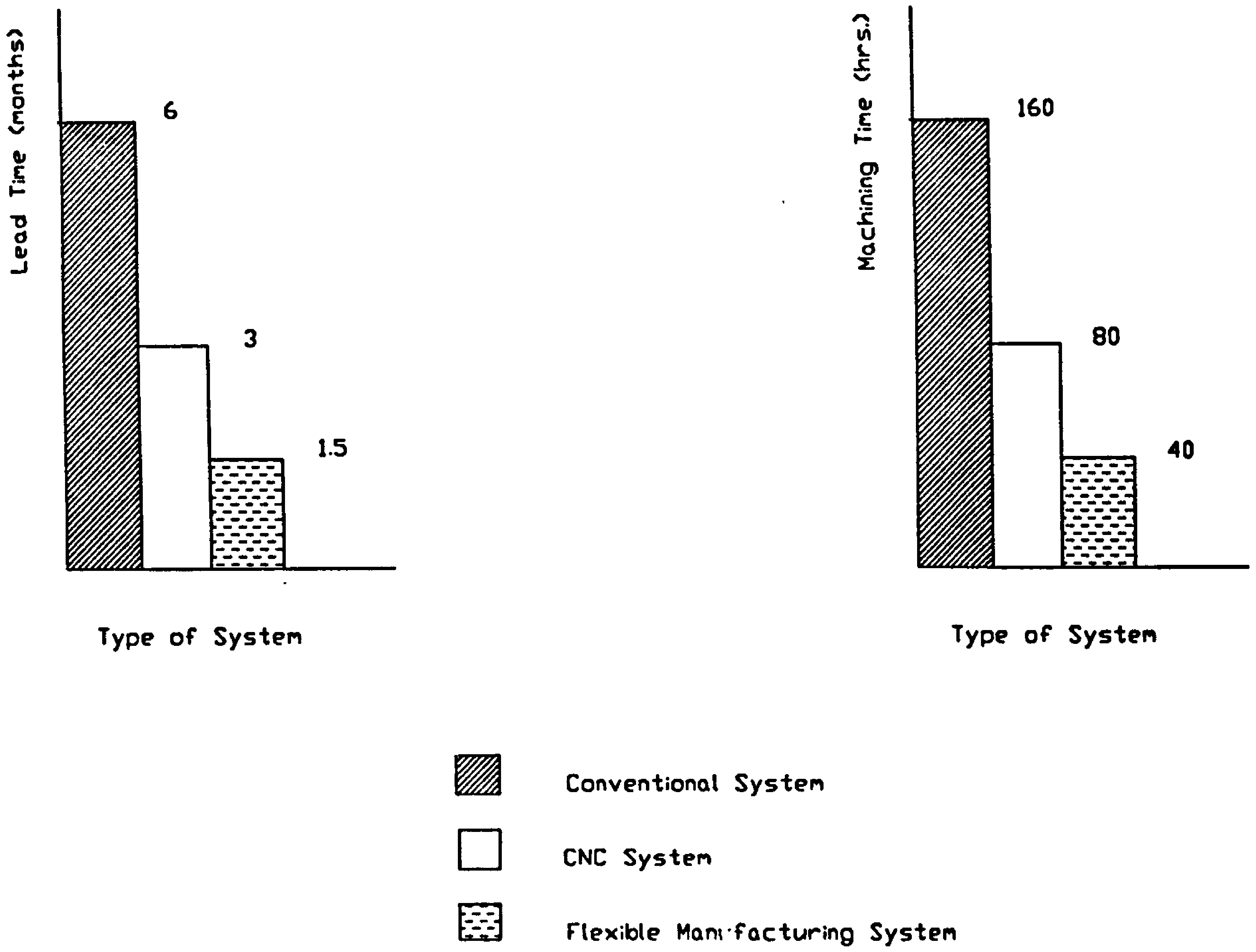


Figure 3.2 Comparison of Conventional Machining, CNC and FMS

modular units comprising electric motors, gear boxes, haulage winches, power pack etc. Units are generally made out of cast steel and weigh upto 2 1/2 tonnes.

The art of coal cutter designing is to make the most powerful possible machine within the most compact dimensions. Since the equipment's dimensions determine the mining parameters, saving inches is a primary objective at the design stage. This however produces a challenge to the production engineer due to the very complex nature of castings and operations.

The total output of units is approximately 1000 units/annum in nearly 30 varieties.

3.3 EVOLUTION OF A FLEXIBLE MANUFACTURING SYSTEM

In early days the major asset of the company was a cluster of conventional horizontal boring machines. Forty five horizontal borers working double shifts were required and the machining time for each casting was approximately 160 hours. Another 20 borers were required for other types of work. The company houses 42 borers and obtained the balance of machines from the other factories of the group or sub-contractors. The resulting lead time was approximately six months.

In parallel with advances in manufacturing technology, the company gradually acquired some NC and CNC machines. This battery of automated machines has halved the machining time and the lead time [Fig. 3.2]. More importantly the company also gained experience in the automation of production facilities and use of computers in managing them.

However, the company reckoned that further improvements were necessary to survive in a competitive international market. The major aims were to reduce the lead time further, improve product quality and to absorb design alternatives and new products with minimum re-tooling. At this stage, the company had two alternatives. Firstly, to re-equip the company with some more CNC borers. Certain drawbacks of this approach were recognized. The most complex casting needed 200-300 tools beyond the capacity of individual machines. And various mixes of products would necessitate considerable

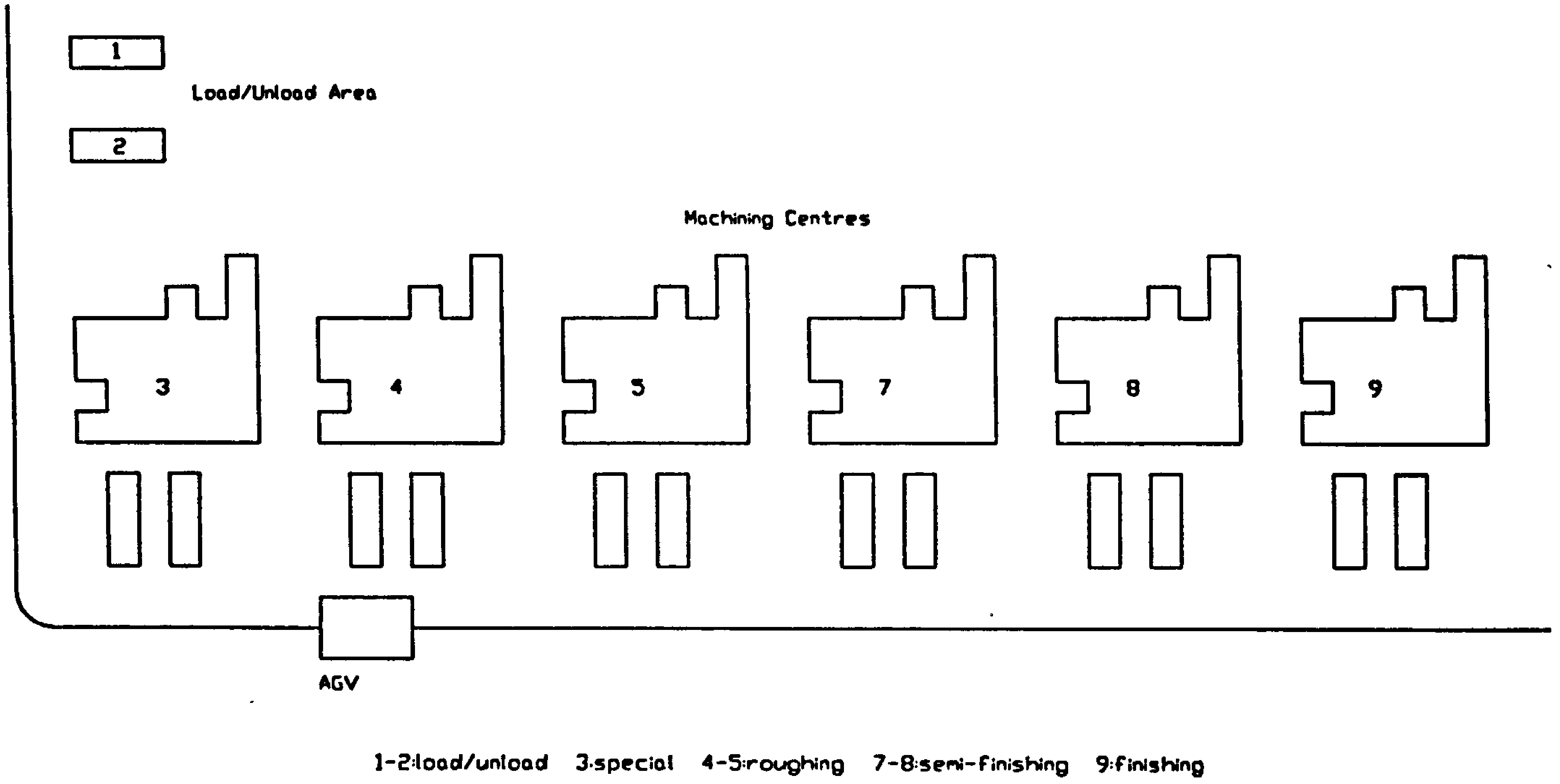


Figure 3.3 The Flexible Manufacturing System

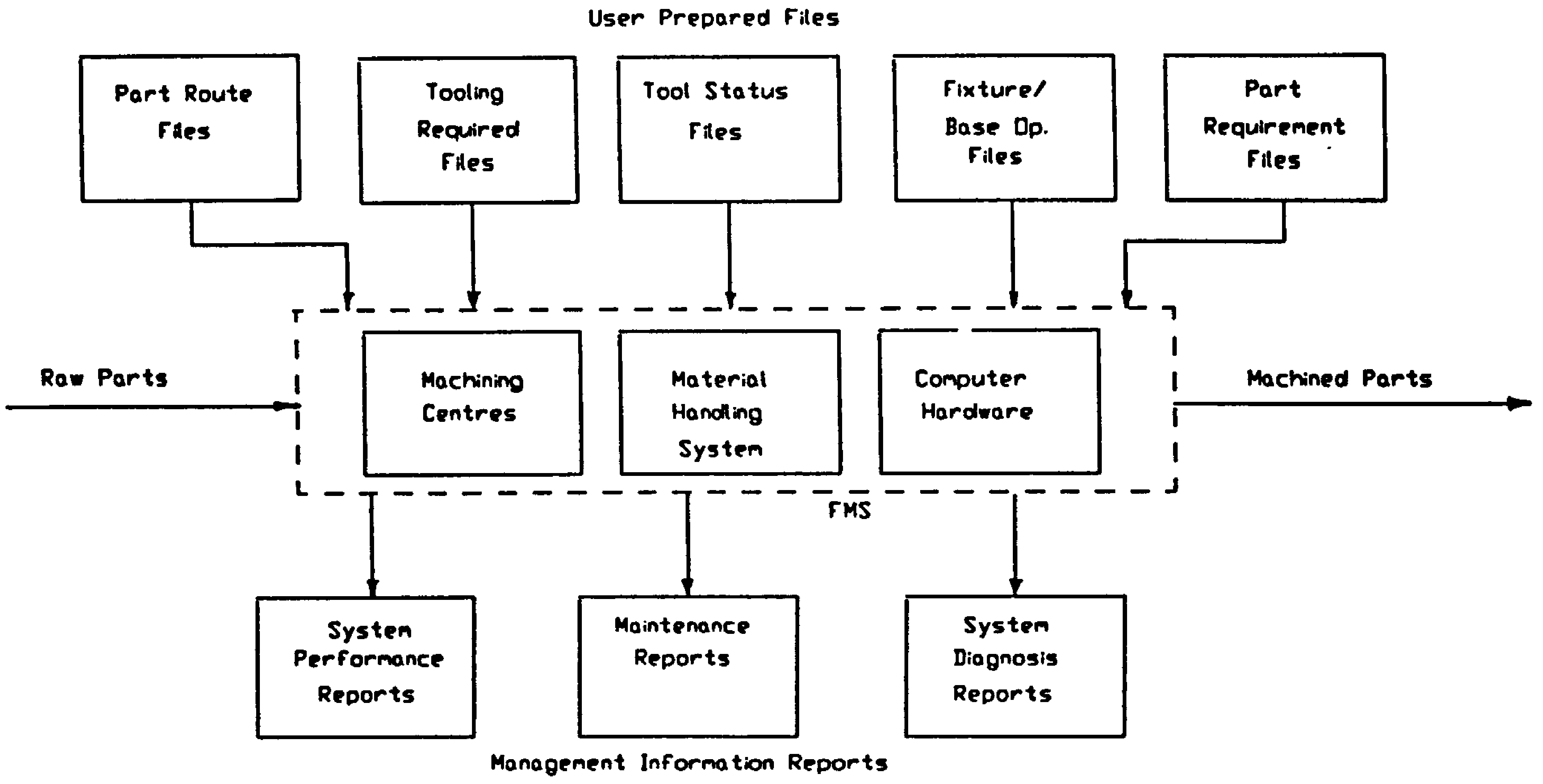


Figure 3.4 The Organization of Data Files in FMS

tool re-setting. The more radical solution was to acquire a FMS. By this time FMSs were coming on stream, particularly in USA and Japan.

Having recognized the advantages of flexible manufacture, a major program was launched to acquire an FMS. This has been now realized after several years of extensive design, planning, installation and commissioning.

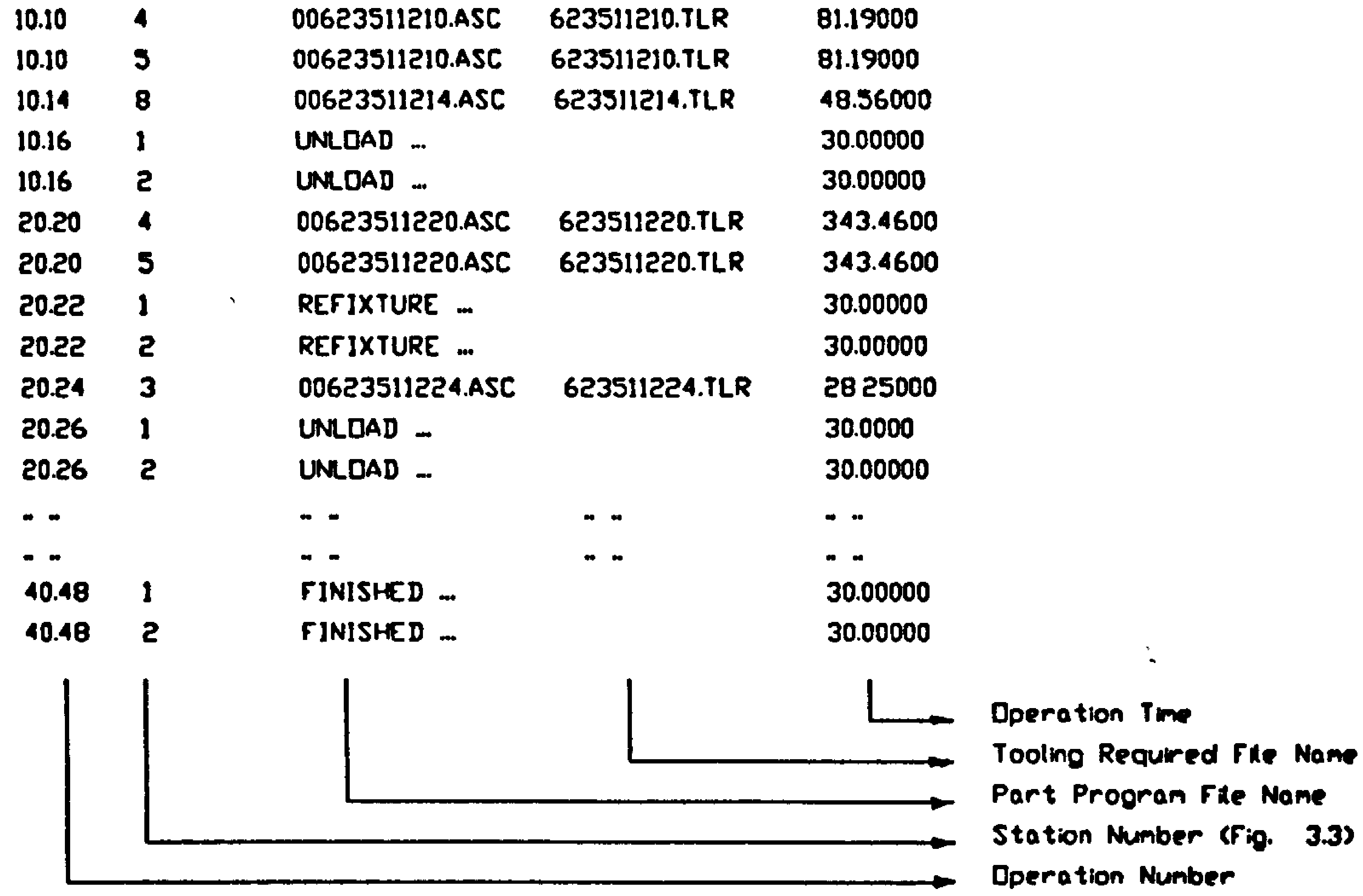
3.4 THE FLEXIBLE MANUFACTURING SYSTEM

The outcome of the massive investment of £7.5 million is shown in Figure 3.3. Stecke and Browne [1984] recognize this as a true FMS (FMS/AGV) in their classification of FMSs. The processing sub-system consists of 5 identical machining centres and one dedicated machining centre to handle special operations which require manual intervention and special tools. The five machining centres incorporate 100 capacity tool magazines. Each workstation has two local buffer positions. Two load/unload stations act as the interface between the system and outside. All pallet stands are served by an addressable AGV. The system is controlled by a PDP 11/44 mini-computer.

The executive computer is programmed to operate from data files prepared by the user (Figure 3.4) [Anderson Strathclyde Plc. 1982]. Prior to the discussion of operational aspects of this system, the structure of these data files are explained.

3.5 OPERATIONAL DATA FILES

In order to produce parts, the data file consisting of their processing characteristics and tool requirements etc, must be made available to the executive computer. For example, part route information is required to select the next workstation. The user can enter this data using the system editor. Optionally the data can be down loaded from a separate computer. The following is the brief discussion on the required files.



```
10.10   4   00623511210.ASC   623511210.TLR   81.19000
10.10   5   00623511210.ASC   623511210.TLR   81.19000
10.14   8   00623511214.ASC   623511214.TLR   48.56000
10.16   1   UNLOAD ..                         30.00000
10.16   2   UNLOAD ..                         30.00000
20.20   4   00623511220.ASC   623511220.TLR   343.4600
20.20   5   00623511220.ASC   623511220.TLR   343.4600
20.22   1   REFIXTURE ..                      30.00000
20.22   2   REFIXTURE ..                      30.00000
20.24   3   00623511224.ASC   623511224.TLR   28.25000
20.26   1   UNLOAD ..                         30.0000
20.26   2   UNLOAD ..                         30.00000
.. ..       .. ..             .. ..           .. ..
.. ..       .. ..             .. ..           .. ..
40.48   1   FINISHED ..                       30.00000
40.48   2   FINISHED ..                       30.00000
```

Figure 3.5 A Part Route File (Part no. 6235112)

3.5.1 Part Requirement File

The part requirement file is a list of part types and their required quantities. This information is basically used to select the next part type for loading. The default part selection strategy works on the following principle.

Step (1):

Calculate the following ratio for each part in the production requirement file;

$$\frac{\text{(No. of parts taken for production)}}{\text{(No. of parts required)}}$$

If none of the parts of a certain type has been released to the system, then the ratio becomes zero. If all part types have been taken for production, it value is one. For a given type this ratio varies linearly between 0 and 1.

Step (2):

Select the next part type with lowest value for the above ratio.

Step (3):

Find the correct fixture for the selected type. If the fixture not found, go to step (2).

The executive computer selects a part type for immediate loading based on the above algorithm and inform the load/unload station operator via the terminal.

3.5.2 Part Route Files

A part route file must exist for every part type which is to be produced. The part route file contains information relating to the path that the part takes through the FMS and various operations performed on it at workstations. Figure 3.5 shows the content of a typical part route file and the following discussion is based on it.

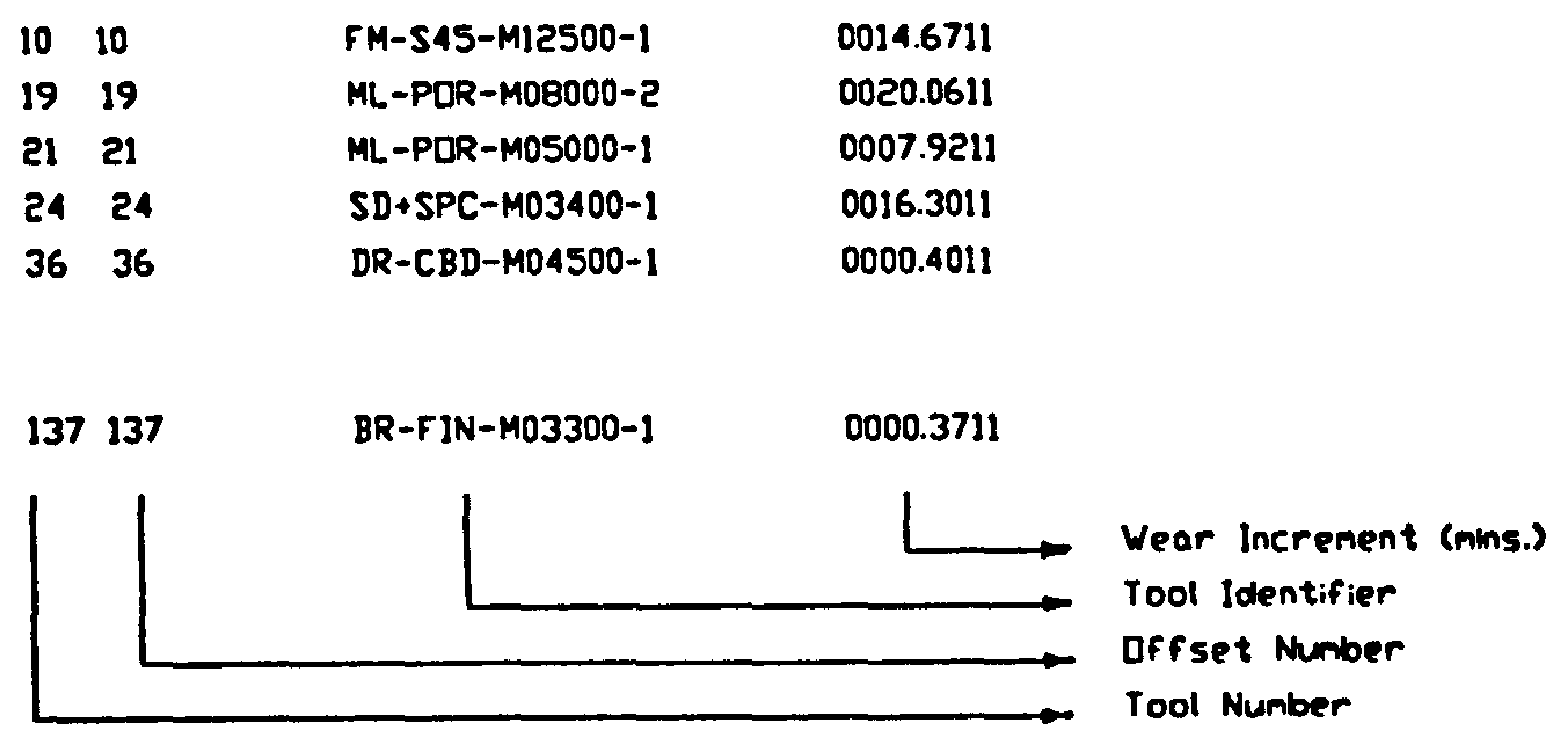
The operation number consists of two parts in the format of XX.YY. XX represents the fixture stage (this is known as base operation number) which can takes value 10,20,30 ... etc. To complete all operations on this part type require 4 different fixture settings (the last fixture stage number is 40). YY component is the operation sequence number. Next to the operation number is the station number which are shown in the figure 3.5. The next two data fields show the part program file name and tooling required file name. These two fields have some values for all workstations except for station number 3. This workstation does not have a tool magazine and tools are loaded manually. The last field in the record is the estimated processing time.

The corresponding part program file and tooling required files are down loaded from the executive computer to the CNC controller, before the processing cycle begins.

A set of alternative workstations for a given operation is shown by records with similar operation numbers but with different workstation number. This structure allows the user to change machine groups very easily. For the part type shown in Figure 3.5 there are two data records for operation 10.10, i.e it can be carried out at station 4 or 5.

3.5.3 Part Program files

These are ASCII or EIA files in CNC format containing the part program data for each operation. These part programs are written by NC programmers. One of the most difficult aspects in NC programming in this system is program proving. Although the company uses computer assisted techniques (off-line), complexity of these parts does not allow on-line program proving to be completely eliminated.



```
10   10          FM-S45-M12500-1          0014.6711
19   19          ML-POR-M08000-2          0020.0611
21   21          ML-POR-M05000-1          0007.9211
24   24          SD+SPC-M03400-1          0016.3011
36   36          DR-CBD-M04500-1          0000.4011

137 137          BR-FIN-M03300-1          0000.3711
```

Figure 3.6 A Tool Requirement File (623511210.TLR [Ref:- Fig. 3.5])

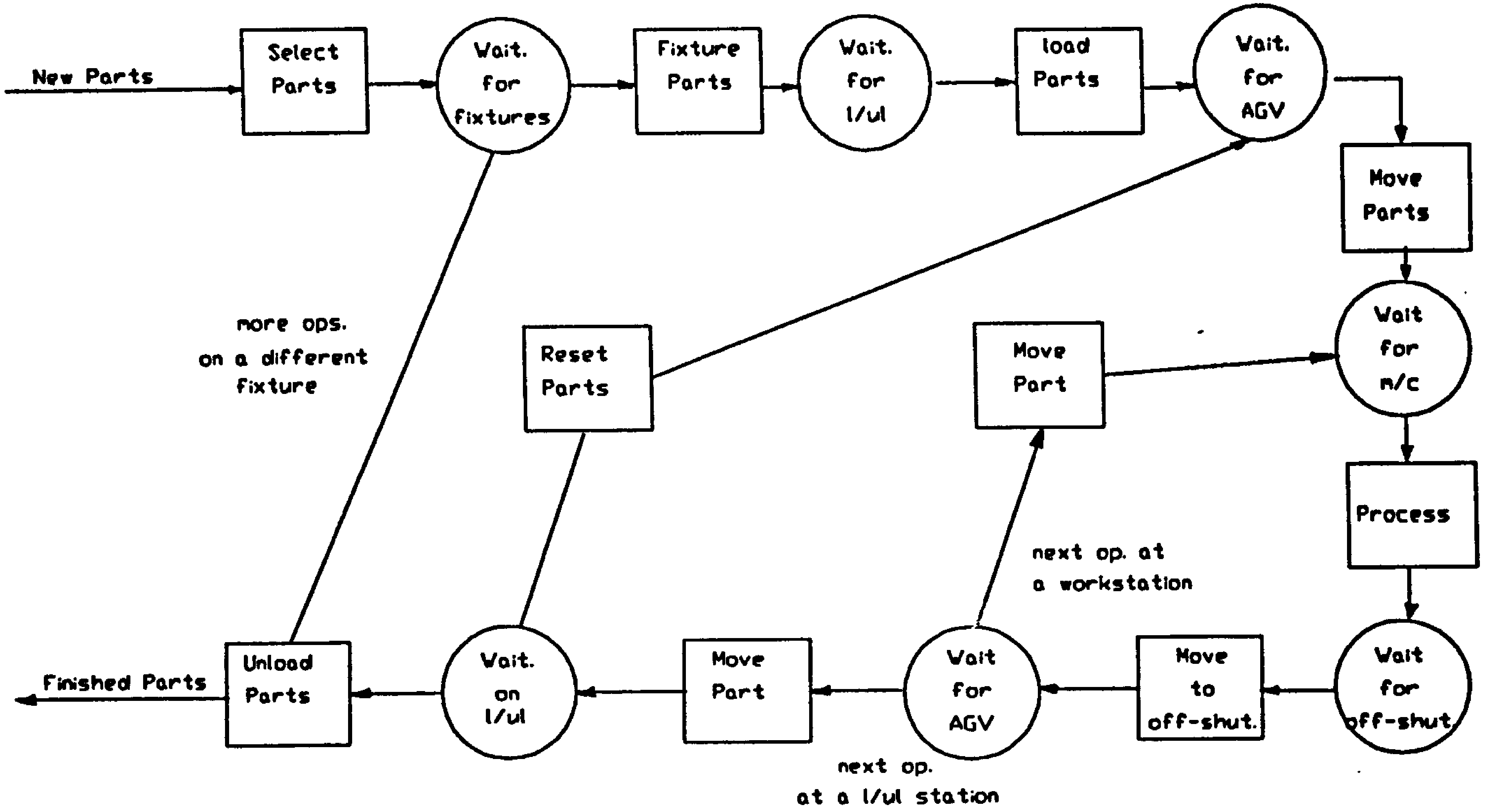


Figure 3.7 The Life Cycle of a Part Withn the FMS

3.5.4 Tooling Required Files

These are lists of tools required for each part program to be executed on the system (Figure 3.6). Each entry consists of the tool number as used in the part program, the tool identifier and the tool wear increments incurred by that tool.

3.5.5 Fixture/ Base Operation Data file

As explained above, parts require multiple fixture settings and each stage is denoted by its base operation number. One or more fixtures can be assigned to each base operation number. When a part is selected for immediate loading, its current base operation number is first checked and fixture numbers assigned to this base operation number are retrieved. If any of the suitable fixtures is available, then the part can be taken for immediate loading.

It is clear that an FMS can create a massive database and accurate, efficient data management is very essential. As most of the data are entered by the user, an intelligent, comprehensive data validation schema would be required to reduce possible human errors.

3.6 SYSTEM OPERATION

The executive computer controls and monitors all sub- systems of the FMS and makes strategic decisions regarding part selection, part routing, AGV assignments etc. All workstations and the material handling system are controlled by CNC or PC units, which allow automatic or manual operation.

The life cycle of a part begins with the directives from the executive computer which suggest the next part to be loaded [Figure 3.7]. However, in order to meet exceptional requirements, the user is allowed to override this decision. Having selected the next part to be released, it is fixtured at a separate bench. Since parts are heavy, a secondary material handling system (a crane) is used in all part handling at load/unload area.

When an empty pallet becomes available at a load/unload station, the fixtured part is palletized. This can take 15 - 30 minutes for a typical part. Once the part is properly placed, the operator will inform the executive, via the terminal, that the part has been loaded.

When the executive computer has decided to move the part, it passes the instructions to the material handling system. Once the command is delegated, the responsibility for implementing lies with the material handling system controller. The executive computer monitors the state but will not issue other commands until it is informed that the last command is complete. The executive computer will inform the system operator of any MHS errors. The system has pallet ID readers and the executive compares the data received from these with its own data. If these disagree, the executive will halt operations associated with the pallets involved.

When the part is successfully delivered to the target workstation, the part is transferred to the in-shuttle of the workstation and when it remains there until the machine is ready to accept it.

The executive is responsible for issuing instructions to the workstations to move parts between shuttles and the machine table. When parts are transferring on to the machine table, the program file, tooling offsets, and any other required data are transmitted. When these items are completed, the executive issues a cycle start command. The CNC is then responsible for executing the part program and informing the executive when it is complete. Should the machine halt, an operator is required to determine the cause, correct the problem and restart the machine. For most errors, a warning beacon will be activated at the machine to attract attention. Once the program complete notice is received by the executive, it will instruct the workstation to move the finished part to the off-shuttle. If the off-shuttle is blocked by another pallet, the part remains on the machine table, until the off-shuttle is cleared.

Once the part is moved to the off-shuttle, the executive will identify the next operation and assign a workstation. The part is then moved to the next station.

There are certain parts which require resetting on the same fixture between operations. These parts are delivered to the load/unload station at the appropriate stage and reorientation of parts are carried out at the load/unload station.

When all operations are complete on the current fixture, the part is unloaded and de-fixtured. If further operations on the part are left, it is loaded again when the required fixture becomes available and any other requirements are met. More information about the system operation can be found in [Capes 1984, Findlay 1982, McBean 1982].

3.7 TOOLING ASPECTS

In the above discussion, the tooling considerations were ignored to simplify the discussion. In the following the executive tasks related with tooling are explained.

The executive computer records the wear incurred by each tool during the execution of a part program. Estimates of tool wear are submitted in the tooling required file associated with the part program. When cycle start command is issued, the estimated wear values are added to the accumulated wear total of the machine tooling status file for each tool used by the part program. Also contained in the machine tooling status file are *Warning Point Limit* and *Maximum Wear Limit.* When a part is considered for routing to a machine, the executive compares the tooling required with the existing tooling. If all needed tools are present, the tool wear limits are then compared with current wear plus predicted wear. If the warning point limit is not exceeded, the part is assigned to the machine. If the warning point limit is exceeded, but not the maximum wear point, the part will be assigned to the machine and a tool wear warning is printed in the toolroom. If the maximum wear limit is exceeded, a tool wear warning is printed and the part will not be routed to the machine unless the operator requests this. If requested, the part will remain in the on-shuttle queue of the machine. It will not be transferred to the machine table until the executive is told that the tool has been replaced and the tool wear interlock is satisfied.

3.8 MANAGEMENT INFORMATION SYSTEMS

It is vital that in any manufacturing system performance is analysed and fed back to the management to take necessary actions to improve the system performance. The executive computer keeps a log of all significant events relating to workstations, material handling system, pallets and parts, tooling etc. These are stored on disc. The logs are used for generating MIS reports as described below;

a. MIS Reports

The MIS indicate part performance, pallet performance, operation performance, station utilization and time between operations. These reports are designed to be used to analyze and improve line performance.

b. Maintenance Scheduling

The executive has the capability of printing, on a scheduled basis, a list of preventive maintenance items. These items are a part of a data file (entered by the user) that describes the maintenance to be performed and the frequency that the maintenance must be performed.

c. System Diagnosis

The executive is used as an aid in problem diagnosis in several ways. Communications with the workstations use error checking and correction techniques and are monitored on a regular basis to ensurethat the links are intact. Workstation and MHS errors are reported to the executive and are logged for analysis later.

3.9 PART CHARACTERISTICS

The nature of operational problems of an FMS are partly attributed by part characteristics such as the number of operations per part, tool requirements etc. For example, in some FMSs, for a given part, all operations can be performed at a single workstation, therefore the routing problem does not arise. At the other extreme, there may be parts

Part type	Fixture Stage												TC
	1			2			3			4			
	F	C	R	F	C	R	F	C	R	F	C	R	
1	0	2	0	1	1	1	0	1	0	1	3	0	9
2	0	1	0	1	4	2	0	3	0	-	-	-	9
3	0	3	0	2	3	1	1	4	0	-	-	-	13
4	0	2	0	1	1	1	1	4	0	-	-	-	9
5	0	1	0	2	4	1	0	3	1	-	-	-	10
6	0	3	0	2	5	1	-	-	-	-	-	-	10
7	0	3	0	1	2	1	0	1	0	1	3	0	11
8	0	2	0	0	5	2	0	3	1	-	-	-	10
9	0	2	0	2	5	2	-	-	-	-	-	-	9
10	0	2	0	1	2	1	1	3	0	-	-	-	9
11	0	2	0	2	5	2	-	-	-	-	-	-	9
12	0	2	0	2	5	2	-	-	-	-	-	-	9

F = no. of operations at the special workstation (stn. no. 3)
C = no. of cutting operations (except at station 3)
R = no. of resetting operations (at load/unload stations)
TC = total number of cutting operations

Figure 3.8 The Distribution of No. of Operations per Part

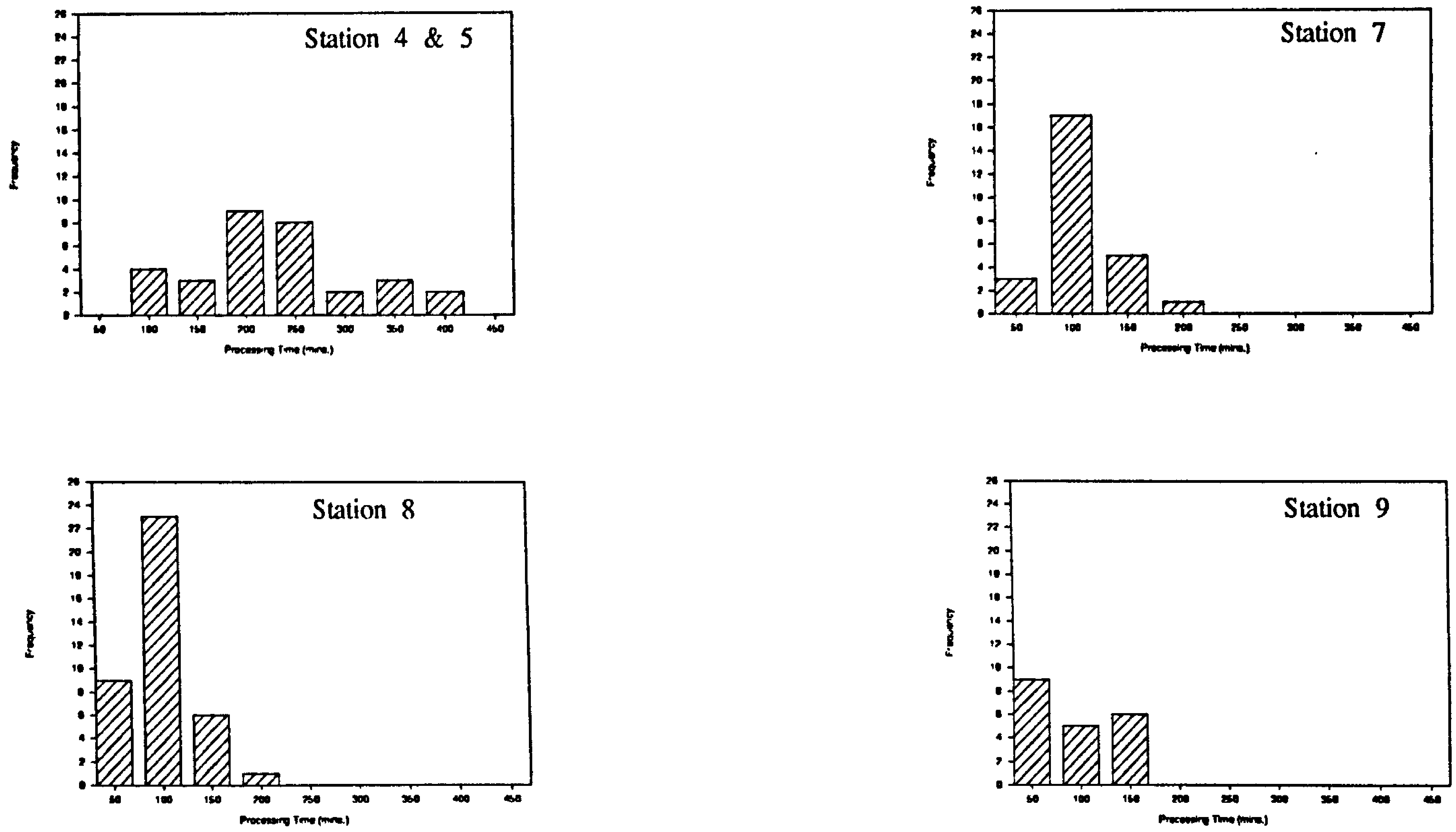


Figure 3.9 The Distribution of Processing Times

with a large number of operations and several fixture settings may be required. This would create more complex operational problems. In the following, the characteristics of parts of the system being studied are explained.

3.9.1 Number of Operations and Number of Fixture Settings

The distribution of operations per part is shown in Figure 3.8. The following conclusions were drawn from these data.

a. Operations at fixture stage no. 2 create more complex part routing patterns as most resetting operations on the same fixture are carried out at this stage (for resetting the part is delivered to load/unload station). These may create deadlocks in material flow at load/unload stations.

b. All parts require two or more separate fixture settings. If number of fixtures assigned to each stage are limited, parts will have to wait considerably long times for fixtures.

3.9.2 Processing Times

The distribution of operation times at workstations are shown in Figure 3.9 (data for station no. 3 are excluded from this discussion as these figures are affected by manual intervention). The following conclusions are evident from these data.

a. High machine utilization figures can be expected for workstations 4 and 5 as average processing times are relatively high.

b. The processing time range is very high (from 10 mins. to 432 mins.) and average waiting time for a given workstation may vary quite drastically.

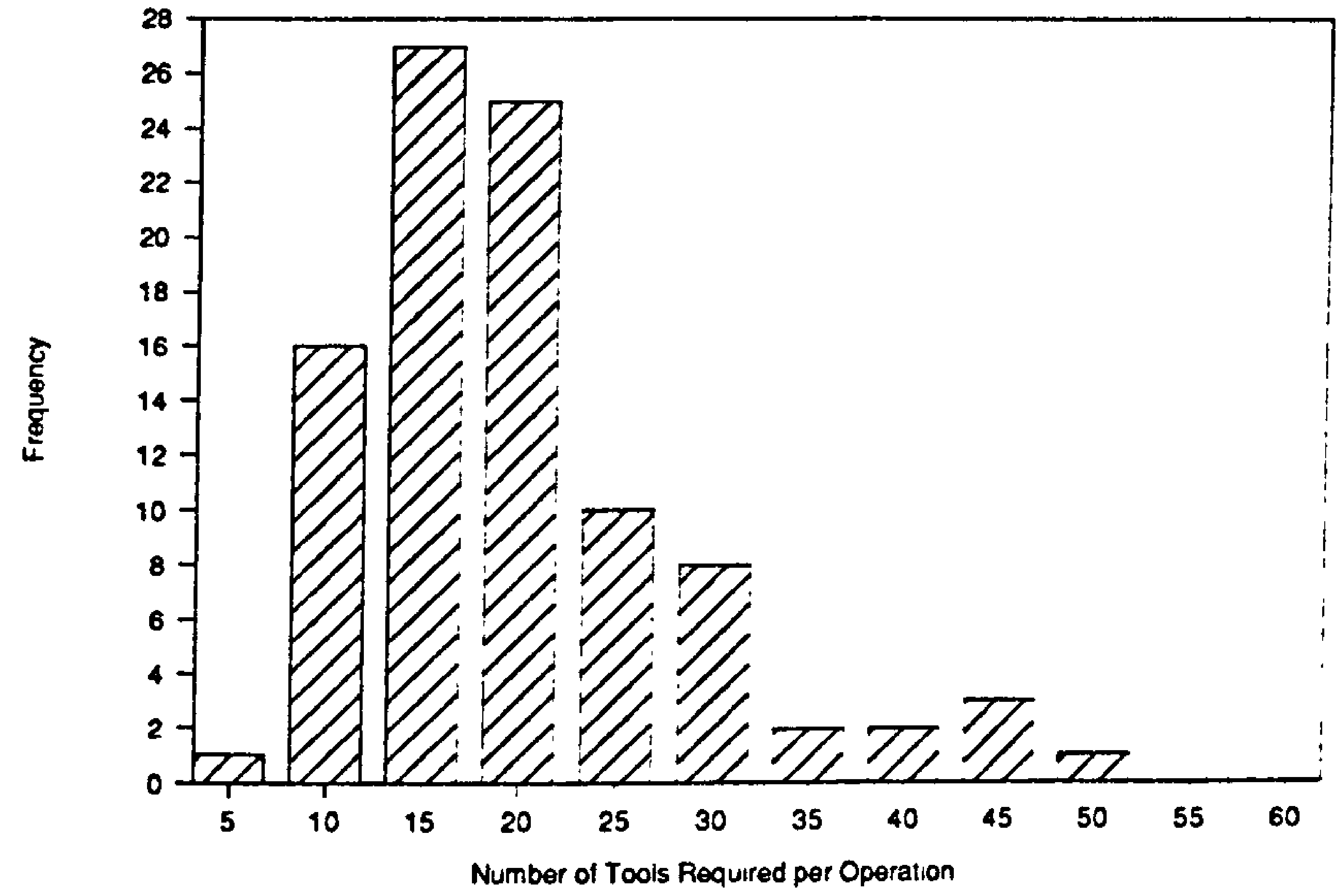


Figure 3.10 The Distribution of No. of Tools Required Per Operation

3.9.3 Tool Requirements

The distribution of the number of tools required per operation is shown in Figure 3.10 . On average nearly 18 tools are required to complete an operation. If none of tools required for given product mix can be loaded, in the worst case nearly 50 tools have to be exchanged.

3.10 BENEFITS SO FAR

The major achievements are reduced lead times and inventory. Moving from conventional to CNC achieved a 50% reduction in lead times. A further 50% improvement has been realized through flexible manufacture.

The reductions in inventory has released £12 M of working capital which is almost enough to buy two FMSs of the same size.

The quality of products has improved. The human element has been reduced and manufacturing times are more consistent. The company argues that the financial saving were sufficient to make the project viable and take no account of other hidden benefits.

3.11 POTENTIAL PROBLEM AREAS

As explained in chapter 1 most of the production planning problem are left to the user. Particularly in this system, these problems are severely constrained by tooling and fixtures. The following are recognized as major operational problems.

a. Part Selection for Immediate Processing.

Although the executive computer suggests next part to be loaded, its computational logic ignores the most important constraint, tooling. Thus a more comprehensive operational strategy must be devised to solve this problem.

b. Operation Assignment Problem

At present the company employs a static machine grouping configuration, i.e. each machine has been assigned the same set of operations, irrespective of changes in product mix. This fixed operation strategy causes under-utilization of some workstations. It is anticipated that a dynamic machine grouping strategy, which depends on the current product mix, would improve the system performance.

Apart from these two major problem areas, it is necessary to develop strategies to react to random failures of system components. Further practical problems associated with this system is discussed in [Perera and Carrie 1987(a)].

3.12 CONCLUSION

Although the system architecture is simple (i.e. a linear AGV layout and six identical workstations)the production planning and control problems are very complex. They are highly constrained by tooling and fixtures.

This system includes all essential features of a true FMS. Furthermore, it has a most complicated routing sequence (multi-fixture, multi operations on each fixture). Its data can be used to test the effectiveness of any operational strategies developed during this research.

CHAPTER 4

MODELLING FLEXIBLE MANUFACTURING SYSTEMS

4.1 INTRODUCTION

The traditional approach of extrapolating past experience in order to predict the performance of a manufacturing facility has been found to be quite inadequate for automated manufacturing systems. The need to identify the key factors which influence the system performance has led to the development of simulation systems and analytical models which can assist system designers and users of highly automated systems. In this chapter basic modelling approaches are reviewed and their application domains and limitations are discussed. The factors which influenced the selection of a modelling approach for the FMS under investigation are explained.

4.2 DIFFERENCES BETWEEN JOB SHOPS AND FLEXIBLE MANUFACTURING SYSTEMS

In job shops historical data in conjunction with experience about the system are widely used to predict the system performance. For example, an experienced production supervisor can estimate the lead time for a given job quite accurately. However this type of perfunctory approach cannot be extended to embrace FMSs due to great differences that exist between informal job shops and formal flexible manufacturing systems;

a. Highly Integrated Components

In job shops, production facilities are used as stand alone resources. Workstations are individually loaded to match pre- determined work requirements. But in FMS, all production resources are linked and operated as a system, therefore the level of interaction between sub-systems is very high.

b. Large Number of Candidate Decisions

In job shops, operational problems are solved at local level, therefore one cannot expect a large number of alternative solutions. But in contrast, most of the decisions related to operational problem of FMS are taken at the system level and the number of alternatives may be enormous due to the variety of flexibilities built into the system. In general, the number of alternatives rises exponentially with the level of flexibility.

c. Limited Resources due to Efficiency Requirements

In job shops a battery of machines is used to manufacture parts and the utilization of resources is low. One of the major objectives of FMS is to reach higher utilization while retaining the flexibility of job shops. Thus the amount of available resources available to achieve higher utilization through flexible manufacture is limited.

d. Multiple Objectives

Although achieving multiple objectives is desirable, in job shops the number of objectives are narrowed down to a few such as due date achievement, work load balancing etc. In FMS, however, a proper balance of multiple objectives must be struck to create a financially viable proposition.

e. Limited Slack in Decision Alternation

Since FMS is operated as a system, once a decision is taken and implemented, it is difficult to change it at an intermediate stage. For example, when a workpiece is released to the system, it would not be taken out of the system, until all operations are completed. Such restrictions do not prevail in job shops.

f. Less Manual Intervention

There are few humans in the system to correct or modify operations due to unexpected changes in conditions. In fact, even an experienced supervisor or manager would have difficulty in perceiving all the consequences of any given decision in an FMS.

The modelling of a manufacturing system is not a new concept. However in job shops, modelling may involve a large number of probabilistic variables and an enormous number of experiments need to be carried out to filter effects of these random variations. Thus in many occasions they do not provide accurate results.

On the other hand FMS create an ideal environment for near perfect modelling, the logic which governs the system is clearly defined in advance and most of the parameters are deterministic. But the great challenge to the model builder is that complex logic rules need to be built into the system to mimic the integration effects.

4.3 A REVIEW OF EVALUATIVE MODELS

Suri [1985] suggests that models can be classified according to their use;

a. Generative (prescriptive) models

These models are invoked by a set of objectives and can provide the best solution or a set of good solutions. They are generally based on mathematical models such as linear programming models. Although they can resolve complex problems quickly, they are quite inflexible i.e. a great modification of the model may be required in order to apply the same model to a different system.

b. Evaluative (descriptive) models

These models can evaluate a given set of decisions. Although models are flexible, finding good decisions may be time consuming.

Though generative models are very effective in solving complex problems, their inability to absorb variations in operating complexities hinders widespread application in industry. Nor do they provide an opportunity to the decision maker to understand the system behaviour. In contrast, evaluative models are more of a tool to help the decision maker to improve his or her intuition about the system; they provide insight rather than decisions. Therefore it has been recognized that that evaluative models will play a major role in design, planning and operation of FMS.

The following classes of models are widely used in analyzing FMSs. For each approach, the underlying technique, application domain, advantages and disadvantages are discussed. Detailed information about evaluative models can be found in the literature [Wilhelm et al. 1983, O'Grady and Menon 1985, Buzzacot 1985, Glenney and Mackulal 1985 Choobineh and Suri 1986, Gershwin et al. 1986]

4.3.1 Static Allocation Models

This is the simplest approach among the all modelling techniques. Basically the principle of superimposition is used to estimate the system performance. In the case of manufacturing system modelling, given the production requirements, the total amount of allocated loads are computed by adding up work loads due to individual orders. For example, the following formula can be used to estimate machine utilization.

$$\text{Workstation Utilization} = \frac{\Sigma\ (\text{processingtime})\text{X}(\text{quantity})}{\text{Workstation available time}}$$

This technique is used in SPAR module of the MAST simulation package [CMS Research Inc. 1988].

The major drawback is that the model ignores the dynamic interactions of the system. In more complex systems, it can be much too coarse a tool and seriously overestimate the system performance, leading to unexpected results when more comprehensive models are used. However, it can detect inferior alternatives quickly, thus avoiding unnecessary detailed simulation of infeasible solutions.

4.3.2 Queuing Network Models

In this modelling perspective, the manufacturing system is viewed as a network of workstations, through which parts circulate and receive service. Each workstation is composed of a queue and set of servers.

Jackson [1957] initiated research on queuing models by defining general characteristics of a network model and subsequently he extended original work to a broader class of networks [1963]. The resulting model was applied to investigate various aspects of job shops. Based on concepts provided by Gordon and Newell [1967], Piosner and Bernhotz [1968] and computational algorithm provided by Buzen [1973], Solberg [1977] was among the first to formulate a queuing network model CANQ of FMS type facilities. The basic assumptions of the model are;

a. The total number of jobs in the system is fixed.

b. All stations with FCFS queue discipline; the service time distribution is exponential.

c. All stations have local storage large enough to accommodate all jobs (i.e. no blockages).

d. Machines are always available for processing jobs.

Solberg's CANQ package [Solberg 1980] has been widely used for preliminary design of FMS and to study some of the issues in production planning and control [Buzacott and Shanthikumar, 1980, Stecke and Solberg 1981, Stecke 1983, Stecke and Solberg 1985]. These models have been further enhanced to incorporate some realistic features of FMS such as limited buffer storage and system blockages [Yao and Buzacot 1986, Suri and Deihl 1986, Dallery 1986, Yao and Buzacot 1987].

More recently, Suri and others [Suri et al. 1986] developed the MANUPLAN package based on queuing network modelling.

The performance measures derived from these models can have a large number of terms. One group of computational algorithms is concerned with developing methods of efficiently evaluating these formulae. The best known of these approaches is mean variance analysis (MVA) [Reiser and Lavenbey 1980, Suri and Hilderbrant 1984]. Applications of this technique can be found in [Shalev- oren et al. 1985, Cavallie and Dubois 1982]. Another related technique is based on operational analysis [Suri 1981, Mainone et al.1985]

Despite these developments, the following features of FMS which may not be represented in the queuing network model include;

a. random arrivals of orders

b. time dependent routing and scheduling decisions

c. central storage

d. interference between transportation facilities.

4.3.3 Simulation

Within the context of manufacturing system modelling, simulation refers specially to computer based discrete event simulation. This has been established as the most powerful and versatile technique and it is widely used by system designers, users and researchers etc.. As far as the simulation of manufacturing systems are concerned, three different scenarios exist. In the following these alternative approaches are discussed. More detailed information can be found in [Talavage 1981, Bevans 1982, Pidd 1984, Glenney and Mackulal 1985, Rahnajet 1986, Carrie 1984, Carrie 1988]

a. Simulation Languages

This is the most popular option among these alternatives. The model of the system is coded in simulation language syntax by the user. Some of the most widely known languages are GPSS [Kahan 1981, Schriber 1985], ECSL [Clemenston 1983], SIMAN [Pedgen 1988] SIMSCRIPT [Markowitz et al. 1963], and RESQ [Chow et al. 1985] etc. Most of them now provide facilities for graphical animation. Some of them have special features to speed up the modelling process (eg. SIMAN [Johnson and Poorte 1988], IMMS [Engelke et al. 1985]).

Though simulation languages are easier to learn and apply than general purpose programming languages (e.g. FORTRAN, PASCAL), yet someone without simulation background may find it difficult. A novice can be easily introduced to simulation with the assistance of a program generator [Paul and Doukidis 1986]. These user-friendly, in some cases intelligent, programs act as a pre-processor which build up the model, through user interaction. A popular code generator is CAPS (for ECSL).

b. Simulation Packages

These are generally made up of a library of program routines for the essential features of any simulation project, such as time advancing, statistics collection and entity handling etc. The logical aspects of the system is coded by the user, in the associated programming language. The GASP package (associated programming language FORTRAN) [Pritsker 1975] is a well known system. Another notable package is SIMON [Mathewson 1984] which is supported by a program generator, DRAFT [Mathewson 1985].

c. Generic Simulators

These packages usually require no knowledge of specialist languages on the part of the model builder. A simulator is an already validated model which is driven by a data file containing system characteristics, such as number of workstations, transport layout, and decision rules etc. Well known simulators are MAST [Lenz 1983, CMS Research Inc. 1988] an enhanced version of GCMS [Lenz and Talavage 1977] and MAP/1 [Roston 1985]. Another simulator KOSMO [Wakai et al. 1986] has been developed in Japan.

Comparison of general features of these alternatives are discussed in [Rahnajet 1986, Mills 1985] . Simulation can used to analyse variety of problems, and some interesting applications can be found in [Makin 1986, Lenz 1986].

4.3.4 Perturbation Analysis (PA)

This relatively new approach was invented to solve some design problems of production lines. Perturbation Analysis works by observing a single experiment on the system, called the Nominal Experiment. It can be a simulation experiment or a series of observations of the system. By doing some minor additional calculations, while the system is being observed, PA can predict the system behaviour due to minute perturbations in the system. The important point is that it is not necessary to re-run simulation as all the predictions are obtained from one setting. More details and application of this can be found in [Suri and Dillie 1984, Ho 1985].

4.4 A MODELLING TECHNIQUE FOR THE SELECTED FMS TYPE

The selection of a modelling technique for a given system is generally regarded as a difficult task, as each technique has its own merits. In the context of this research work, the modelling technique must possess :-

a. The ability to model essential features of FMS such as system blockages, complex decision rules, etc.

b. The ability to model constraints imposed by production ancillaries, such as fixtures, pallets etc.

c. The ability to predict system performance in transient periods.

d. The ability to model tool flow within the system.

As static allocation models ignore dynamic interactions between sub-systems, these would not be appropriate to solve problems at operational level.

Although queuing network models can capture some realistic features of FMS. They have little application potential in the type of FMS under investigation and cannot meet the above pre- conditions (a),(c),(d).

Though Perturbation Analysis appears to be a promising technique, it cannot however, deal with extensive disturbances of system parameters and tooling aspects of FMS.

Thus it is clear from the above discussion that only simulation can capture the essential complexities of the selected FMS type. Simulation is the only approach which can model tool flow.

4.5 SIMULATION OF PART FLOW WITHIN A FLEXIBLE MANUFACTURING SYSTEM

In most FMSs, particularly in high tool variety environment, the tool flow within the system is governed by the part flow. Therefore it is absolutely necessary to get the simulation model of the part flow correct, in the first place. In the following section various simulation approaches used, problems encountered and remedial actions adopted are described referring to the simulation of the FMS mentioned in Chapter 3.

4.5.1 On the Accuracy of the Control Logic

The most difficult task in any FMS simulation exercise is to decide the proper control logic for sub-systems and they can vary from one system to another. This is one of the major factors which hinders the development of an universal simulator for FMS. If an existing system is studied, the control logic may be available to the modeller. But in some cases vendors of FMS do not provide details of operating policies, even surprisingly to the buyer. Perhaps vendors would not like to see an outsider revealing some inefficiencies of control software which are not generally bug free. One such deficiency in the control logic of the system under investigation was reported by Carrie [1983(a)], in association with system blockages. Thus it is essential to check the completeness of the control logic and its ability to respond to variations in system parameters such as part routing data [Perera 1988(b)].

4.5.2 ECSL-based Model and Its Limitations

As an outcome of a previous research programme [Adhami 1983], a ECSL based simulation model was available at the beginning of this research work. A broad knowledge about the system behaviour was acquired by executing the model under various test environments. Observations of previous researchers can be found in [Carrie et al. 1983(b)].

During these preliminary simulation exercises, the following major observations were made.

a. Excessive number of pallet movements

As stated in the Chapter 3, one of the special feature of this system is that empty pallets are circulated within the system. Consequently, the control software was enhanced to govern empty pallet movements. However in some experiments excessive number of pallets movements were noted without any apparent reason.

b. Material flow deadlock

Previous researchers incorporated a logic module to handle possible blockages between two workstations. But with some changes in part route data, unexpectedly, blockages re-appeared.

c. Long Waiting Times

A detailed analysis of the components of queuing times indicated that waiting time between fixture stages are quite high. It was anticipated that waiting times can be reduced by adopting a proper priority scheme for partially processed parts.

The solution strategies for the first two problems were developed with the assistance of a graphical post-processor. The design and development of the graphical post-processor and the way it was used to redefine the control logic is explained in detail in chapter 6.

One of the objectives of this preliminary work was to assess the suitability of ECSL for tool flow simulation. It was rejected on the following reasons:

a. Limited Data File Handling

As stated in chapter 8 a massive database is required for the tooling system. The efficient data file handling must be an essential feature. However in ECSL, the number of input files is limited to one and it is difficult to include all tool data in a single file. This drawback impairs the power of the ECSL language.

b. Long Execution Time

The execution speed of the model is quite slow and it took nearly 30 minutes to simulate a period of two weeks (average output 10 parts/week). Undoubtedly, the inclusion of tools in the model would worsen the situation.

Having identified these major constraints of ECSL an alternative modelling approach was sought. It was expected that GCMS, a generic FMS simulator could be extended to mimic tool flow.

4.5.3 GCMS and Its Limitations

This data driven simulator has been constructed with the assistance of GASP routines [Lenz and Talavage 1977]. The modeller prepares the input file which contains the information about the system such as number of workstations, layout, material handling system, part characteristics and the types of decision rules.

Several input data files were prepared with varying degrees of complexity, but none of the experiments produced any satisfactory results i.e. the execution was terminated at an intermediate stage. This in fact contradicted the GCMS author's claim (a generic simulator) and it was decided to study the model in detail to identify its limitations. The following are recognized as major general constraints:

a. Inability to Handle System Blockages

Although the simulator is equipped with a comprehensive logic to handle possible collisions of transporters, it cannot handle dead-locks in the part flow.

b. Identical Part Handling Logic for load/unload stations and Workstations

This simulator uses the same logic to handle parts at load/unload stations and workstation. In many instances, separate logic is required at load/unload stations. For example, if a part is released to the system, before the target station becomes available, the probability of blockage is increased. This can be averted by adopting a different logic at load/unload station.

c. Inability to Model Fixture Constraints

The constraints imposed by the limited number of fixtures and multi-stage fixturing cannot be modelled. The part selection logic could be modified to capture fixture constraints, but the simulation run terminated due to blockages.

Furthermore, with reference to the system under investigation, empty pallets cannot be modelled.

Although the authors claim that it is quite easy to construct user-written module to handle individual cases, generally a good knowledge about the internal working of the package and associated program variables is vital.

4.6 CONCLUSION

It is clear that a large number of simulation systems are available for manufacturing system simulation. However, the selection of an appropriate simulation system is not straightforward. It can be influenced by the complexity of the logic of the system being modelled, cost, programming effort required, interfacing capability etc. As different packages score different points for these factors, the selection of a simulation system is quite difficult. This could be a candidate problem area for expert system application.

Having failed to adopt a simulation language (ECSL) and a generic simulator (GCMS) to model the system under investigation, other alternative approach, a simulation package was considered next.

CHAPTER 5

SIMULATION OF A PART FLOW WITHIN A FLEXIBLE MANUFACTURING SYSTEM

5.1 INTRODUCTION

One of the major objectives of this research programme is to develop a simulation model which can mimic the tool flow within a FMS and hence to study tool management systems. Generally, a flow of parts through the system triggers the tool flow. Thus it is essential to have a accurate model for part flow, in first place.

As pointed out in the previous chapter, certain constraints imposed by existing modelling systems (GCMS and ECSL) would not allow the part flow model to be extended to capture tooling aspects of the system.

In this chapter, the selection of the GASP as an alternative modelling approach is justified. The design, implementation and validation of the model are presented in detail.

5.2 AN ALTERNATIVE MODELLING APPROACH

Having failed to use existing modelling systems for tool flow modelling, the GASP simulation package was considered next.

This package essentially provide a library of basic program routines (coded in FORTRAN) required for any simulation exercise, including time updating routine, statistics collection routines, entity handling routines, etc. The model builder has to identify all possible events that can take place within the system and their relationships to form event links which sustain the dynamic nature of the simulation model (i.e. occurrence of one event leads to another event). Then program routines corresponding to these events are coded in FORTRAN, compiled and linked to the GASP routine library to generate the executable form of the program.

As a high level general purpose language (FORTRAN) is used, this modelling system provides higher flexibility to the model builder. There are certain drawbacks in this approach;

a. In the case of complex manufacturing systems, it is quite difficult to identify event links as integration effects are very high. This is however, one of the major drawbacks in any event based simulation system.

b. A good knowledge of FORTRAN is essential.

c. Although the GASP system includes some routines to detect possible logical errors in the model, it is generally a laborious task.

Despite these obstacles, GASP simulation package was selected since it does not constrain data file handling which is vital in tool flow simulation. Having studied the package and its modelling methodology, it was realized that the above difficulties could be overcome to some extent.

5.3 SIMPLIFICATION OF GASP ROUTINES

The standard GASP package is written in FORTRAN IV and consists of a large number of program routines. It was decided to modify the package, for variety of reasons :-

a. The GASP system can cater for both discrete event and continious simulation models. However, modelling of manufacturing systems requires only the discrete event components. Thus by eliminating program statements related to continuous modelling components, the speed of the simulation can be improved and the model size can be reduced.

b. In a typical simulation exercise of this nature, the modeller does not use all GASP routines. The performance of the model can be improved if these unnecessary routines are eliminated.

Thus all essential GASP routines were studied and re-written in FORTRTAN 77. In the following, these modified routines are explained [Pritsker 1975] (standard routine name is given within brackets).

SUBROUTINE X_GASP [GASP]

This is the heart of the GASP modelling system. The dynamism of the model is sustained by this routine until the simulation end time is reached and/or the system runs out of scheduled events. This routine selects the next scheduled event, updates the simulation clock and calls the corresponding event routines to continue the simulation.

SUBROUTINE X_QUEU [FILEM]

This is one of the most complex routines and is used to place entities in appropriate queues. In the case of event list updating, it also sets the next event time. It embodies four standard queue discipline rules such as FIFO, LIFO etc.

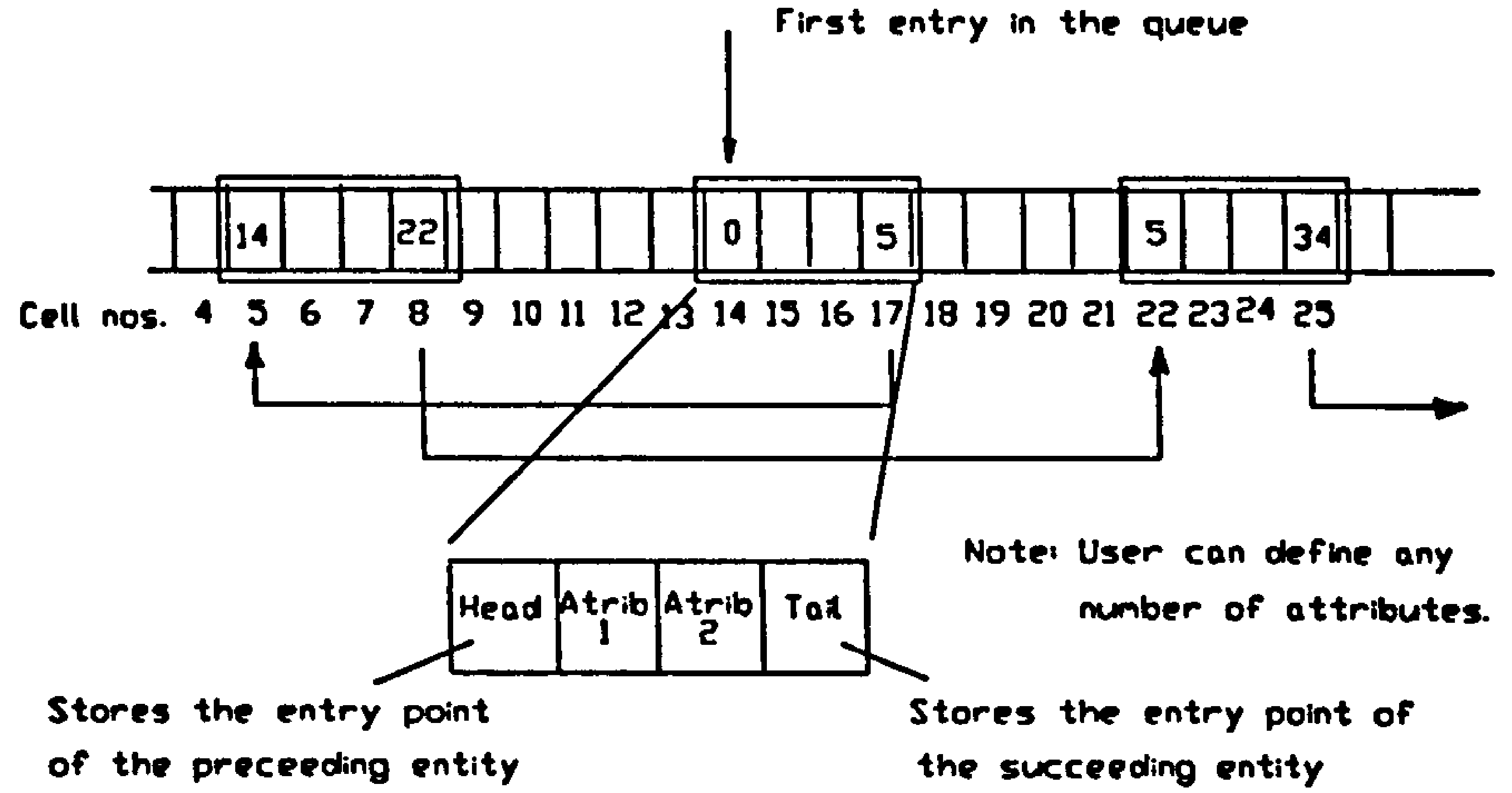
SUBROUTINE X_RMOV [RMOVE]

This routine removes a given entity from a defined queue.

FUNCTION X_FIND [FIND]

The corresponding standard GASP subroutine was tailored to meet requirements in manufacturing system modelling. This routine checks the existence of a defined workstation in a given queue. If the workstation exists its location in the queue is returned by the function value.

This exercise provided an opportunity to understand the internal workings of the GASP system and as a result, a more efficient simulator was delivered at the end.

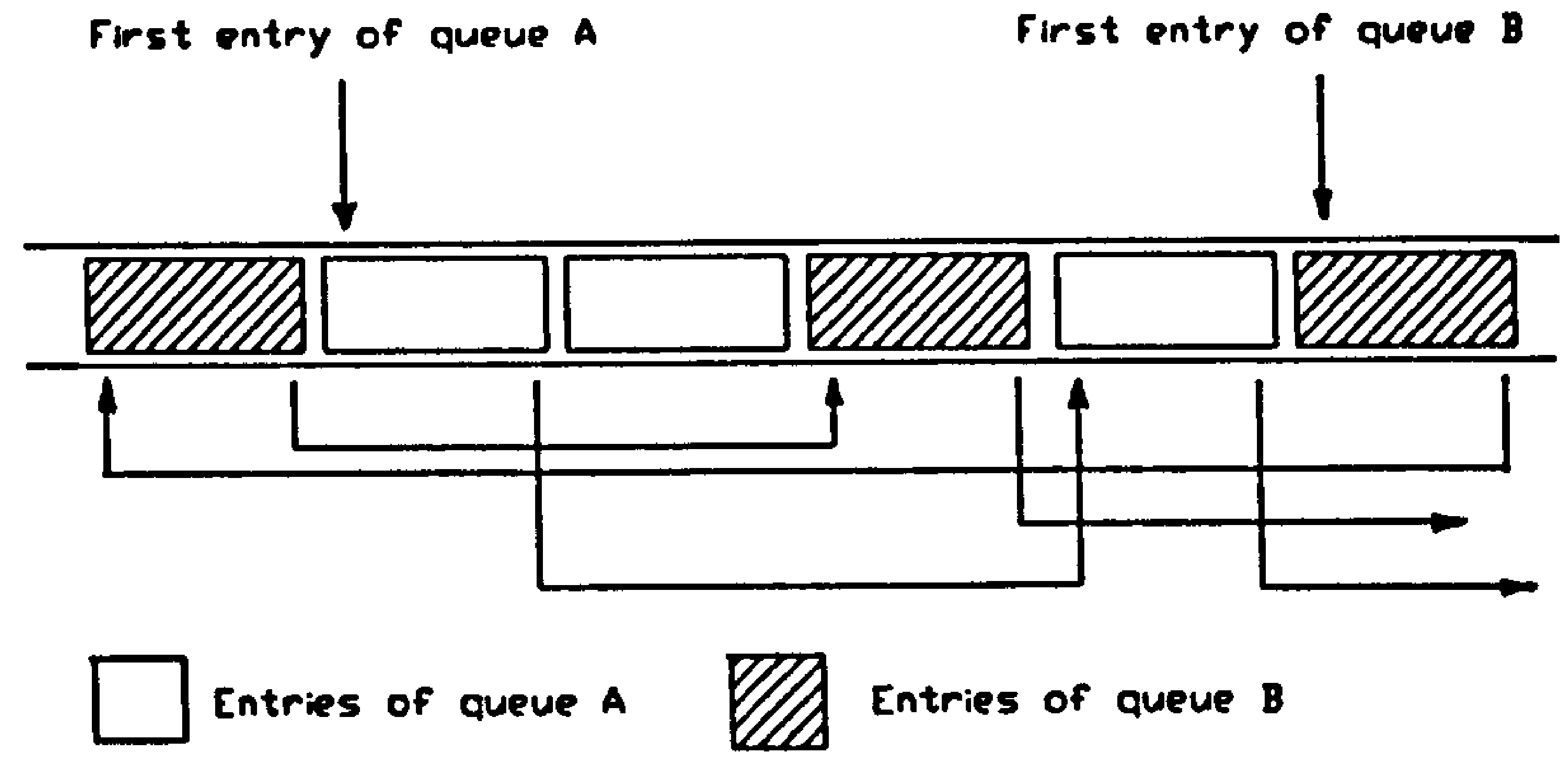


Note: User can define any number of attributes.

Stores the entry point of the preceeding entity

Stores the entry point of the succeeding entity

Figure 5.1 A Set of Entities in a Queue



For each queue the following parameters are defined;

- the number of entities in the queue
- the entry point of the first entity
- the entry point of the last entity
- ranking attribute and ranking discipline

Figure 5.2 Entries of Multiple Queues

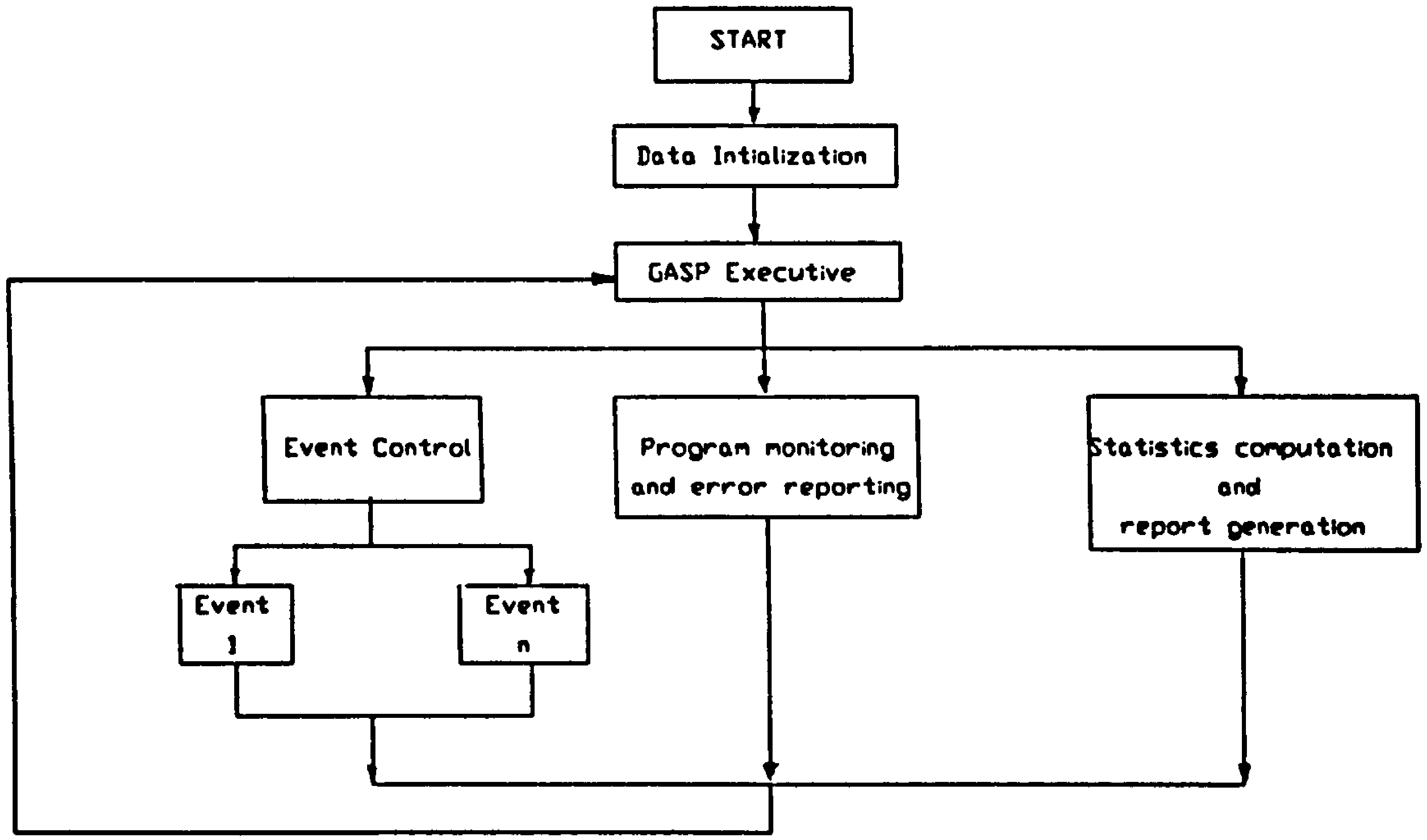


Figure 5.3 Main Functions of GASP Simulation System

5.4 THE GASP SIMULATION METHODOLOGY (DISCRETE EVENT SIMULATION ONLY)

In the GASP modelling environment, the system being modelled is represented by entities, events and a system of queues. Entities can have one or more attributes. Firstly, the modeller must develop a system of queues to accommodate entities which move through the system. The current state of the system is depicted by the content of queues and values of attributes. Then as explained above event links are established.

The most interesting features of the GASP system are event execution and entity handling. In the system of queues described earlier, the queue number one is dedicated to store scheduled events (events generated by execution of previous events) and any number of further queues can be defined by modeller.

All these queue entries are stored in a single array with real and integer data read/write facility (this is achieved in FORTRAN by using EQUIVALENCE statement). Entities of a given queue are linked through a system of pointers (Figures 5.1 and 5.2). These pointers are updated when entities are added to the queue or are taken out of the queue.

The operation of the GASP system can be described as follows. First all system variables are initialized and first event(s) is(are) scheduled. These events are stored in the queue number one (scheduled event list). From this point, the execution of events is handed over to the GASP executive routine (X_GASP). When the next event time is reached, the corresponding event is removed from the event list and passes it over to the event executor (X_EVNT), which in turn calls the associated subroutine to update the system state. At the same time termination of this event triggers one or more further events. This cycle of executing events continues until simulation end time is reached and/or event list run out of events (Figure 5.3).

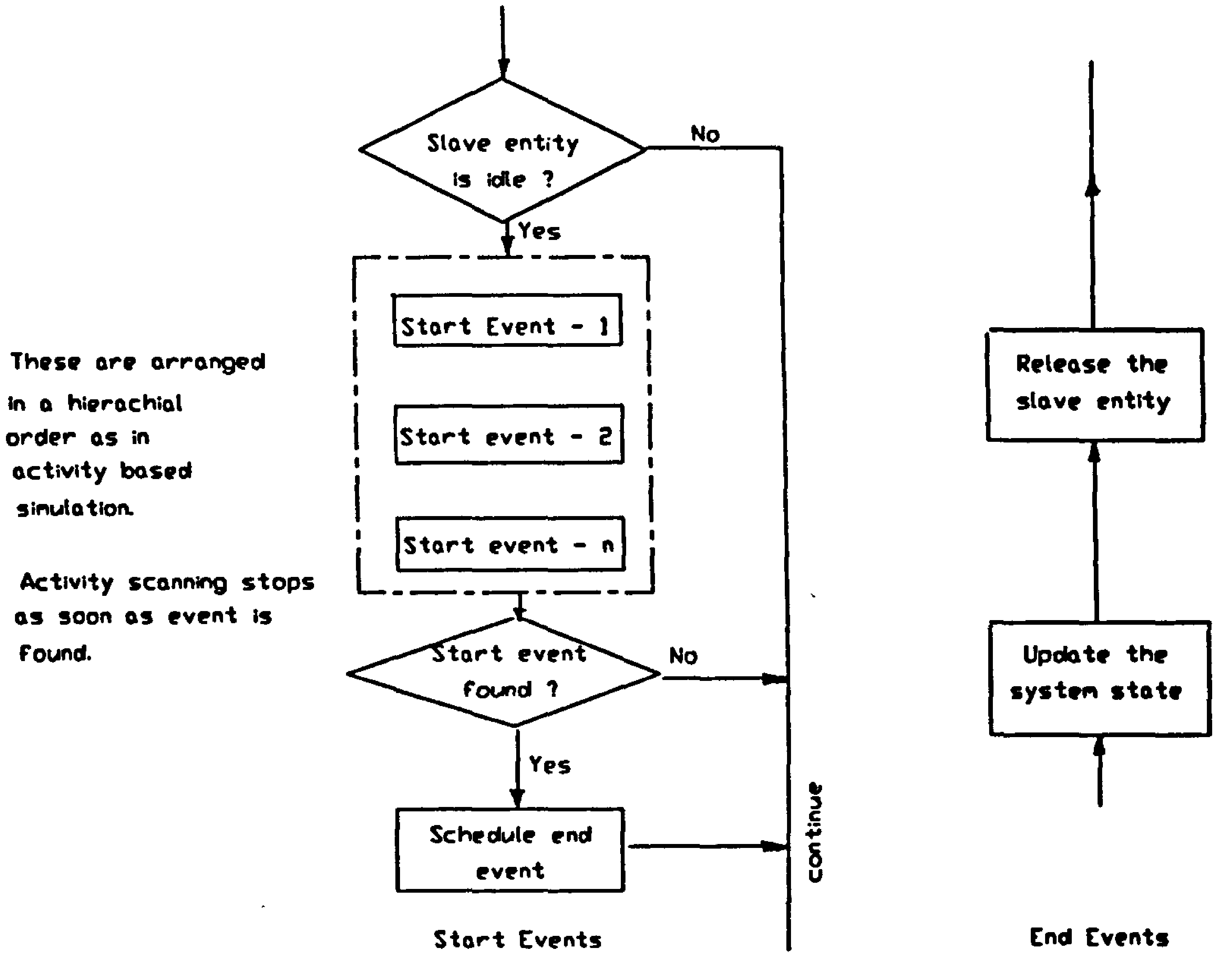


Figure 5.4 A Hybrid Modelling Approach

5.5 A HYBRID MODELLING APPROACH

One of the inherent drawbacks of the event based simulation system is that the modeller has to list out all possible events and their relationships. This could be a quite difficult task in complex systems. There is also a problem of maintaining a hierarchial order of events when resources are shared by several events. But the execution of the model is comparatively fast as only the relevant events are fired.

In contrast, activity based simulation works by scanning a pre- arranged activity list. Although it is quite easy to construct an activity list, the execution speed is low as the system checks all activities at each clock value.

It was thought that a hybrid simulation methodology could be devised to capture essential advantages of both techniques. In the following, this novel approach is presented.

As far as the part flow is concerned, there are several major slave entities (such as crane, AGV and workstations) which serve the master entity, part. Once the activity cycle diagram is constructed (taking the advantage of activity based modelling), activities can be grouped under slave entities (Figure 5.4) When a slave entity becomes idle, activities under that slave are scanned in a pre-defined hierarchical order. If an activity can be started, the corresponding start event is fired and the end event is scheduled. When the end event is reached, the slave entity is released and the activity scanning will proceed. A special structure was used so that the hierarchical order of activities can be changed without re-compiling the program (in other activity based simulation systems the hierarchical order is changed by editing the program and re-compilation is required). More details can be found in software documentation section (Volume 2).

5.6 DESIGN AND IMPLEMENTATION OF THE PROGRAM

A modular programming approach was adopted and a large number of program routines were developed to support the following requirements.

Initialisation Routines

These routines initialise the GASP storage area for entities and other variables related to the system being modelled, such as part route information.

Start Event Routines (crane based)

Routines in this section are called when the crane become idle. The hierarchical structure of events can be changed by changing appropriate values in the experimental frame.

Start Event Routines (AGV based)

Very similar to the above set of routines, except that they are fired when AGV become idle.

Start Event Routines (workstation based)

These events are tried whenever a workstation become available.

End Event Routines

All of the above start event routines have associated end event routines. An event routines may be shared by one or more start event routines (for 16 start events, there are only 7 end events).

Entity Handling Routines

These routines helps to store or retrieve attribute values of entities.

Shuttle Assignment Routines

These routines are called when a given shuttle position is required to reserve in advance and when it is released.

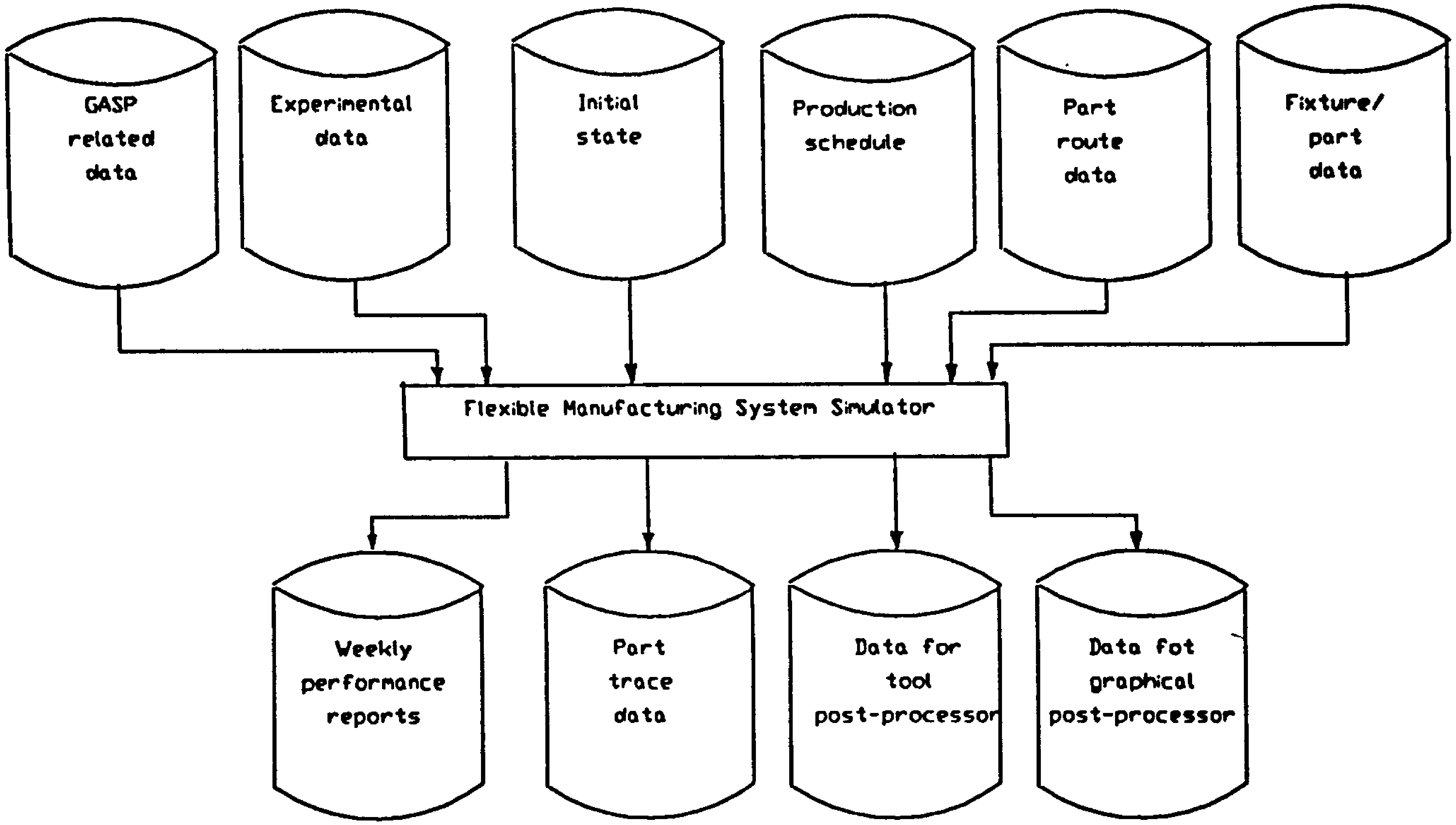


Figure 5.5 Flexible Manufacturing System Simulator

Resource Selection Routines

These routines are used to select one of the multiple resources such as fixtures, workstations and shuttle positions.

Order/Part Selection Routines

These selects parts or orders for immediate processing.

Pallet Selection Routines

These routines are used to identify busy pallets requiring moves and blocked pallets etc.

Utility Routines

This includes report generators and debugging routines etc.

All routines were written in FORTRAN 77 and implemented on VAX 11/780 minicomputer running under VAX/VMS environment. This program consists of 65 program routines, exceeding more than 2000 executable program statements. The overall arrangement of the simulator is shown in the Figure 5.5.

5.7 VALIDATION OF THE SIMULATOR

One of the most important aspects in the modelling process is the model validation. Whatever the type of model employed, it must be valid, if it is to be useful at all. In the context of manufacturing system modelling, the process of validation can be split into two sections.

5.7.1 Model Output Validation

This method uses black box validation i.e. ignoring the detailed internal workings of the model, it is checked whether model output reflects that of the real system. This validity is concerned with the predictive power of the model.

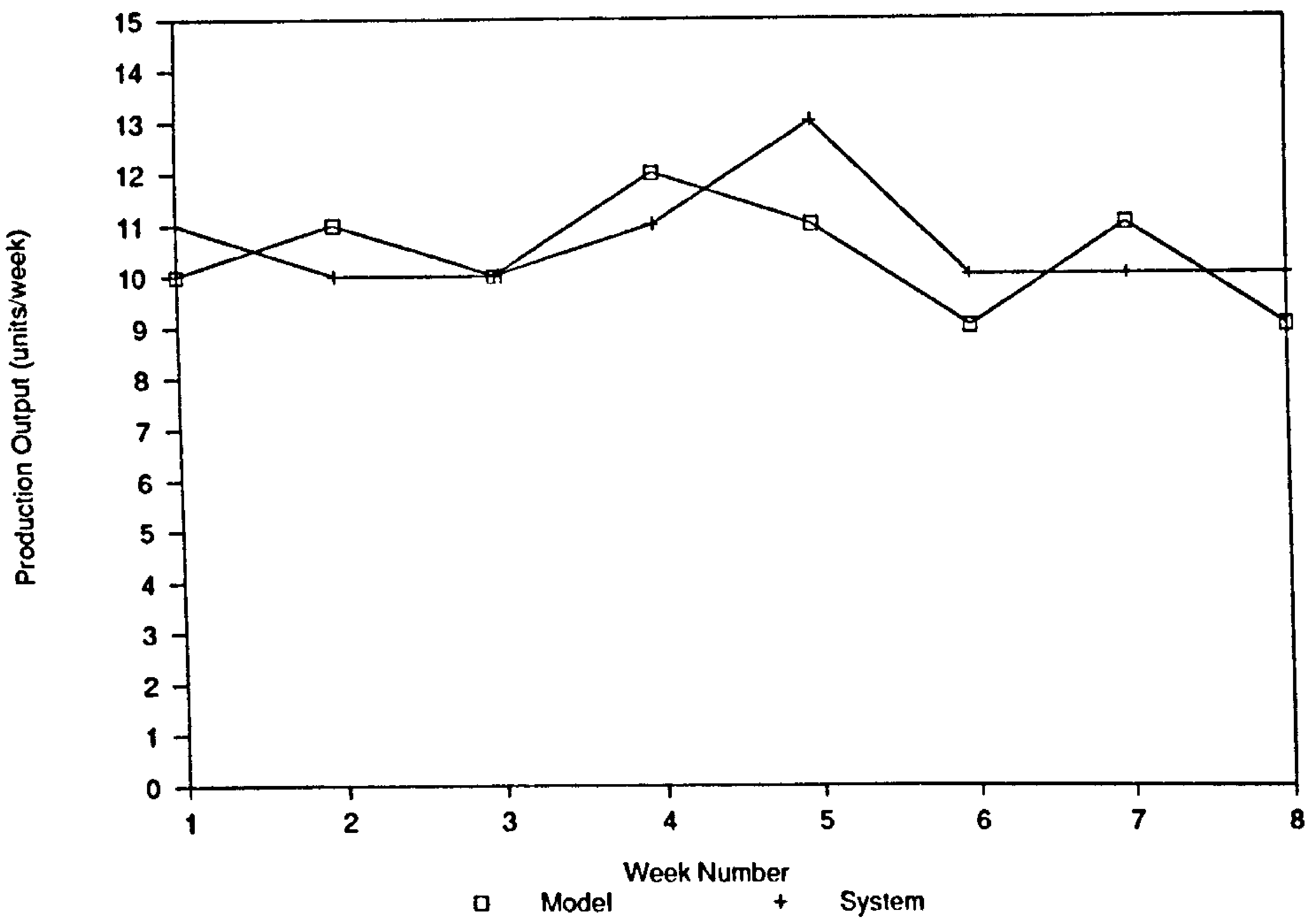


Figure 5.6 Comparison of Production Output Rates

In manufacturing system modelling, the types of output could include the number of parts produced and machine utilization etc. The past schedules were collected and the simulator was driven under the same set of data. A typical set of values obtained from the simulator and actual values for the number of parts produced are shown in the figure 5.6. Several different schedules were used and they all indicated similar results. This confirmed that the model's predictive power is satisfactory.

5.7.2 Model Logic Validation

The above black box approach alone is not sufficient to validate the model, as there is a chance that the model could predict the output values quite accurately with inaccurate behaviour. Thus it would be essential to check the logical aspects of the model as well. In the following, three different techniques are described.

a. Single Part Test

In this case the model is stimulated by entering a single part. All movements of the part and its attribute values are checked at each stage. This test can be repeated for different types of parts with different processing sequences.

If the part flow through the system as intended, it gurantees that all associated events are fired in the correct sequence. For example, at the early stage of development, this test had to be carried out to detect a possible logical error associated with AGV calling sequence. When a schedule with different part types was fed, many of the parts got through the system and some were locked into off shuttle positions. With the assistance of the single part test it was found that the AGV is not called when parts are moved to the out shuttle position. However when there are large number of parts within the system, AGV may be called indirectly by other events, as activity scanning is incoportaed into the model.

b. Multiple Part Test

When a single part is taken through the system, the behaviour of the system is very predictable as there is nothing to interact with the part. In order to check system interactions a set of different part types are released to the system and their movements and attribute values are monitored. This allows the modellor to check the queue discipline and accuracy of resource selection strategies etc.

c. Graphical Animation

Although the above two techniques improve the confidence on the model behaviour, they are laborious tasks. A graphical animation could be useful to some extent, when the model is validated. Specially entity movements and AGV allocation etc. can be monitored quite easily. A Graphical post-processor (chapter 6) developed for the ECSL system can be used with this system as well. However it should be beared in the mind that graphical animation alone is not sufficient to validate the model. For example a graphical animation can hardly reveal values of attributes.

All the techniques were repeatedly used to validate the model. At the end it was concluded that model is logically correct as well.

5.8 OTHER VERSIONS OF THE SIMULATOR

The original version (on VAX/VMS) was later modified to generate other two simulators for specific applications.

a. PDP 11/40 Version

On the request of the company, an enhanced version of the original simulator was constructed. This has some advanced features such as shift pattern adjustments and automatic capturing of certain system data. This suite of programs also include an interactive input data processor and several software interfaces to the system database [Perera 1987, Perera and Carrie 1987(a)]

b. IBM/PC Version

Very powerful microcomputers are now available at the fraction of the cost of a minicomputer. They are becoming very popular as IBM/PC compatibles emerge. The original simulator was successfully re-configured for MS/DOS environment. IBM/AT or compatible is recommended and Intel 80287 (or 80387) maths co-processor is required.

5.9 CONCLUSION

This exercise provided an opportunity to understand all most every aspects of manufacturing system model building. This model can be easily reconfigured to mimic other types of FMSs.

It was realized that a considerable amount of time is spent on debugging and validation. Therefore it is proposed that a structured model validation schema must be developed to check the different aspects of the model in a logical manner.

CHAPTER 6

THE GRAPHICAL POST-PROCESSOR

6.1 INTRODUCTION

The development of operational strategies for FMS is reckoned to be one of the most difficult tasks. In many systems, the operating policies have to be redefined from time to time to overcome new operational problems created by the changes in the production environment.

The ECSL-based model indicated that the system logic is imperfect for the FMS under investigation. The standard output reports and non-graphical tracing facility of simulation systems were found to be inadequate to discover the cause of deficiencies.

The graphical animation is a powerful supplement to computer simulation and it can improve the system designers and users intuition about the system behaviour. However at this stage of the research work, graphical animation was scare and an expensive tool.

In this chapter the design and development of a low cost graphical post-processor is presented. The way it was used to redefine certain aspects of the operating logic of a real FMS is discussed.

6.2 THE CHANGES IN THE PRODUCTION ENVIRONMENT

During the life cycle of an FMS, various changes in the production environment may be encountered by the system users [Perera 1988(b)];

a. Changes in system hardware configuration.

b. Changes in part characteristics.

c. Changes in product mix.

Among these causes, the last two are more frequent. In many systems, part attributes such as the part route sequence, processing time and tooling requirements, often change due to design modifications. These changes may have some impact on the operating policy. Generally, different product mixes are processed in different planning periods. A more flexible, product mix dependent control logic may well improve the system performance.

6.3 GRAPHICAL ANIMATION

In recent years there have been many significant developments in discrete event simulation. Among them graphical animation is an outstanding improvement. This uses computer graphics to animate movements of entities, through the simulated system.

Most simulation languages now support graphical animation facilities (e.g. FORSSIGHT [British Steel Corporation 1981], BEAM for MAST [CMS Research Inc. 1988], CINEMA for SIMAN [System Modelling Corporation 1988], SEE_WHY [Fiddy et al. 1981], HOCUS [P-E Consulting Services, 1988] etc.). Except in very few systems, two dimensional animation graphics are employed to display the movements of entities and the background features through which they move. In GRASP [Yong et al. 1983] and AUTOGRAM [AutoSimulations Inc. 1987], three dimensional graphics allows the user to view the operations of the system from different perspectives. They are generally used to study small work cells.

The graphical animation facilities can be broadly classified as follows.

6.3.1 Graphical Post-processors

In this case the graphical animation program is available as a separate module. The associated simulation program is first executed and the output is stored in a separate file. The graphical post-processor then reads this file and animates the entity flow. BEAM is a graphical post-processor.

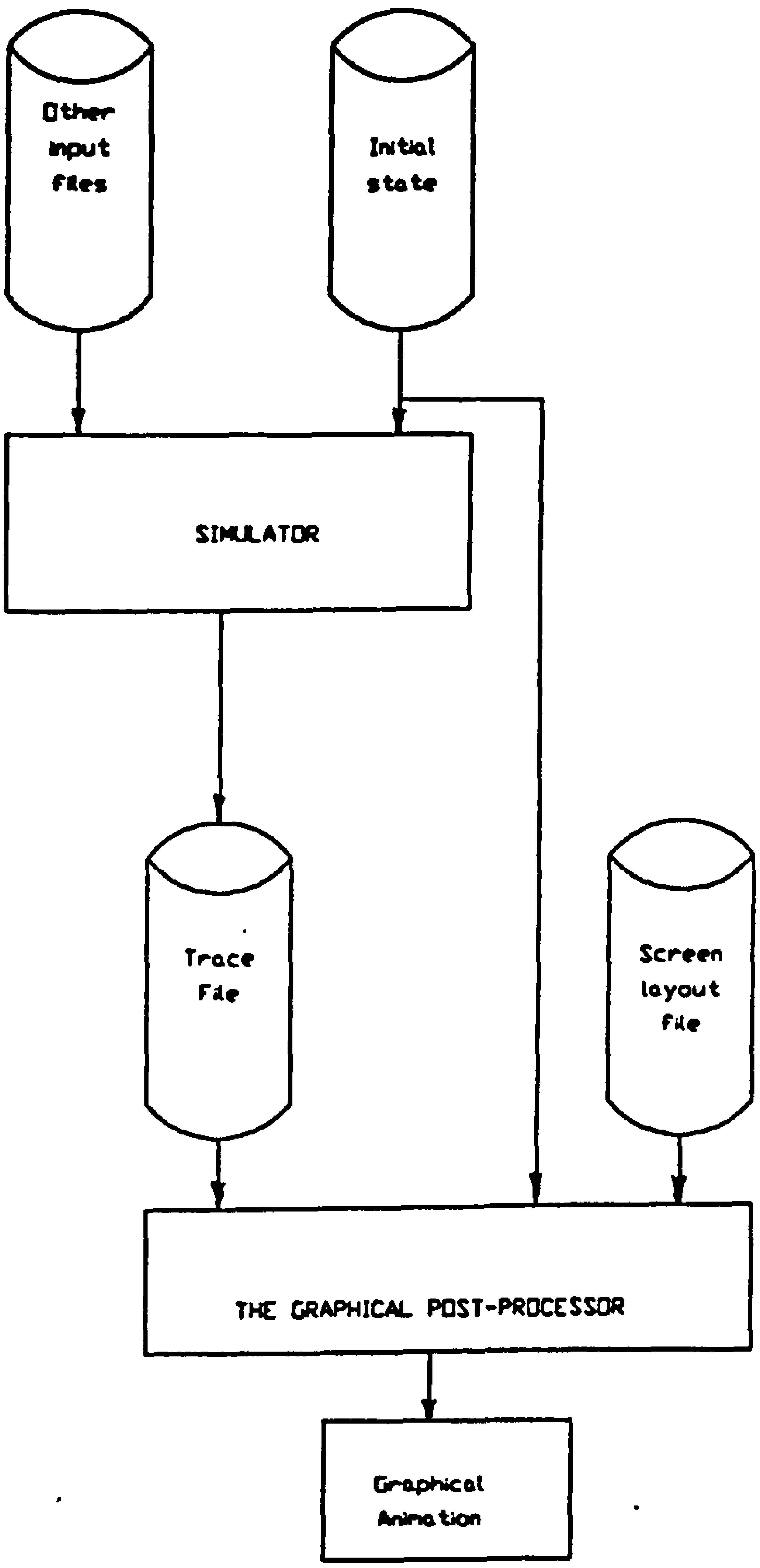


Figure 6.1 Basic I/O of the Graphical Post-processor

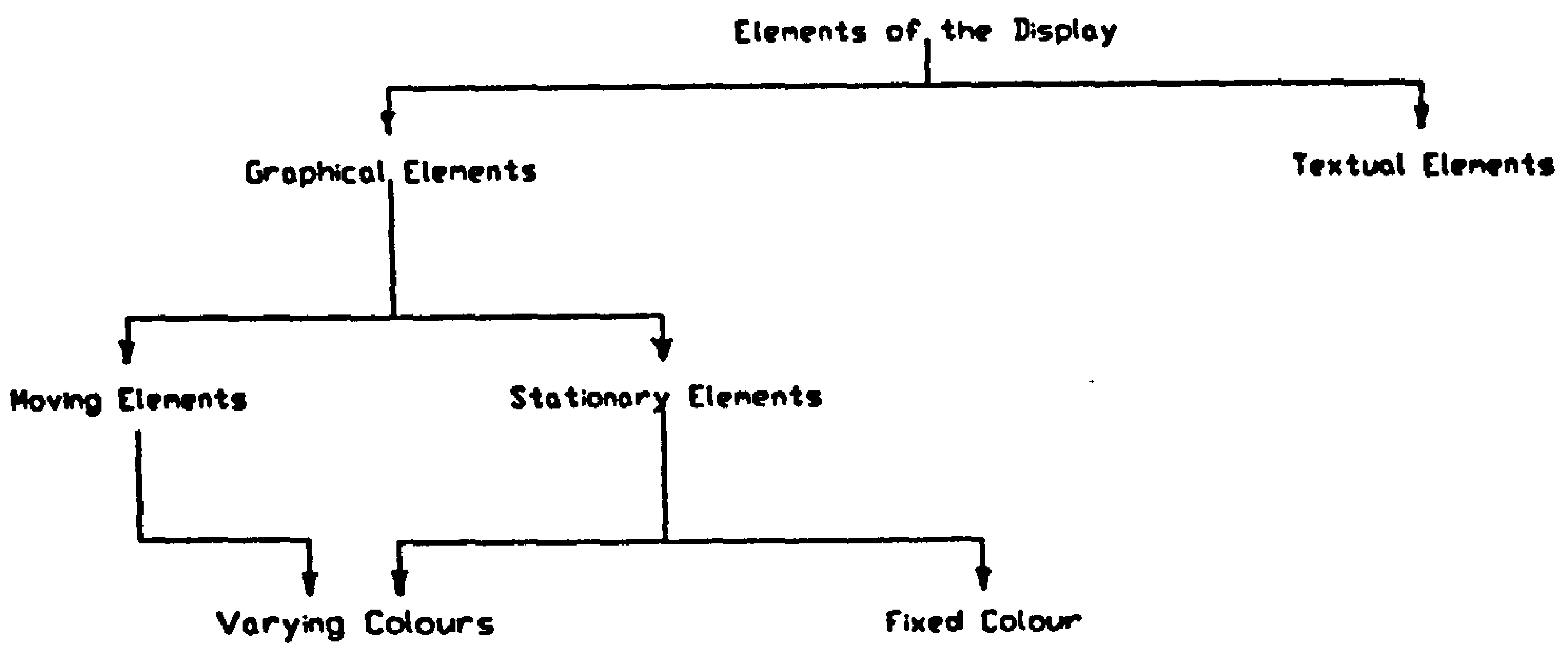


Figure 6.2 The Elements of the Graphical Display

6.3.2 Concurrent Animation

The current trend is to make the animation displayable concurrently with the simulation. In this mode of operation, the user can stop the simulation, while it is running, make changes and continue running it. The immediate effect of the changes on the simulated operations can be observed. SEE-WHY and HOCUS provide concurrent animation facilities.

Although concurrent animation is more useful in some applications, a graphical post-processor has a major advantage, i.e. it is independent of the simulation language. Generally, commercial graphical post-processors are dedicated to a simulation system, but it is possible to develop a generic graphical post-processor which can process output files from different simulation systems. Most of the simulation systems provide textual tracing facilities, and required data can be extracted from this to drive the graphical post-processor.

It is generally accepted the graphical animation facilities contribute to the high cost of simulation packages. More details about graphical animation can be found in [Grant et. 1986, Bernard 1985, Pope 1984].

6.4 DESIGN ASPECTS OF THE GRAPHICAL POST-PROCESSOR

The basic inputs and outputs of the graphical post-processor are shown in Fig. 6.1 . The graphical display can be decomposed into the following elements [Fig. 6.2] ;

6.4.1. Textual Elements

These are basically the captions used to define various items of the display, such as workstations, load/unload stations and layout, etc.

6.4.2 Graphical Elements

These constitute the elements of the graphical display and can be classified as follows.

a. Moving Elements

Within the context of FMS, the material handling system and parts are moving elements. In this preliminary version, moving elements are limited to the AGV type of MHS. The colour of the AGV element can vary depending on its status (i.e. idle AGV, AGV with a loaded pallet and AGV with an empty pallet).

b. Stationary Elements

These elements take fixed positions in the display. They can be further classified as;

Varying Colours

Workstations, shuttle positions etc., have fixed positions in the display, but the colour of the element is altered to show its different states.

Fixed Colour

These are generally the background and other elements which are used to enhance the presentation.

Textual elements can be displayed quite easily by defining their colour attributes (foreground and background) and positional attributes. However for graphical elements further attributes such as element type (representing different shapes), target colour, etc. need to be defined. The stationary graphical elements possess only one dynamic attribute, colour, whereas moving elements have many dynamic attributes, such as colour, position and even element type (for example the AGV has to be displayed in different orientations in different parts of the track).

6.5 DEVELOPMENT AND IMPLEMENTATION OF THE GRAPHICAL POST-PROCESSOR

Having defined the individual elements in the display, it is necessary to link them into the events in the trace file. As in the part flow simulator (chapter 5) the master-slave modelling approach can be used. In particular, the behaviour of slave elements need to be rationalized as they can be involved in many activities. For example, AGV can be used in different types of activities, but for the purpose of graphical animation, all activities can be represented by a single animation feature by defining the current location, target location, element colour etc. Therefore, activities with similar animation requirements can be grouped and separate programming modules can be constructed for the each group.

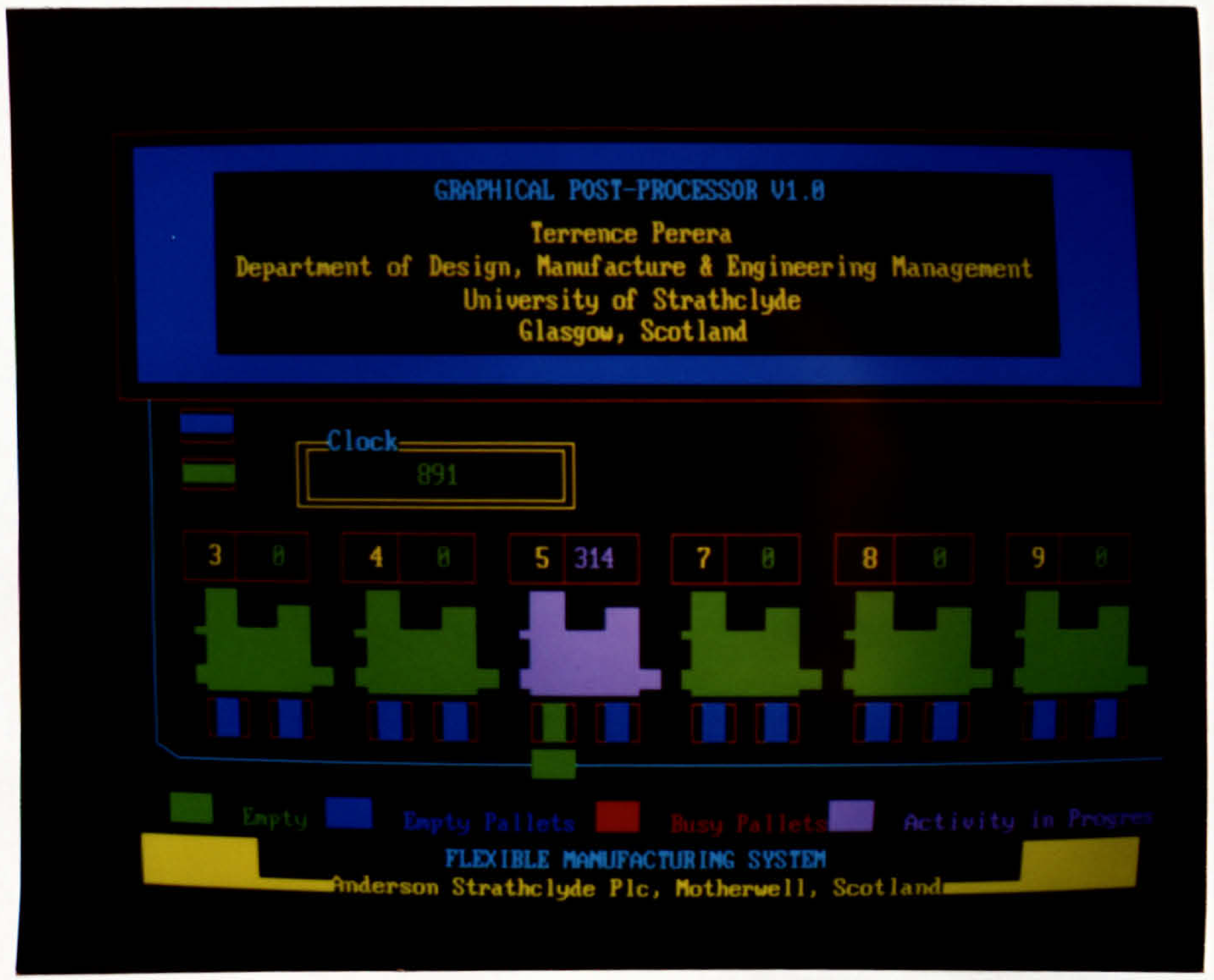
A set of programming modules were developed to represent various elements in the display. FORTRAN has been used as the programming language. To obtain graphical features, this language was blended with other graphical systems. Different types of graphical systems were used in different versions of the post-processor.

a. VAX/VMS Version

In this version, an advanced colour monitor LYME 6000 [Gresham Lion Plc. 1980] was used. A special set of ANSI ESCAPE sequences dedicated to this monitor was coded in FORTRAN. One of the major drawback in this version was the size of the graphic screen, and workstations had to be arranged in two lines.

b. IBM/PC Version

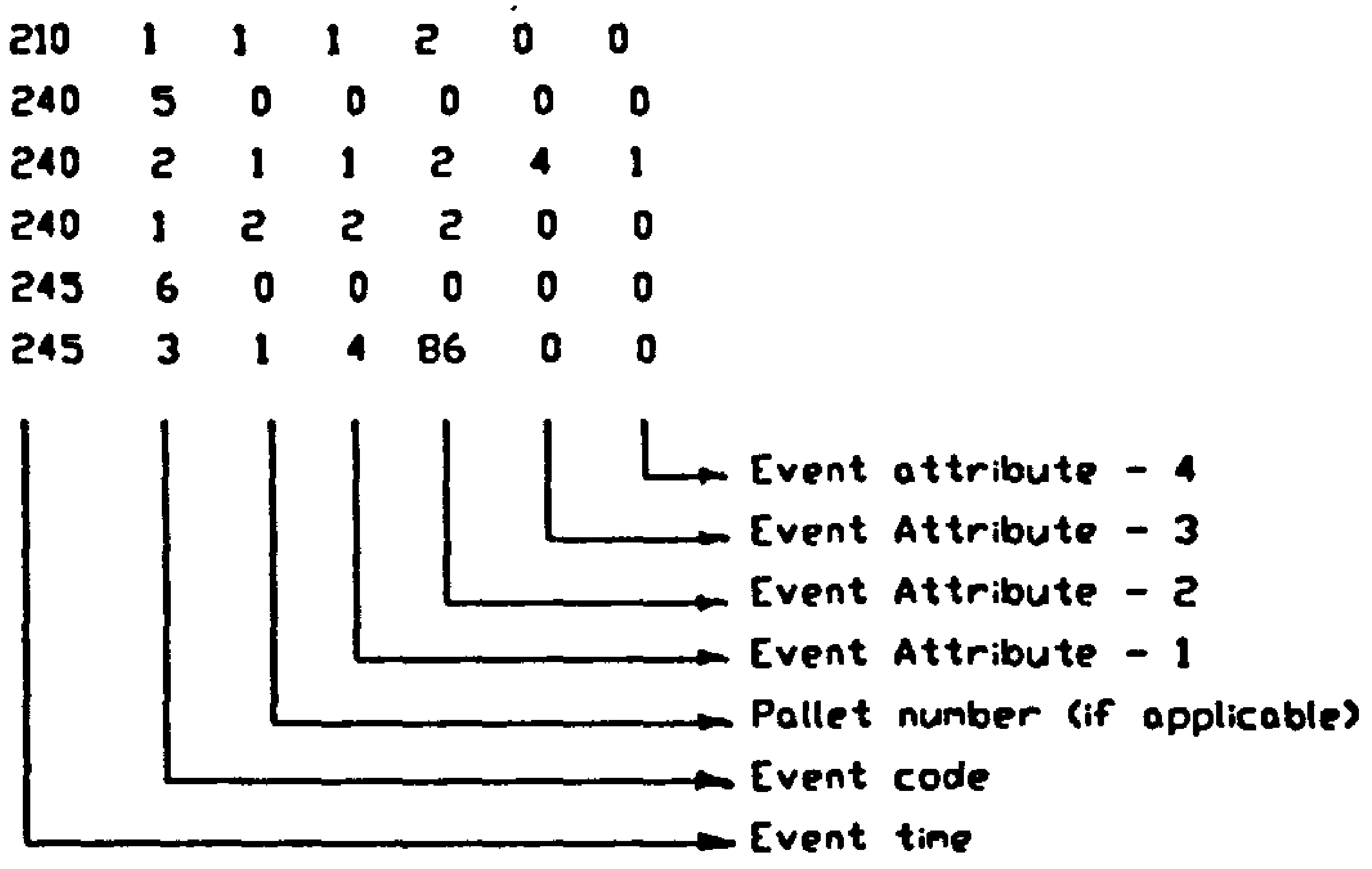
More recently, the original graphical post-processor was re- written for IBM/PC and its compatible machines. In this version Graphical Kernel System was used



GRAPHICAL POST-PROCESSOR V1.0
Terrence Perera
Department of Design, Manufacture & Engineering Management
University of Strathclyde
Glasgow, Scotland

FLEXIBLE MANUFACTURING SYSTEM
Anderson Strathclyde Plc, Motherwell, Scotland

Figure 6.3 A Snapshot of the Animation



```
210   1   1   1   2   0   0
240   5   0   0   0   0   0
240   2   1   1   2   4   1
240   1   2   2   2   0   0
245   6   0   0   0   0   0
245   3   1   4  86   0   0
```

Note: Event attributes have different definitions for different events

Figure 6.4 A Segment of the Trace File

and a better graphical representation was obtained [Fig. 6.3]. More information about this version can be found in chapter 4 of volume 2.

In both versions, when the main simulator is executed, the output related to graphical animation is stored in the trace file . The graphical post-processor first sets up the initial display with the assistance of the initial state file. Then each record of the trace file is decoded and entities are displayed accordingly [Fig. 6.4].

As explained in the section 4.5 two major deficiencies of the ECSL model were discovered and in the next section, the way the graphical post-processor was used to solve these problems is explained.

6.6 THE PROBLEM OF EMPTY PALLET MOVEMENTS

When a pallet becomes idle at a load/unload station (i.e. a part is unloaded) it may not be possible to load it immediately. Either fixtured parts may not be available and/or all target stations for fixtured parts are busy. When this occurs, the empty pallet needs to be circulated within the system. Its movements should be carefully controlled to minimize possible interference with the part flow. The following system states may trigger empty pallet movements.

State 1

The current operation at a workstaion is near completion or has been completed, but the off-shuttle of the workstation is occupied by an empty pallet.

State 2

A part is waiting at the off-shuttle of the workstation or at a load/unload station, but the in-shuttle of the target workstation is occupied by an empty pallet.

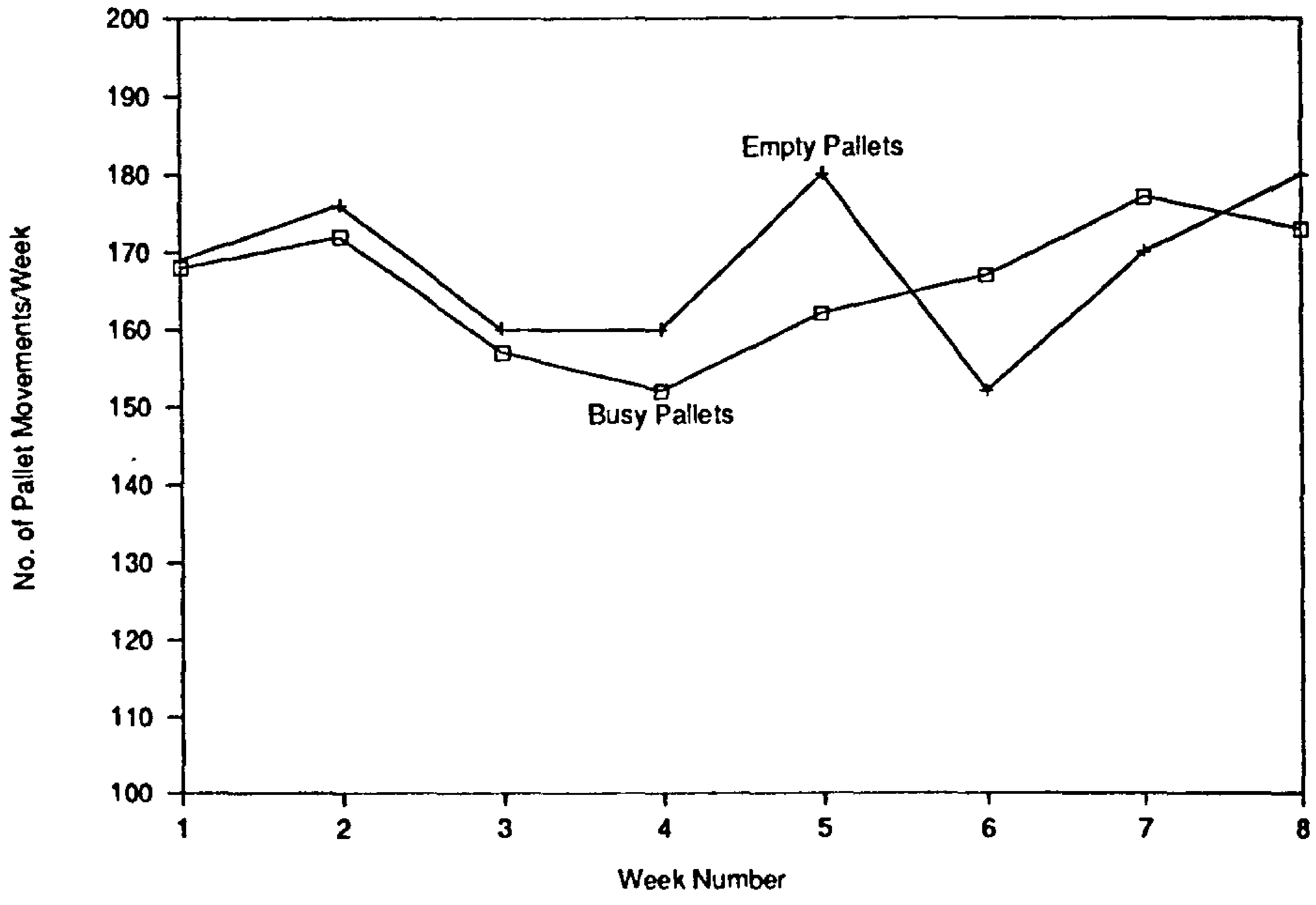


Figure 6.5 The Pallet Movements in the Flexible Manufacturing System

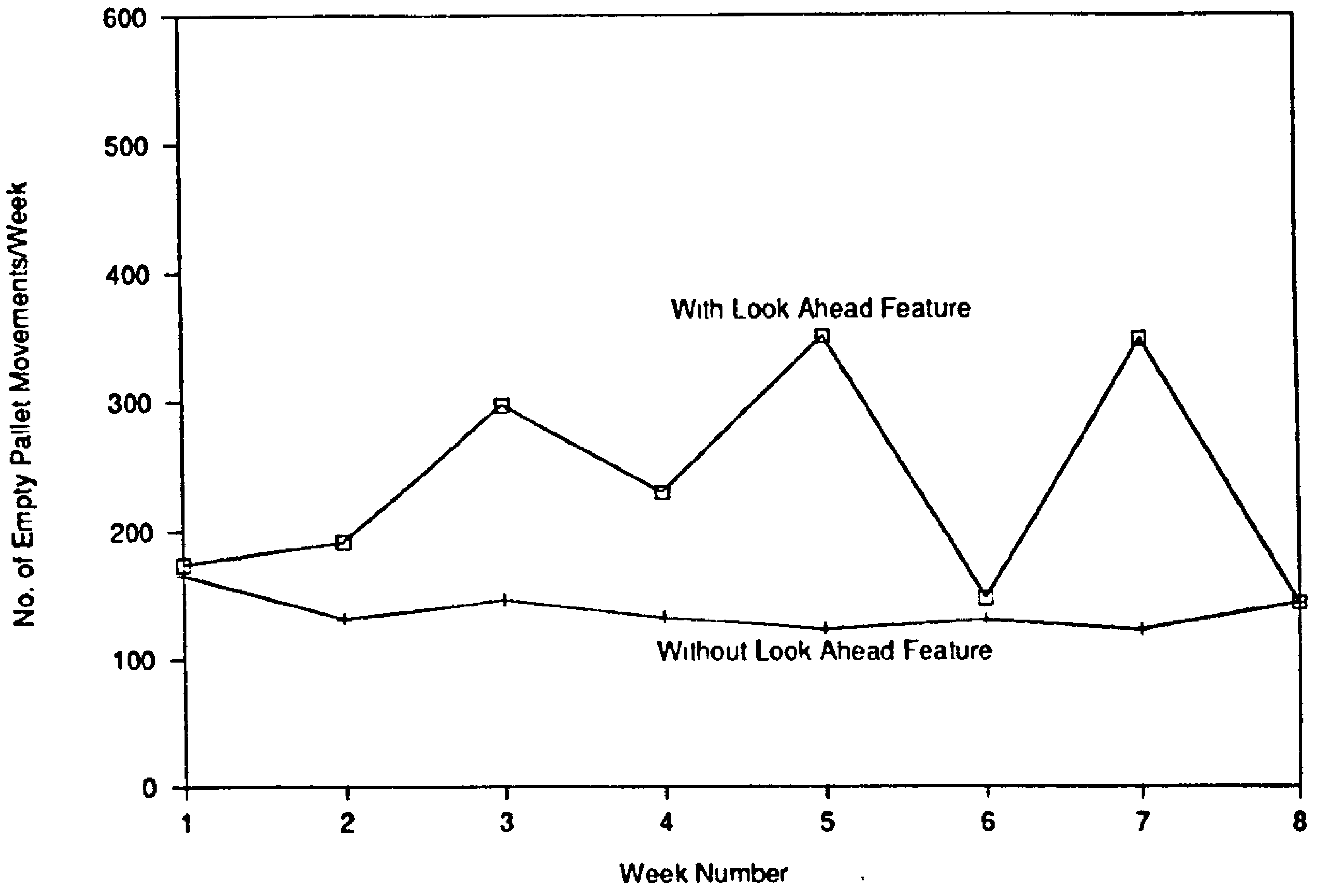


Figure 6.6 The Distribution of Empty Pallet Movements

State 3

A part is waiting at the off-shuttle, for a load/unload station which is occupied by an empty pallet.

State 4

A fixtured part is available for loading, but no empty pallet is available at the load/unload station.

In order to estimate the average number of empty pallet movements per period (e.g. week), AGV assignments were individually monitored. In most experiments the number of empty pallet movements were roughly equal to the number of busy pallet movements. [Fig. 6.5]. However, in some periods an excessive number of empty pallet movements were observed [Fig 6.6]. At this stage the graphical post-processor was called to identify the cause of the excessive empty pallet movements. It was discovered that the AGV moves empty pallets in a circular manner, due to pre-condition of the state 2 (see above). In this state empty pallets on an in-shuttle is moved away when one of the following pre-conditions prevails;

a. Workstation as a target station

The workstation has become the target station for a part at another workstation or load/unload station.

b. Look ahead feature

The fixtured parts waiting for loading are scanned and their first target workstation is identified. If the in-shuttle of the target workstation is occupied by an empty pallet, then it is moved away pending the loading of the part.

Since the State 2 caused this problem, the empty pallet movements due to the above two components were individually monitored. It was observed, the number of empty pallet movements due to the look ahead feature was very high.

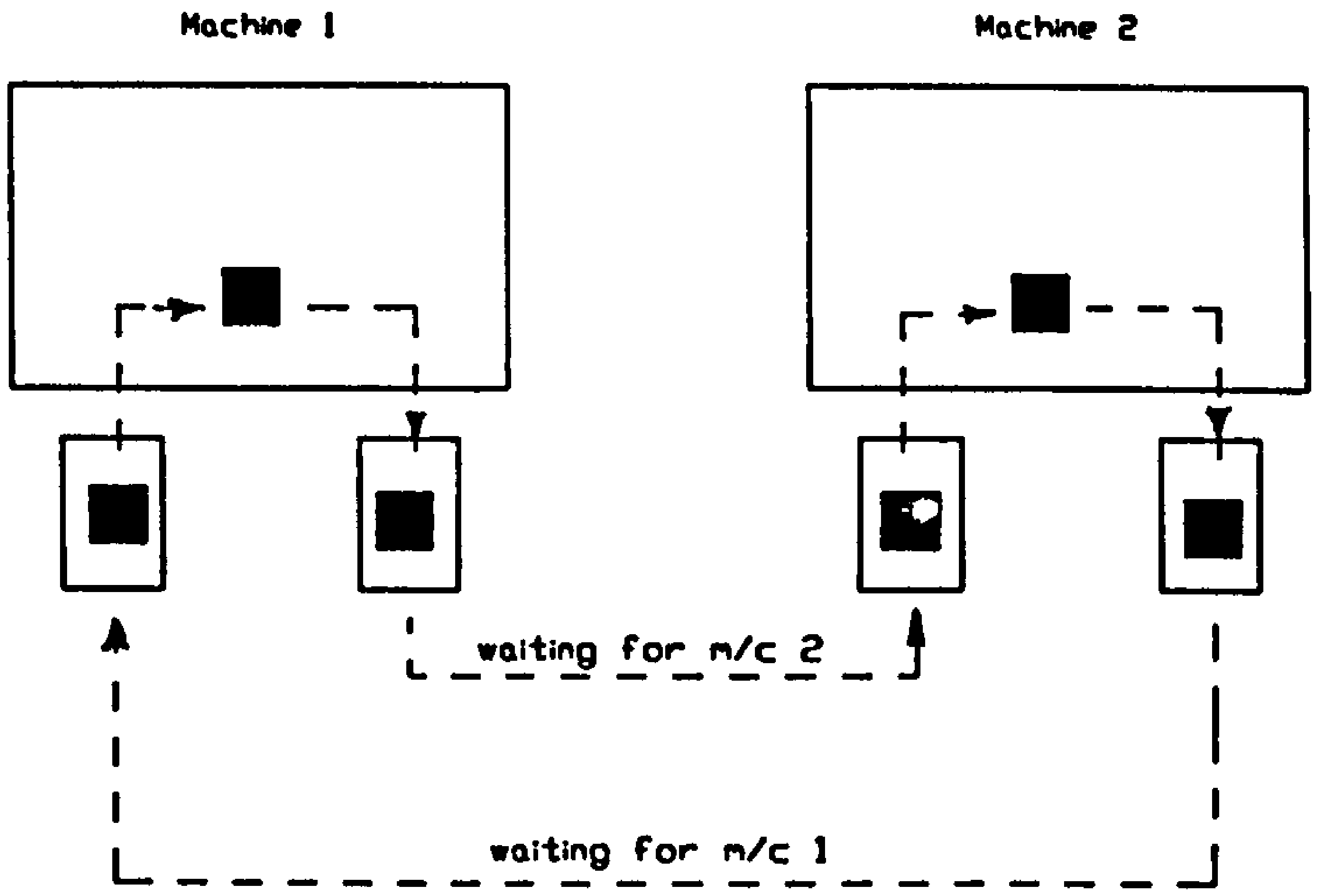


Figure 6.7 A Typical Deadlock in Material Flow

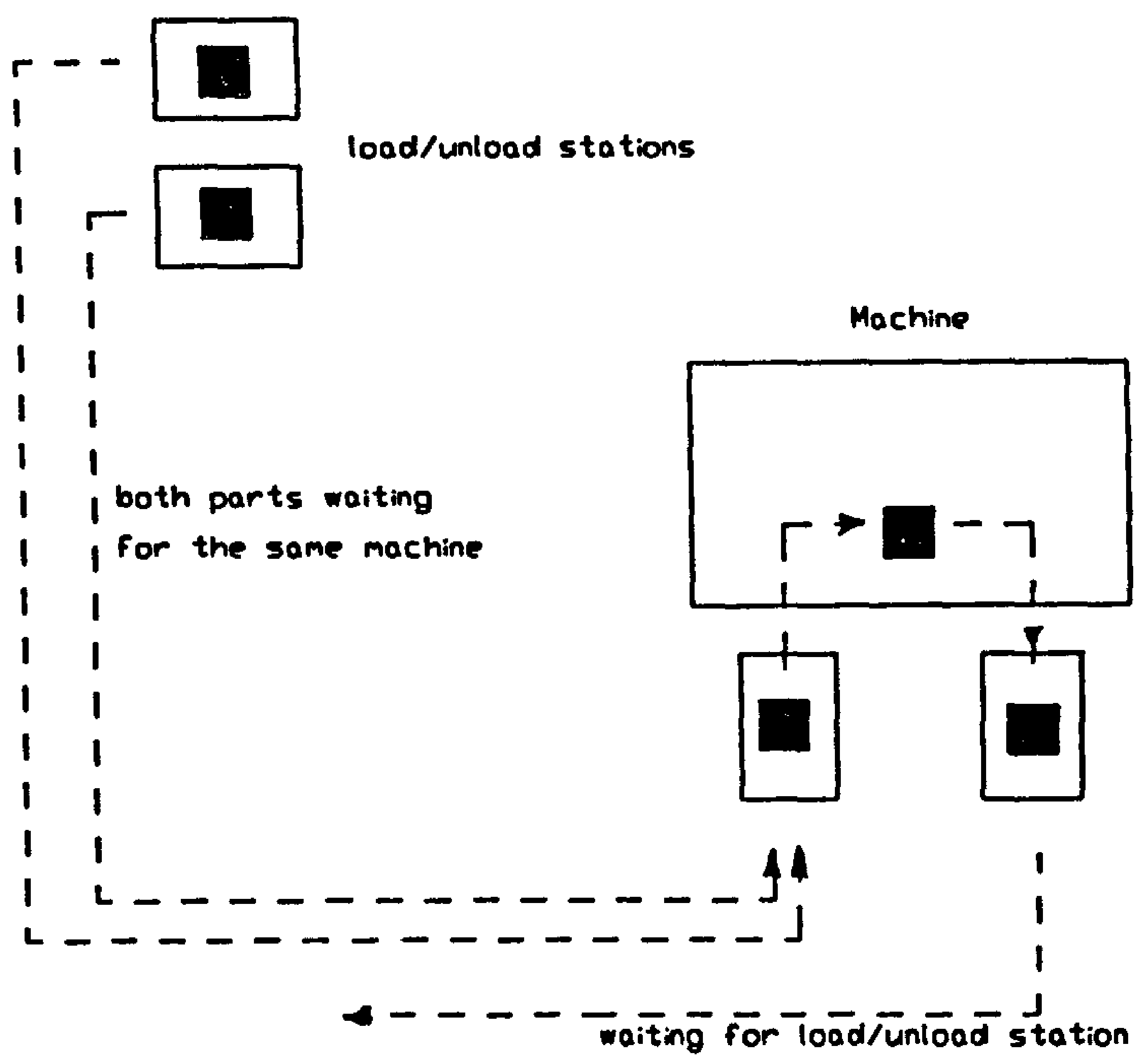


Figure 6.8 A New Type of Material Flow Deadlock

The reason for this circular movement of pallets was also identified. Although the look-ahead feature moves an empty pallet away from the target in-shuttle for an unloaded, but fixtured part, it cannot be loaded immediately, due to subsequent changes in the system state. Whenever this activity is scanned, unnecessary empty pallet movements are triggered.

The look-ahead feature of this logical module was removed and the model was re-run with same product mixes . The results are shown in Fig. 6.6.

6.7 THE PROBLEM OF SYSTEM BLOCKAGES

The problem of deadlock in material flow has been investigated by various researchers and a comprehensive review on this aspect of manufacturing systems can be found in [Wilson 1985]. A typical deadlock in material flow is shown in Fig 6.7 This type of deadlock is known as deadly embrace or circular waiting in the computer operating system literature [Kuzzaban et. al. 1975].

Previous researchers incorporated logic into the model to relieve blockages between any two workstations. When dead-lock in material flow is detected a pallet is taken out of the circular wait and placed at some other place to alleviate the blockage. Despite this, some abrupt termination of simulation experiments were observed.

Again, the assistance of the graphical post-processor was sought and a new type of dead-lock was discovered which involves load/unload stations. This can occur when the following conditions exist [Fig. 6.8];

a. Two loaded pallet are waiting at load/unload station for the same workstation (target station).

b. All pallet positions of the target station are busy.

c. The pallet on the off-shuttle of the workstation is waiting for a load/unload station.

Operation	Station
Load	1,2
Op-11	4,5
Op-12	7
Op-13	8
Unload	1,2
(de-fixturing/fixturing)	
load	1,2
Op-21	4,5
Op-22	7,8
Reset	1,2
Op-23	3
Unload	1,2

Old Part Route File

Operation	Station
Load	1,2
Op-11	4,5
Op-12	7
Op-13	8
Unload	1,2
(de-fixturing/fixturing)	
load	1,2
Op-21	4,5
Op-22	7,8
Op-23	3
Reset	1,2
Op-24	3
Op-25	7
Unload	1,2

This segment contributed to new type of blockages.

New Part Route File

Figure 6.9 Changes in Part Route Files and Cause of the Blockage

However this discovery raised another problem.

> *Why did not previous researchers encounter this type of blockage despite enormous number of simulation experiments carried out ?*

Obviously, the formation of system blockages is unpredictable. Action can be taken to avoid blockages, but it is difficult to identify factors which contribute to the formation of blockages. However in this case, changes in part route data were suspected as the prime cause for these deadlocks. Due to variety of reasons, the part routes are constantly changed. Therefore one of the major differences between early experiments and this work is new part route. Thus the progress of each part within the simulated setting was traced and the stage at which the system became stagnant was noted. Surprisingly, the part types involved and the stage of the part route sequence at which blockage took place were the same for all deadlocks. The trouble-causing segment of the part route is shown in Fig. 6.9. The main cause is that the parts returned from the workstation No. 3 [Chapter 3] are waiting for the same workstation after re-orientation of fixtures.

Thus new logic was incorporated to handle this type of blockages. Basically it unloads a part involved in the blockage and the part is given a higher priority over others when parts are scanned for loading.

6.8 CONCLUSION

The development of the control rules for integrated manufacturing systems is a complex task. In some real FMSs, even after several years of operation, the control logic is constantly modified in response to unpredicted situations.

During technical visits to FMS, it was realized that the role of graphical animation in the industry is enigmatic, as it cannot assist management to solve day to day operational problems. However, it has been an useful tool at the system design stage.

Within the context of FMS modelling, it is a powerful de-bugging tool which helps the model builder to identify integration effects of advanced manufacturing systems.

CHAPTER 7

TOOL MANAGEMENT IN FLEXIBLE MANUFACTURING SYSTEMS

7.1 INTRODUCTION

As flexible manufacturing systems evolve through several generations, its associated technologies have been constantly enhanced to solve various operational problems generated by these systems. Sadly, not all of these technologies have received attention from the system designers, users and researchers. One of the lagging areas appears to be tool management.

In first few generations of FMSs, more effort was focused on part flow management and except in very few systems tool management aspects were largely ignored. This negligence has created many operational problems in some FMSs.

In this chapter, several UK based FMSs are reviewed to highlight the varying nature of the tool management problem. The system parameters which influence the management and control of tool flow are defined.

7.2 EXAMPLES OF FMS TOOL MANAGEMENT

There are about 40-50 flexible manufacturing cells and flexible manufacturing systems in UK [Bessant and Hayward 1986]. Although all systems encompass similar hardware subsystems such as workstations, a material handling system, a computer system, etc. , they are operated in different ways. In particular, in the management and control of tool flow, a wide variety of operational strategies are adopted. A number of UK FMSs were visited and a few examples were selected to show the varying complexity of the tool management problem.

7.2.1 System A: Gear Pump Housing Flexible Manufacturing Cell

This system is a flexible manufacturing cell for the production of aluminum housings for gear pumps [Kochan 1985(a)]. There are 5 basic component types making up one housing and each part can have a number of variations. The

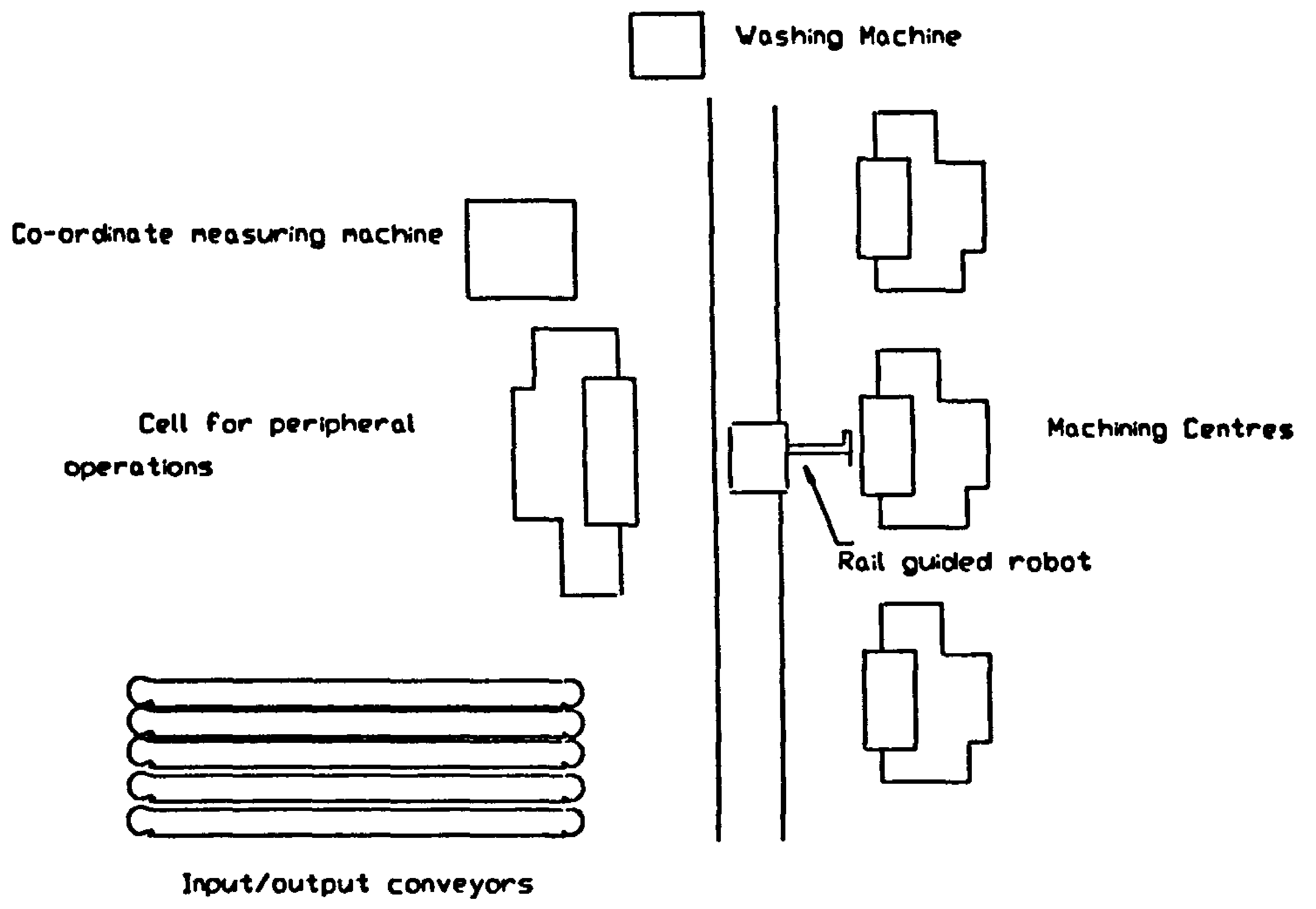


Figure 7.1 System A: Gear Pump Housing Flexible Manufacturing Cell

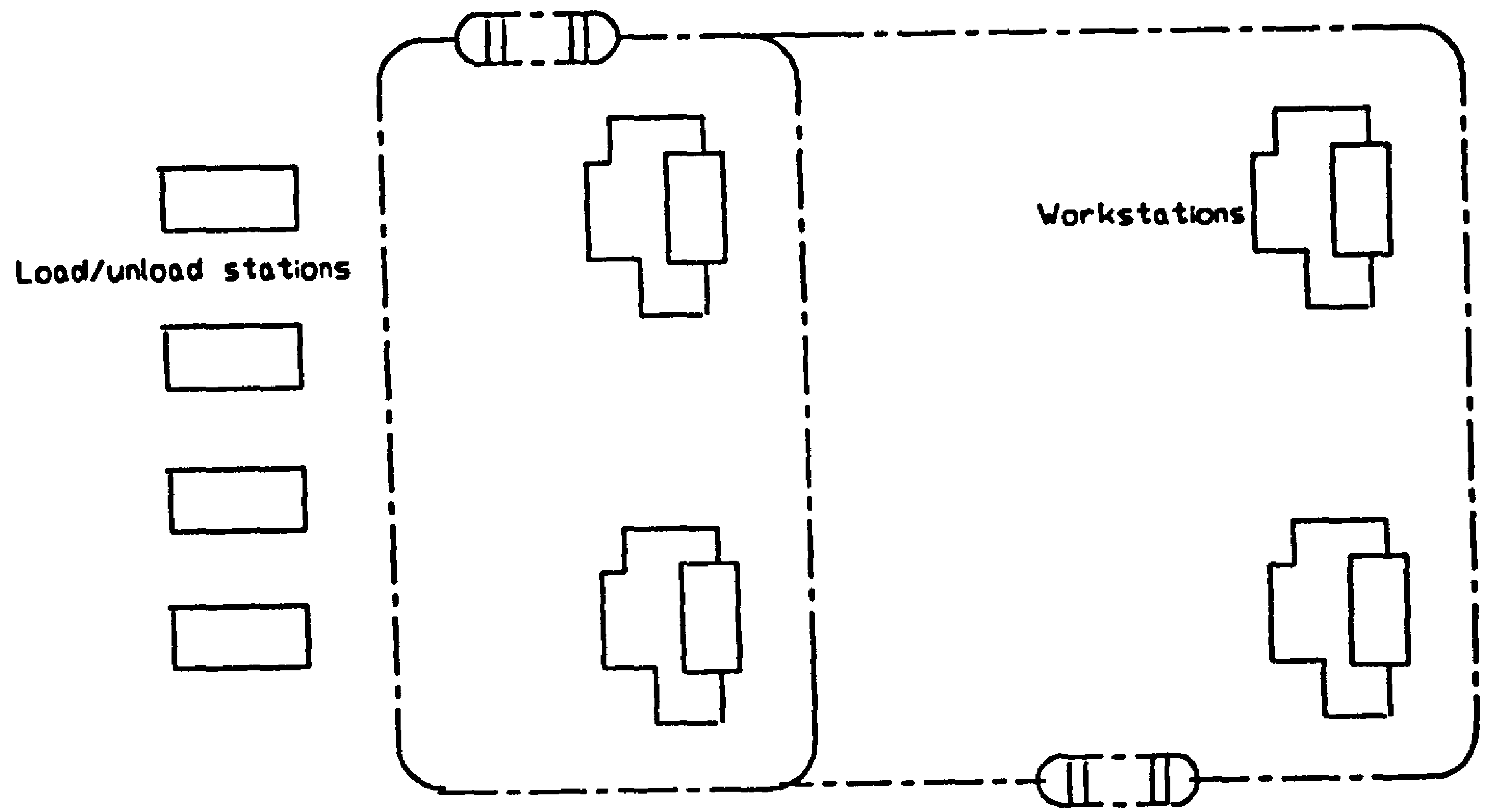


Figure 7.2 System B: Valve Components Flexible Manufacturing System

company claims that there may be about 1000 different models when all permutations and combinations are considered. However they have very similar processing requirements. A typical production run may consist of batches of 50-500 parts.

The cell consists of 3 identical machining centres, a washing station and a coordinate measuring machine [Fig. 7.1]. There is also a cell for peripheral operations. All machining centres are identically tooled. The cutting requirements of a given part can be carried out in a single visit to a workstation. The tool magazine on each machining centre has space for 32 tools which is sufficient to give duplications of all the tools requiring tight tolerances.

In this system, virtually there is no tool management problem. A closed set of tools which are held permanently can cater for all part types. The tools are exchanged due to tool wear only.

7.2.2 System B: Valve Components Flexible Manufacturing System

The second system is a relatively small FMS for the production of valve components [Kochan 1984(b)]. This system includes 4 identical machining centres each with a free standing tool magazine with space for 100 tools. Pallet transfer between load/unload stations and machine is performed by two wire guided vehicles [Fig. 7.2].

Some 25 part families have been selected for flexible manufacture. Batch sizes can vary between 10 - 500. One important feature in this system is just-in-time type manufacture. Instead of discrete batch manufacture, FMS is used in assembly-related batch manufacture, so that the sets of parts for a valve assembly will be produced in line with the assembly programme.

The tool types at a machining centre are left in place until the product mix changes at which point some of the tools in the magazine are replaced by new tool types. This approach of bulk tool exchanges keeps the tool management problem relatively simple.

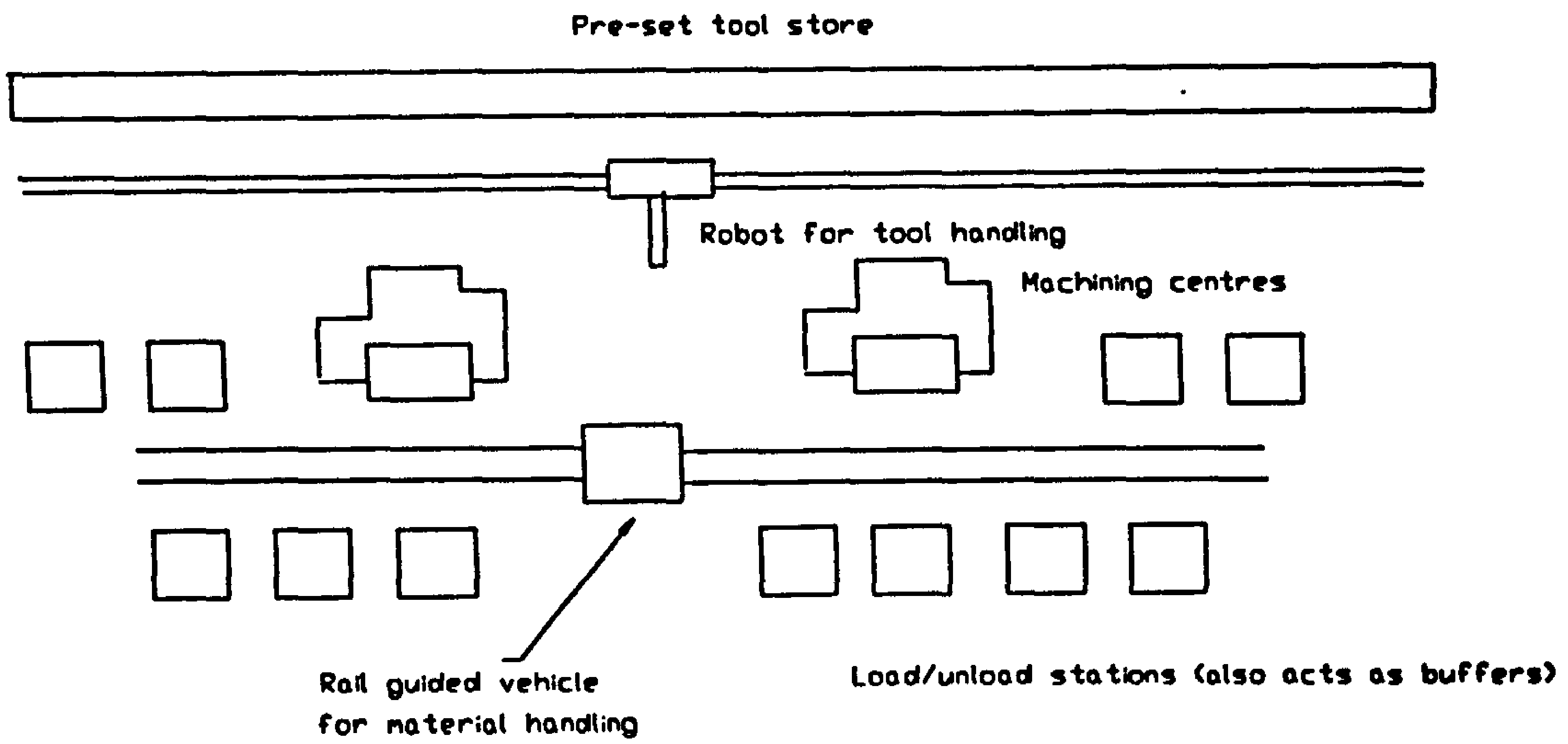


Figure 7.3 System c: Lineage Part Flexible Manufacturing Cell

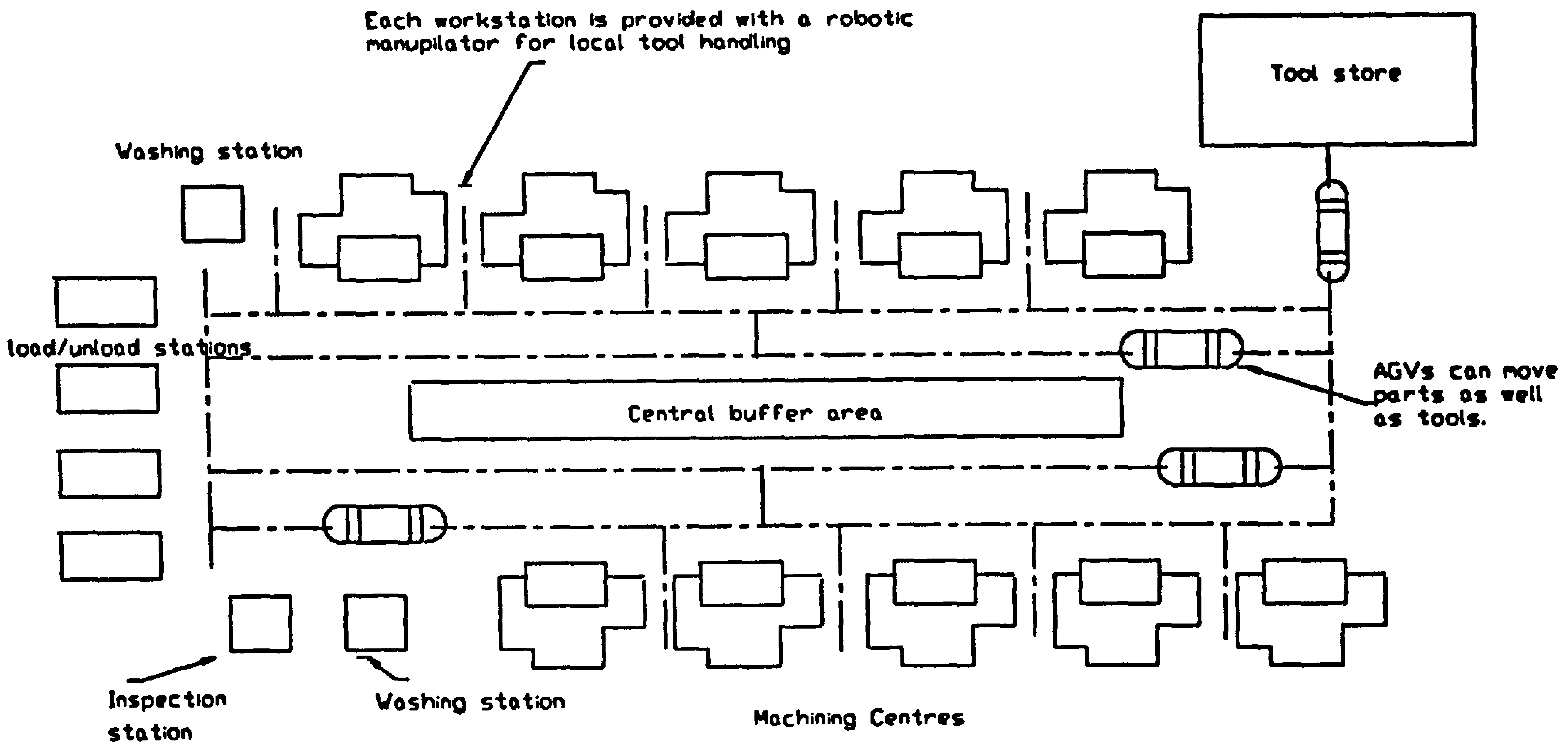


Figure 7.4 System D: Earthmover Component Flexible Manufacturing System

7.2.3 System C: Lineage Part Flexible Manufacturing Cell

The company manufactures a range of diesel engines with powers up to 8700 kw and it involves many forms of production, one-off, very small batches (6-12) and small batches (up to 150) [Kochan 1984(c)]. Although the company supplies a standard range of engines, only a few components are common to all models. These common parts are termed as lineage parts. A set of 20 - 25 different part types have been selected for flexible manufacture and altogether about 300 tool types are required.

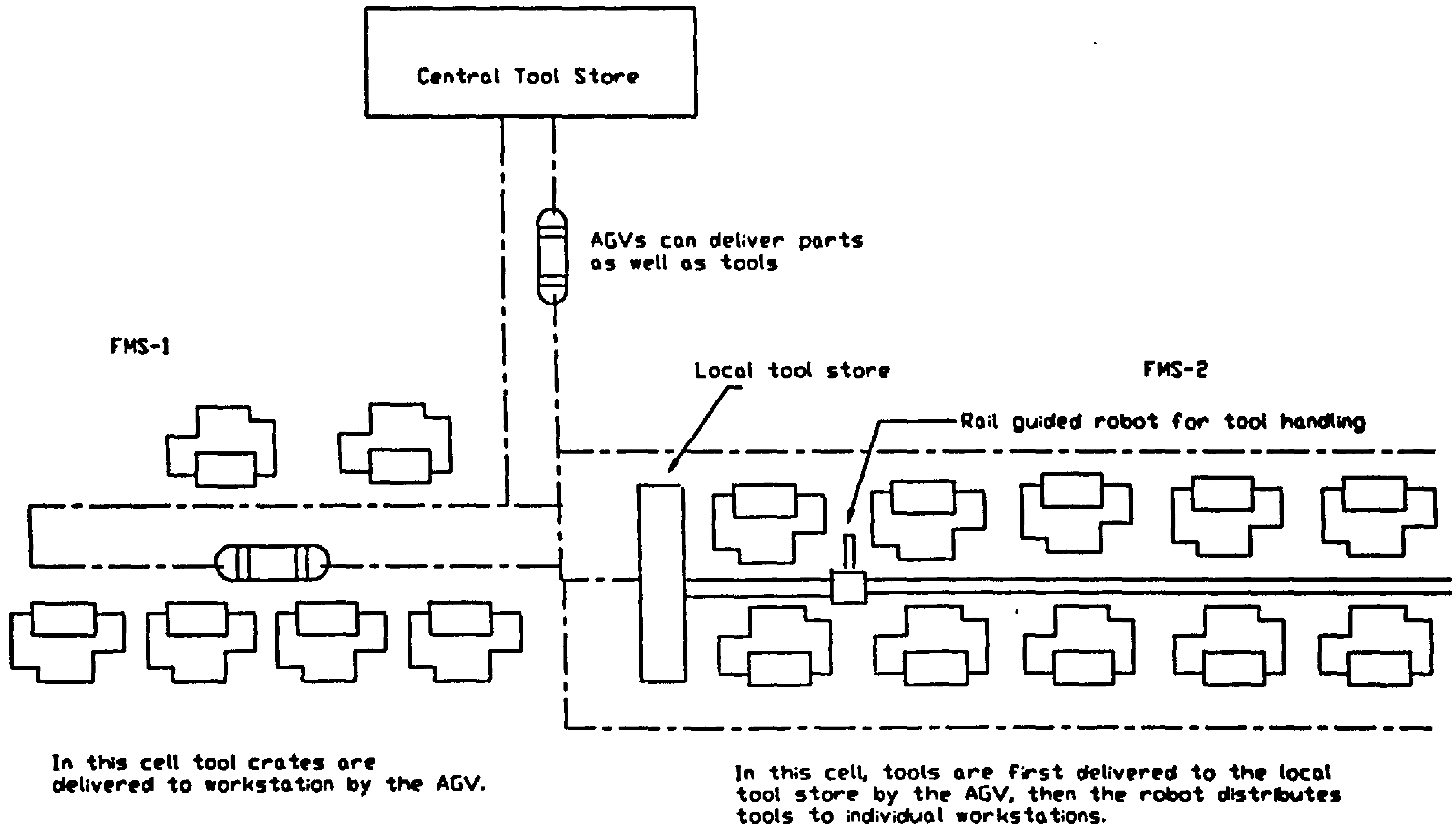
At present the system consists of two workstations and they are served by a single rail guided pallet transfer device [Fig. 7.3]. The company expects to add two more workstations in the next stage of implementation.

The high tool requirements forced the company to install an automatic tool delivery system between the tool store and tool magazines. At the back of machining centres there is a tool store with capacity for 180 tools. A rail guided truck with integral tool transfer device takes worn tools out of the magazine (72 pockets) and replaces them with new tools from the store.

Although the system consists of two workstations, it has a modest tool management problem due to high tool variety. It is vital to plan tool requirements in advance to avoid possible machine down time due to tool starving.

7.2.4 System D: Earthmover Component Flexible Manufacturing Systems

This is one of the most advanced flexible manufacturing facility in UK [Kellock 1985]. This system has a capacity to machine 28 basic part types and their variants, at a rate of 1400 per week. It consists of seven machining centres each with an 80 station tool magazine and an auxiliary 24 tool carousal, a co-ordinate measuring machine and two component washing machines [Fig. 7.4]. There is also a 60 position pallet buffer store. Three AGVs move parts and tools around the system.



In this cell tool crates are delivered to workstation by the AGV.

In this cell, tools are first delivered to the local tool store by the AGV, then the robot distributes tools to individual workstations.

Figure 7.5 System E: Aircraft Component Flexible Manufacturing System

AGVs can deliver and remove 24-tool turret at each machining centre. Worn tools are removed from the turrets at a centralized tool maintenance and presetting facility. New tools are replaced in the turret, ready for an AGV to deliver back to the workstation concerned. A second tool changer at each workstation exchanges tools between the turret and magazine.

There is a computer link between the company and the tool supplier to ensure replenishment of all tools and tooling components within 24 hours, with deliveries probably everyday when production reaches its peak.

The integral tool handling system and the nature of production set a complex tool management problem.

7.2.5 System E: Aircraft Component Flexible Manufacturing System

This is the largest, and most sophisticated flexible manufacturing system in UK [Kochan 1987, Capes P 1985]. The most remarkable aspect of the system is its ability to machine a very high variety of parts in very small volumes. It is capable of machining about 1500 parts in steel, titanium and aluminium alloys in batches of 5 - 10.

The flexible manufacturing facility consists of 2 cells with different hardware configuration and operational features [Fig. 7.5]. Notably, different methods of tool handling systems are adopted.

In the first system [FMS-1 in Fig. 7.5], crates of tools are delivered to the workstation by AGVs. At workstation AGV exchanges the new crate with the old crate which is then delivered to the central tool storage area. A tool crate can accomodate 63 tools which may be sufficient for several different part types.

In the second cell [FMS-2 in Fig. 7.5, dedicated to titanium and steel parts] a more dynamic tool handling system has been installed. These hard materials consume cutting tools quickly, therefore tool exchanges are more frequent. The AGV delivers crates with new tools to the cell and then they are transferred to a robot trolley which exchanges new tools with used tools in the magazine. Although there is very little opportunity for re- use of cutters used on titanium and steel, the cost of the chucks is very high so it is most important to minimize the number of chucks in the system and this means returning finished tools to the tool store as frequently as possible for break down.

Tool management is a major task in this system. Most parts require their own kits of tools. An enormously large number of tools have to be managed within the system.

The above description of different FMSs manifests the varying nature of the tool management problem which undoubtedly depend on a number of parameters such as product variety and tool exchange rates, etc.

7.3 DEFINITIONS FOR FMS TOOL MANAGEMENT PARAMTERS

So far the FMS research community has not provided any formal definition to tool management system parameters. It is vital to identify these influential parameters which may help to design and operate an appropriate tool management system for a given system.

The above review of tool management systems also indicated that the different values of these parameters will result in tool management systems with different levels of complexities. In the next section these parameters are defined and formulae are suggested to estimate their values. First a few basic terms are defined;

Product Variety

Product variety measures the number of different parts in the system.

Tool Variety

Tool variety describes the number of different tools required by a part in its manufacture.

Tool Complement

Tool complement is the set of tools needed to be present in a machine's magazine to carry out a specified set of operations on some set of part types.

The FMS tool managnement parameters are as follows;

7.3.1 The number of part types and part similarity

The number of part types alone cannot decide the nature of the tool management problem (i.e. a large number of part types does not mean a complex tool management problem). It must be related part similarity the extent to which the different part types require the same tool. Generally, high part similarity reduces the complexity of the tool management problem. The part similarity between two parts can be measured as follows;

$(NT)_A$ = The number of tools for part type A.

$(NT)_B$ = The number of tools for part type B.

$(TC)_{AB}$ = The number of tools common to parts A and B.

$$\text{Part Similarity Index (PSI)} = \frac{\text{The number of common tools}}{\text{The average number of tools per part}}$$

$$PSI = \frac{(TC)_{AB}}{((NT)_A+(NT)_B)/2} = \frac{2(TC)_{AB}}{((NT)_A+(NT)_B)}$$

For parts with completely different tool requirements (TC=0) PSI becomes zero and for parts with identical tool requirements PSI is one. As a rough estimate, when the part similarity index is greater than 0.7 the parts are assumed to have very similar tool requirements.

Although System A processes a large number of different parts, the part similarity is high so a simple tool management system will suffice. On the other hand, in System C, most product mixes require a large tool complement due to low part similarity.

7.3.2 The number of tools per operation and the average tool kit size

The average number of different tool types required per operation has some impact on the tool management system, in particular on tool handling aspects.

Generally, the average number of tool exchanges per operation increases with the number of tools required per operation. Therefore the tool kits destined for machining centres tends to have a large number of tools when the tool requirements per operation are high.

This is an important parameter to be controlled when automated tool handling systems are used. If the tool kit size exceeds the capacity of the tool handling system, all required tools may not be delivered in a single visit to workstation causing the machine idle time due to tool starving.

Therefore, some estimate of the average tool kit size is required, before the tool handling system is designed. The computer simulation seems to be the only technique which can provide the statistics about the tool kit sizes.

System D and System E use automated tool handling systems and therefore the average number of tools per operation is a vital parameter to be controlled when new part types are introduced and/or existing parts are modified. For example, the capacity of the tool handling system in System-D is 24. If more than 24 tools are required by an operation then multiple visits of the AGV are required.

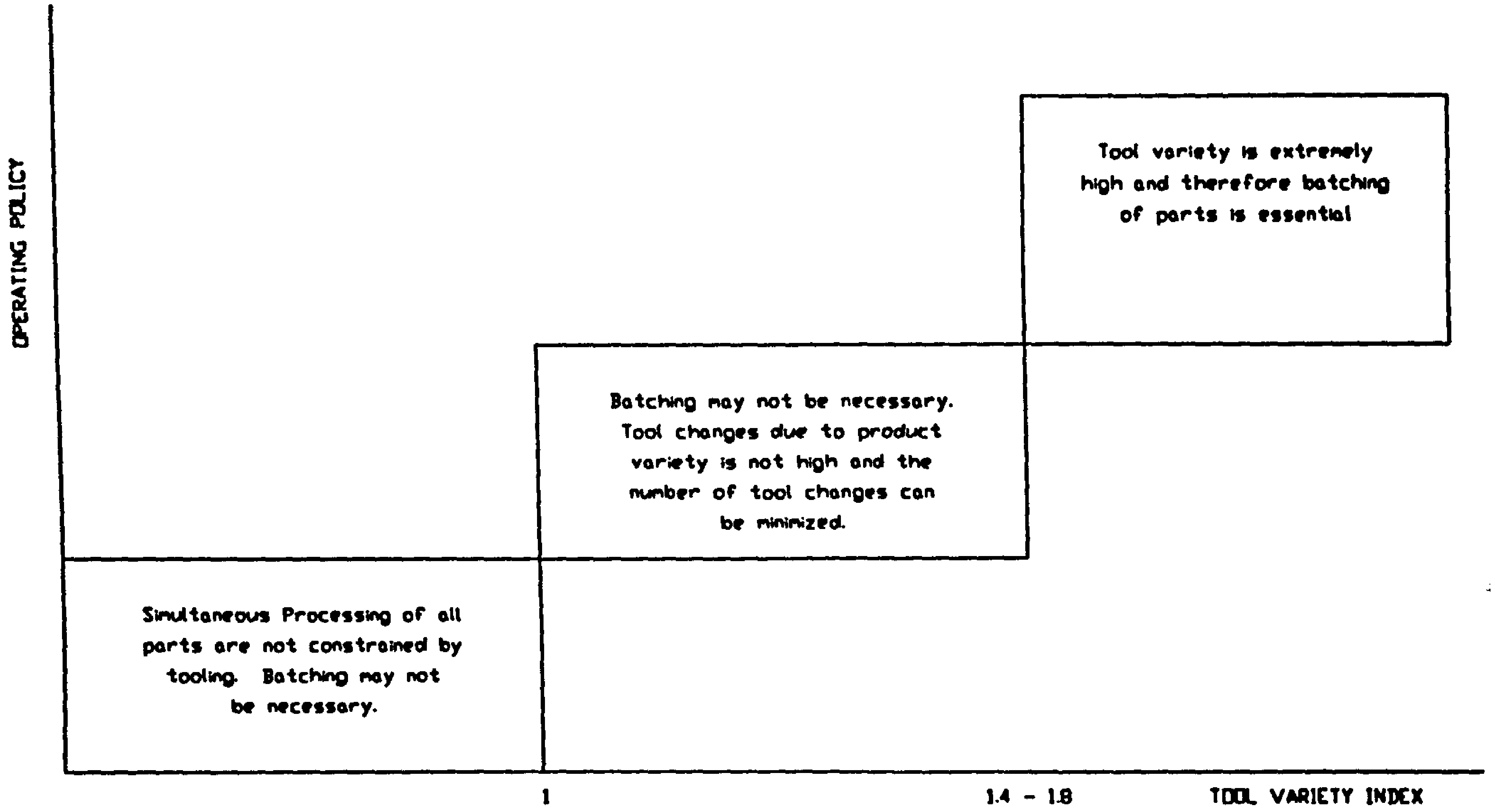


Figure 7.6 The Effect of the Tool Variety Index on the Operating Policy

7.3.3 Tool Magazine Capacity and Tool Variety Index

Generally, a high tool magazine capacity reduces the complexity of the tool management problem. However, a more meaningful parameter can be defined, if the tool complement for a given product mix is considered, namely the tool variety index.

$(TC)_i$ = The tool complement at ith station for a given product mix.
$(TM)_i$ = The tool magazine capacity of ith station.
$(TVI)_i$ = The tool variety index of ith station.

$$(TVI)_i = \frac{(TC)_i}{(TM)_i}$$

The system tool variety index can be computed as follows;

n = The number of station with tool magazines.

$$(TVI)_{system} = \frac{\sum_{i=1}^{n} (TVI)_i}{n}$$

It can be argued that the value tool variety index can decisively set the way the system is operated [Fig. 7.6].

When the tool variety index is less than one, all tools required can be mounted on the magazine, and it simplifies the tool management problem. However for larger part variety and tool variety, the tool complement exceeds the tool magazine capacity. Once this situation arises, it will be necessary to change tools from time to time as different part types arrive at the workstation. These tool exchanges are referred to as tool exchanges due to product variety. In this case tool management is a complex task.

With the exception of System A, for all systems described the tool variety index appears to exceed 1 for most product mixes. It is vital to understand that this

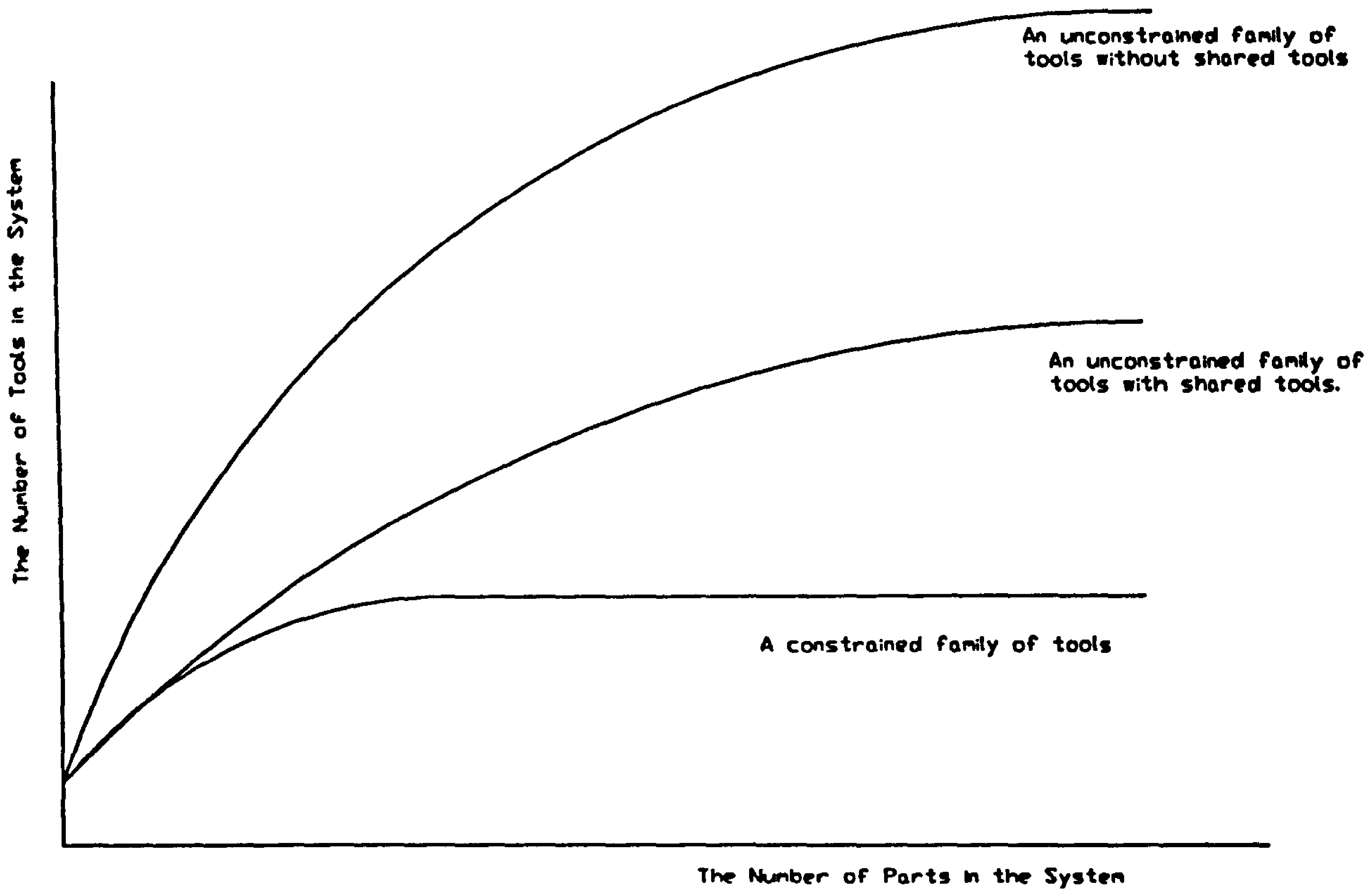


Figure 7.7 The Growth of Tool Population

parameter is dynamic as it depends on the product mix being processed. Therefore different strategies need to be implemented in different planning periods.

So far the tool complement has been expressed in terms of the number of tools. However, in many systems, different sizes of tools are used. Therefore, when the tool variety index is computed, the number of tool pockets must be considered instead of the number of tools. It is difficult to generalize the different sizes of tools as many non-standard tools are used. The different sizes of tools found in a real FMS are described in section 7.4.3.

7.3.4 The total number of tools

The number of tools in the system has a large impact on tool management cost and tool inventory costs. Generally, the tool population increase with the number of part types. Two major scenarios exist as shown in the Fig. 7.7.

A constrained family of tools

The number of tool types rises steadily for certain numbers of part types and reaches a constant level. The expansion of the tool family is explicitly constrained to avoid complex tool management problems. A fixed number of tool types is maintained by selecting parts which have similar tooling requirements. System A is a classic example of this nature.

An unconstrained family of tools

In this case the number of tools constantly increases, as part types are added to the system, resulting a complex tool management problem. However the rate of growth depends on the number of tools shared (common tools) different part types. System D demonstrates a lower growth rate where as System E has a higher growth rate.

7.3.5 The rate of tool exchanges

The rate of tool exchange is a predominant parameter which influences the various aspects of tool management. The tools are exchanged due to variety of reasons;

a. Tool wear

As the machining progresses, useful life of the cutting tool is reduced due to wear and the tools are exchanged when they reach a certain percentage of the useful tool life. The rate of tool exchanges due to tool wear, for a given workstation can be estimated as follows;

(PT) = The system operational time per period (mins/week).
$(UT)_i$ = The expected utilization of ith station (%).
$(TL)_i$ = The average cutting life of tools assigned to ith station (mins).
$(RTWR)_i$ = The rate of tool exchanges due to wear at ith station(per week).

$$(RTWR)_i = \frac{(PT)(UT)_i}{(TL)_i}$$

The rate of tool exchanges for the system can be computed as follows;

$$(RTWR)_{system} = \sum_{i=1}^{n} (RTWR)_i$$

The second FMS described under System E has a higher rate of tool exchanges due to wear.

b. Tool Breakage

By nature they are random failures and the mean time between failures can be used to compute the number of tool exchanges due to breakages. Generally, this component of the total tool exchange rate is negligible. If excessive tool exchanges due to breakage were observed, either cutting conditions must be altered or different types of tools must be used.

c. Product variety

As explained above, in some system tool exchanges can take place due to product variety. The estimation of the rate of tool exchanges due to product variety (RTPV), however depends on the way the system is operated.

Part batching and bulk tool exchanges

In order to overcome the problem of limited tool magazine capacity, the production orders can be grouped into several batches which have similar tooling requirements. These batches are released sequentially to the system with bulk tool exchanges between batches. In this case the following formulae can be used *t*o compute the rate of tool exchanges due to product variety.

$(NT)_i$ = The number of tools at ith station due to last batch.
$(CT)_i$ = The percentage of common tools between the last batch and the current batch at ith station (expressed as a value between 0.0 and 1.0).
BT = The expected processing time of the current batch.
$(RTPV)_i$ = The rate of tool exchange due to product variety at ith station.

$$(RTPV)_i = \frac{(NT)_i * (1-(CT)_i)}{(BT)}$$

System-B descibed above, is operated in this way.

Continous tool exchanges

When batching of parts is not permitted due to the nature of the production environment, discrete tool exchanges takes place as different part types visit the workstation. In this case, no formulae can be suggested and the computer

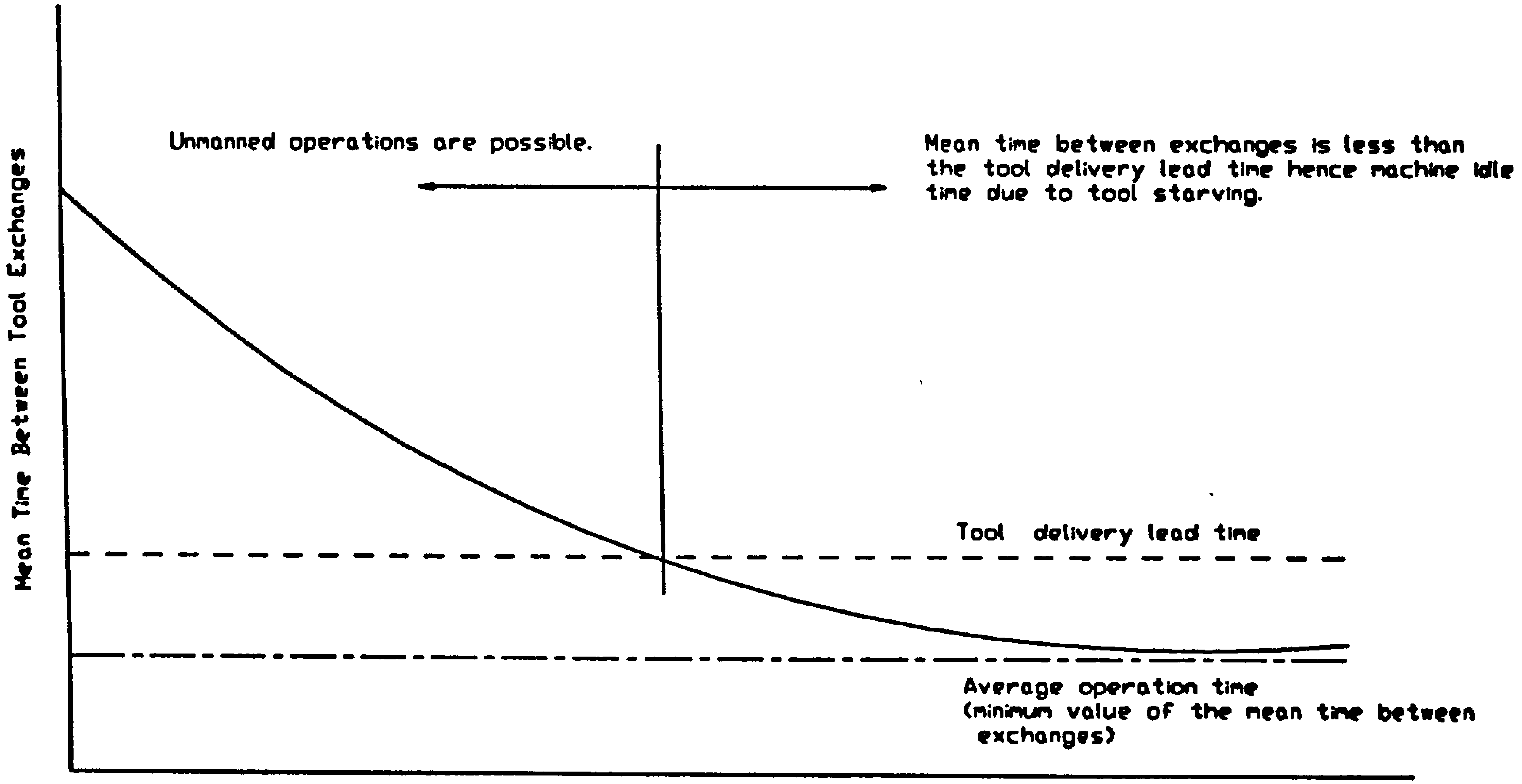


Figure 7.8 The Effect of Mean Time Between Tool Exchanges on System Operation

simulation is regarded as the only way of computing the tool exchange rate due to product variety.

System C has a higher number of tool exchanges due to product variety and tools are exchanged discretely.

7.3.6 The mean time between tool exchanges

The mean time between tool exchanges is another vital parameter which may be useful in system design and tool scheduling. By comparing this parameter with tool delivery lead time (the time elapsing between the request for tool and tool delivery), the following general rules can be drawn [Fig. 7.8];

a. Tool delivery lead time < mean time between exchanges

In this case tools required for the next exchange can be assembled during the period between exchanges. For higher ratios (of mean time between exchanges/tool delivery lead time), tools required for several batches can be assembled and makes unmanned operation possible for certain periods.

b. Tool delivery lead time > mean time between exchanges

If this occurs, the machine waiting time due to tool starvation may be high. The different courses of actions, which may be appropriate in different cases;

Tool exchanges due to tool wear is high

Majority of tool exchanges are carried out due to tool wear. The loss of production can be minimized by providing more sister tools in the magazine.

Part Type

	1	2	3	4	5	6	7	8	9	10	11	12
1		0.4567	0.5018	0.3524	0.4375	0.4020	0.6667	0.3717	0.3182	0.3429	0.302	0.3119
2			0.4784	0.4724	0.5385	0.5227	0.4238	0.4747	0.4271	0.4505	0.4505	0.4105
3				0.3684	0.5190	0.3805	0.5302	0.3524	0.3801	0.3697	0.3836	0.3744
4					0.4120	0.4564	0.3306	0.3977	0.8455	0.8903	0.8344	0.8466
5						0.3714	0.4290	0.4655	0.3540	0.3981	0.3929	0.3839
6							0.3470	0.4595	0.3944	0.4697	0.4143	0.4143
7								0.3568	0.3319	0.3200	0.3262	0.3176
8									0.3780	0.4156	0.3704	0.3704
9										0.7973	0.7692	0.7692
10											0.8082	0.8219
11												0.9740

Figure 7.9 The Part Similarity Matrix

Tool exchanges due to product variety is high

In this case a large number of tools are exchanged due to product variety. The frequency of tool exchanges may be reduced by changing operational strategies, for example by controlling the part release sequence.

In both cases, the addition of a tool backup and/or the expansion of the tool magazine capacity can be considered as a long term solutions.

7.4 SYSTEM PARAMETERS OF A REAL FMS

For the system described in chapter 3, the tool management parameters were computed with the following result;

7.4.1 The number of part types and part similarity.

Although 7 part types were considered at the design stage, having identified the benefits of flexible manufacture, further 5 types has been added to the system. The part similarity indexes are shown in Fig. 7.9. Part types 4,9,10,11 and 12 appears to have very similar tooling requirements (the part similarity index 0.7).

7.4.2 The number of tools per operation.

The average number of tools used in an operation is about 18 with a maximum of 54 tools in one case (for more information see chapter 3).

7.4.3 Tool variety index

As pointed out in section 7.3.3 the tool requirements must be expressed in the number of pockets instead of the number of tools. Generally, tools can be categorized as follows.

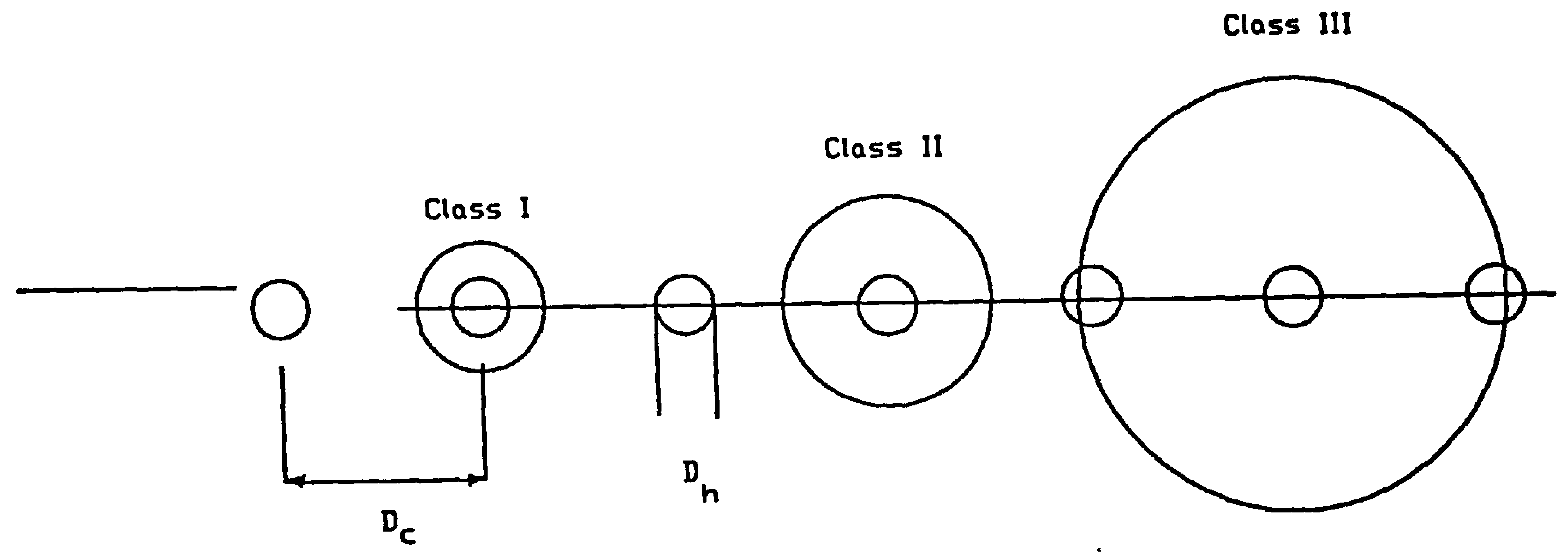


Figure 7.10 Different Classes of Tools

Asymmetrical Tools

The outer envelope of the tool is not symmetrical about the central axis of the holder.

Symmetrical Tools

The outer envelope of the tool is symmetrical about the central axis of the holder.

These symmetrical tools can be further categorized upon the size of tools. The following notation is used with conjuction with Figure 7.10.

D_c = centre distance between adjacent pockets.
D_h = the largest diameter of the tool holder.
d = tool diameter

The following classes of symmetrical tools were found in this system;

Class I $d < D_c$

These tools do not interfere tools in adjacent pockets.

Class II $D_c < d =< 2D_c - D_h$

Although these do not cover neighbouring pockets, tools of the Class II cannot be placed in adjacent pockets.

Class III $d >= 2D_c - D_h$

Adjacent tool pockets are covered, hence no tools can be placed in neighbouring pockets.

According to the above classification Class II tools impose neighbourhood constraints while Class III tools demand multiple pocket requirements.

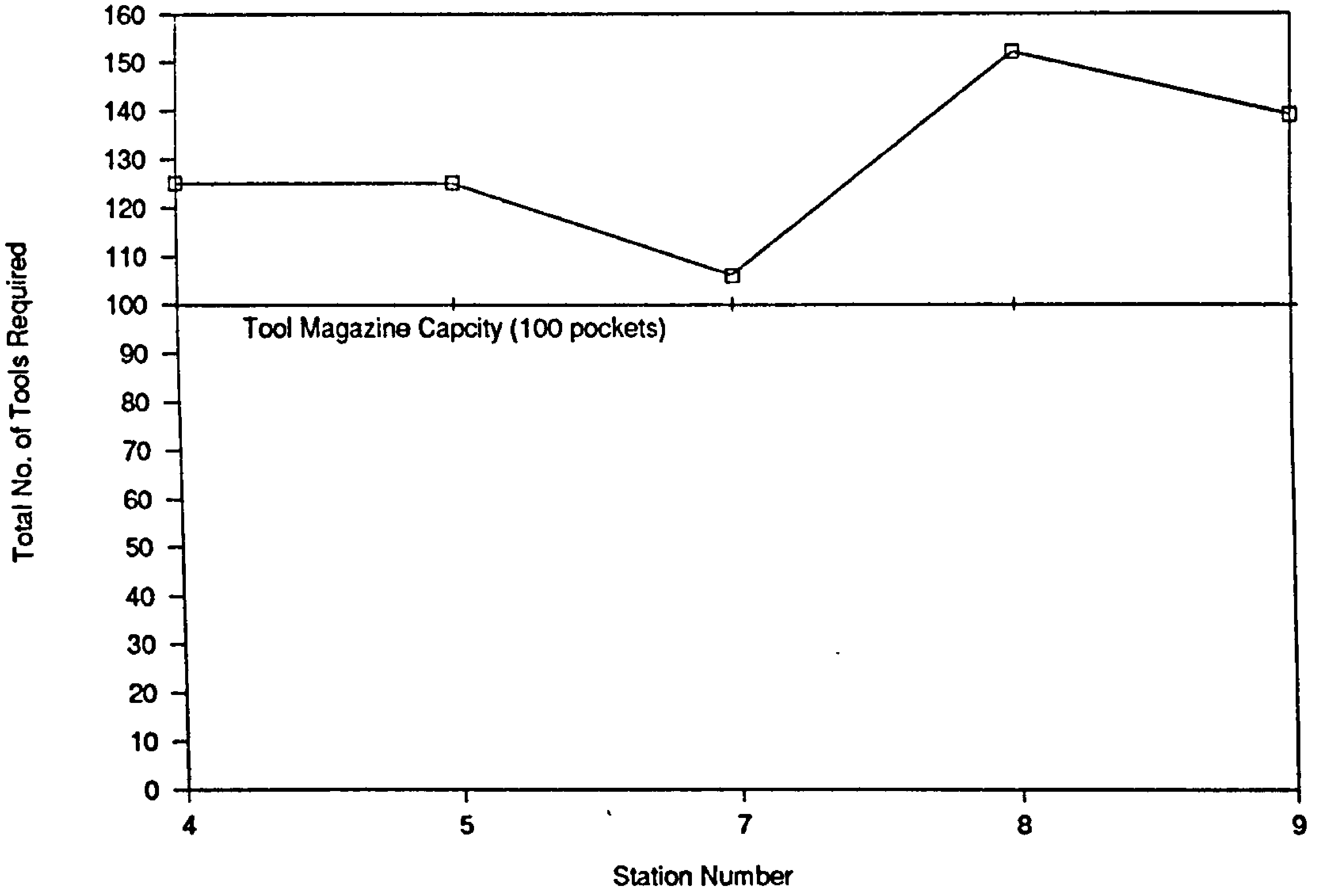


Figure 7.11 The Total Tool Pocket Requirements

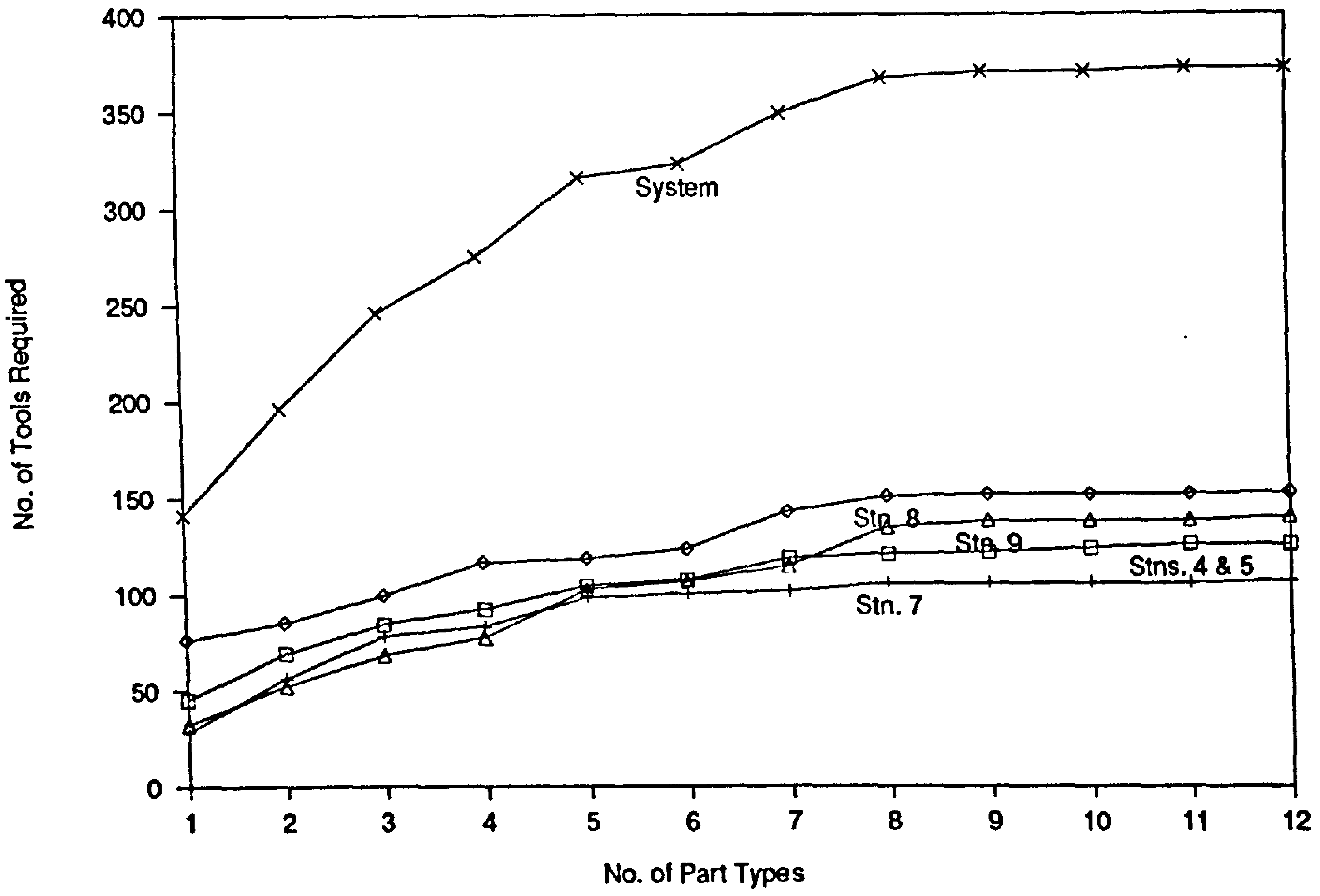


Figure 7.12 The Growth of Tool Population

No asymmetrical tools are used in this FMS and the number of symmetrical tools of each class are as follows;

Class	I	II	III
No. of tools	293	34	45

As explained above, the tool variety index is a dynamic parameter. However its maximum value can be computed assuming that all part types are simultaneously processed. The tool pocket requirements at each workstation are shown in Fig. 7.11. As the tool variety index exceeds one a higher number of tool exchanges due to product variety can be expected.

7.4.4 The total number of tools

The growth of tool requirements at workstation and the system is shown in Fig. 7.12. At this stage it has a low growth rate.

7.4.5 The rate of tool exchanges

a. Due to wear

Using very rough estimates of the spindle cutting time, which varies considerably between machines , say 30%, and an average tool life of 30 minutes, for a two shift week, about 200 tool exchanges per week can be expected.

b.Due to product variety

This highly depends on the characteristics of parts being processed. It was found that for certain product mixes, the number of exchanges can be as high as 400 exchanges per week [section 8.7.1].

7.4.6 The mean time between tool exchanges

This parameter also depends on the nature of product mix being processed [please see section 8.7.2 for more information].

7.5 CONCLUSION

The management and control of FMS may be a complex task and there are enormous number of parameters which can influence the nature of the tool management.

It is possible to generate rules, based on above parameters for design and operation of tool management systems. These rules can be regarded as the catalyst for a rule based expert system for tool management system.

CHAPTER 8

MODELLING TOOL FLOW: A TOOL POST-PROCESSOR AND A TOOL FLOW SIMULATOR

8.1 INTRODUCTION

In the quest for improved operational strategies to overcome constraints imposed by tools, it is vital to understand the scale of the problem in first place. In particular, for the selected type of FMS, the rate of tool exchanges due to product variety may be high. However, this requires a model which can estimate the number of tool exchanges.

Undoubtedly, the first attempt would be to extend the part flow simulation model to mimic the flow of tools. As explained in chapter 4, two simulation systems concerned (ECSL and GCMS) have certain inherited drawbacks which prevent them being used for tool flow modelling.

However the data generated from such models in conjunction with a tool post-processor can be used to obtain the essential statistics of the tool management system. Having perceived the scale of the tooling problem with the assistance of the tool post-processor, it was realized that a tool flow simulator which can provide real time data is essential when production planning problems are solved. The program modules of the tool post-processor were further enhanced and linked to the GASP based part flow simulation system.

In this chapter the design and development of the tool post- processor and the tool flow simulator are presented. The application domains of these tools are also discussed.

8.2 THE TOOL POST-PROCESSOR: DESIGN CONSIDERATIONS

At the first stage of the research program it was necessary to identify the scale of the tooling problem. Before committing the effort into the development of a tool flow simulator it was thought that the existing model (ECSL) could be used with a tool post-processor to obtain essential statistics about the tool management system.

The underlying principle of the tool post-processor is quite similar to that of the graphical post-processor. By adding afew program statements to the base simulation system, the information about *completed cutting operations* can be directed to a separate data file. The relevant attributes of cutting operations such as operation start time, part type and operation number, etc. are stored in this file.

The tool post-processor reads this data file and uses the system data such as tool requirements of operations, etc. to compute the system parameters related to the tool management system. Although the method of estimation is straightforward it requires a massive amount of data and quite complex logic for tool handling.

8.3 DATA REQUIREMENTS

The number of cutting tools in a medium sized FMS can easily run into thousands [Perera and Carrie 1987(b)]. Each of these tools may have a large number of attributes which define its status. The management of this data within a simulation program may be a quite intricate task. The data base management systems (DBMS) can make a valuable contribution as they provide a mechanism that can be used to control, manage, store and retrieve data. Among the different types of DBMSs (i.e. hierarchical, network and relational) [Atre 1980], the relational approach provides a simple but powerful way of building the conceptual model. It uses two dimensional *tables* as the basis for data representation. The concepts provided in relational approach were used when data associated with tooling system were established.

Generally, more than one tool of the same type is used within the system (for example backup, tools). Each *tool type* inherits a large number of static data attributes such as cutting edge geometry, tool life and tool size etc. Therefore each tool in the system has its tool type attributes and a set of dynamic data attributes such as the location of tool and accumulated wear etc. Following the ideas supplied in relational data management systems, these data are stored in two separate tables (or files). The following are regarded as the minimal set of data required for tool flow modelling [Perera and Carrie, 1987(b)];

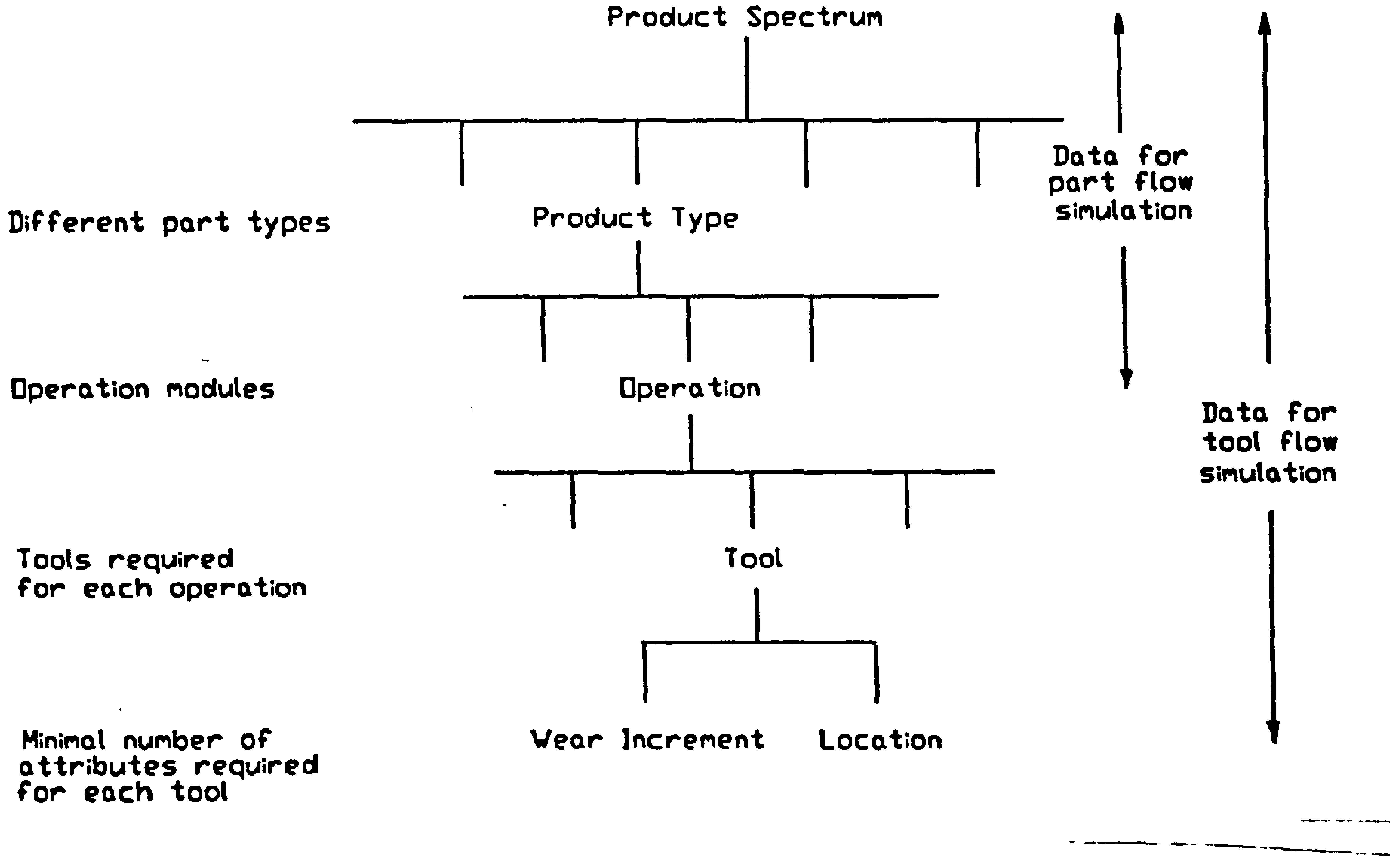


Figure 8.1 The Expansion of Input Data for Tool Flow Simulation

Entity	Attributes
Tool Type	Tool Type ID, Tool Class ID, Maximum tool life
Tool	Tool ID, Tool Type ID, Location, Accumulated wear

Having defined the system tool database, it is also necessary to declare tool requirements for each operation which uses one or more cutting tools. Generally, the tool requirement files hold data about tools needed for operations. In these data files, an estimation of tool wear for each tool is also included (see chapter 5 of the volume 2 for more information).

It is clear that even a simple FMS may have a massive tool database. The explosion of data required for tool flow simulation is shown in Fig 8.1. Effective and efficient management of simulation data becomes more important when tooling aspects are taken into account.

8.4 SETTING UP THE TOOL CONFIGURATION

In part flow simulation studies, generally, it is assumed that the system is empty at the start and the collection of statistics is begun after a certain period to eliminate any transient effects. However, when tools are involved, it is necessary to setup the tool configuration (which tool in which pocket) prior to simulation. The following major steps are involved in setting up the tool configuration.

8.4.1 Selection of the initial product mix

The tools associated with this product mix are assigned to workstations at the start. It well may be a subset of parts which go through the system in the first planning period or a set of representative part types.

8.4.2Generation of tool requirements at stations

Given the initial product mix, the tool complements at each workstation are computed next. The part route files are decomposed into individual operations and the tools required at each station are listed.

8.4.3 Tool Loading

Having obtained the lists of tools required at each workstation, the tools are placed in the magazine. At this stage, however several aspects associated with the tooling system need to be considered.

8.5 CONSIDERATIONS IN TOOL LOADING

When different sizes of tools exist, it is vital to place them in a logical manner to reduce the number of empty pockets and/or the number of subsequent tool exchanges. This discussion refers to the tool classes defined in the section 7.4.3.

8.5.1 Reducing the number of empty pockets

The class III tools take three consecutive pocketsbut they do not impose any constraints on the types of tools to be placed in neighbouring pockets. Although class II tools take a single pocket, two class II tools cannot be placed in adjacent pockets. Thus class II tools must be alternatively placed with either class I or class III tools.

8.5.2 The nature of tool exchanges and the rate of exchanges

When tools are exchanged due to tool wear and breakage, the exchange strategy is simple, i.e. the old tool is replaced by a new tool of the same tool type. Therefore the same pocket can be used by the new tool.

However, when tools are exchanged due to product variety, the situation is more complex, because a suitable pocket must be found for the new tool. In particular, it is difficult for class II and class III tools. For example, when the tool magazine is full, and a pocket is being sought for a class III tool two different strategies can be adopted: another class III tool not used in the current operation or a set of class I and class II tools can be selected for removal. However the later strategy increases the tool exchange rates.

8.5.3 Tool Encoding System

The way tools are placed in the magazine is greatly influenced by the manner and system of tool encoding. Different methods of tool encoding are employed and the following are basic variants [Hans 1986].

Method 1: Direct Magazine

Tools are called upon consecutively in a fixed sequence and have been pre-arranged in the magazine.

Method 2: Location Encoding

Individual magazines are encoded from 1 to n (n=magazine capacity) and stored tools within these locations are called up. After use, each tool is returned to its assigned location in the magazine.

Method 3: Tool Encoding

Each tool receives encoding ring on its cylindrical shaft as its unique identification.

The direct magazine concept is no longer used in modern NC controllers. Other two approaches have several advantages and disadvantages [Hans 1986]. These essential advantages of the last two techniques have blended to form the most popular tool encoding system.

Method 4: Variable Location Encoding (Random tool selection)

This technique embodies the desirable features of the techniques (2) and (3) above . This approach has the following advantages;

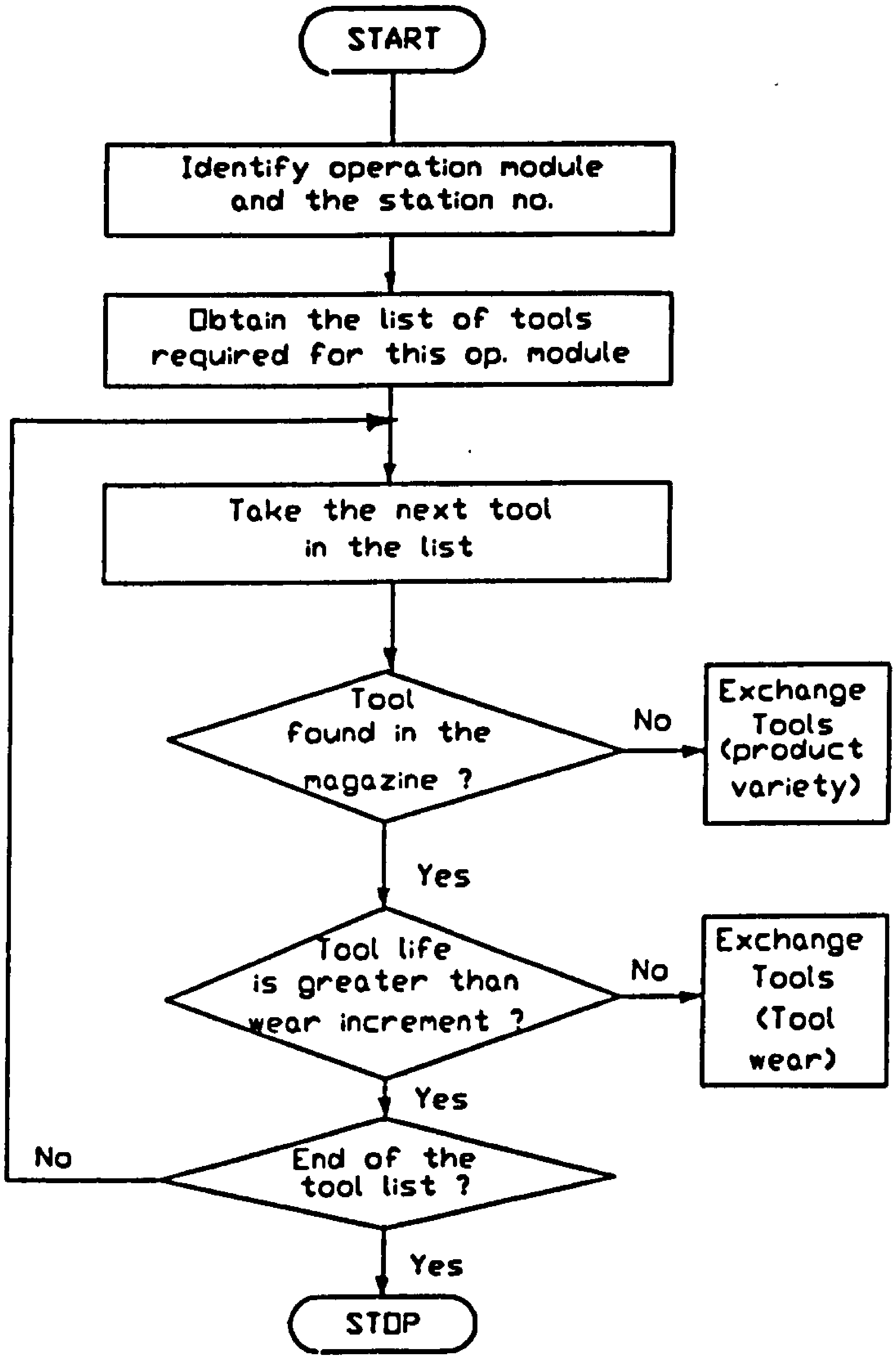


Figure 8.2 The Different Types of Tool Exchanges

- Use of uncoded tools.
- use of reliable location encoding.
- programming of the tool number in the program.
- search via short route.
- short exchange time through dual grippers.

It is clear that the relative size of tools and the tool encoding system need to be considered when tools are exchanged. These aspects of tool handling are catered for in the tool post-processor which embodies the random tool selection strategy.

8.6 OPERATIONAL ASPECTS AND THE IMPLEMENTATION OF THE SIMULATOR

The tool post-processor accesses the trace file and decodes records one by one. Attributes (times, station number, part type, etc.) of the records are passed to the processing modules of the processor. The part type and the operation number are used to obtain the the list of tools required at the station. Then the corresponding tool magazine is searched to check the presence of required tools. The following scenarios may exist [Fig 8.2];

Senario 1

The required tool is found with adequate tool life to complete the current operation. No tool exchange is required in this case.

Scenario 2

The required tool is found, but with inadequate tool life to complete the current operation. The tool is exchanged with a new tool of the same type and the new tool will take up the same pocket.

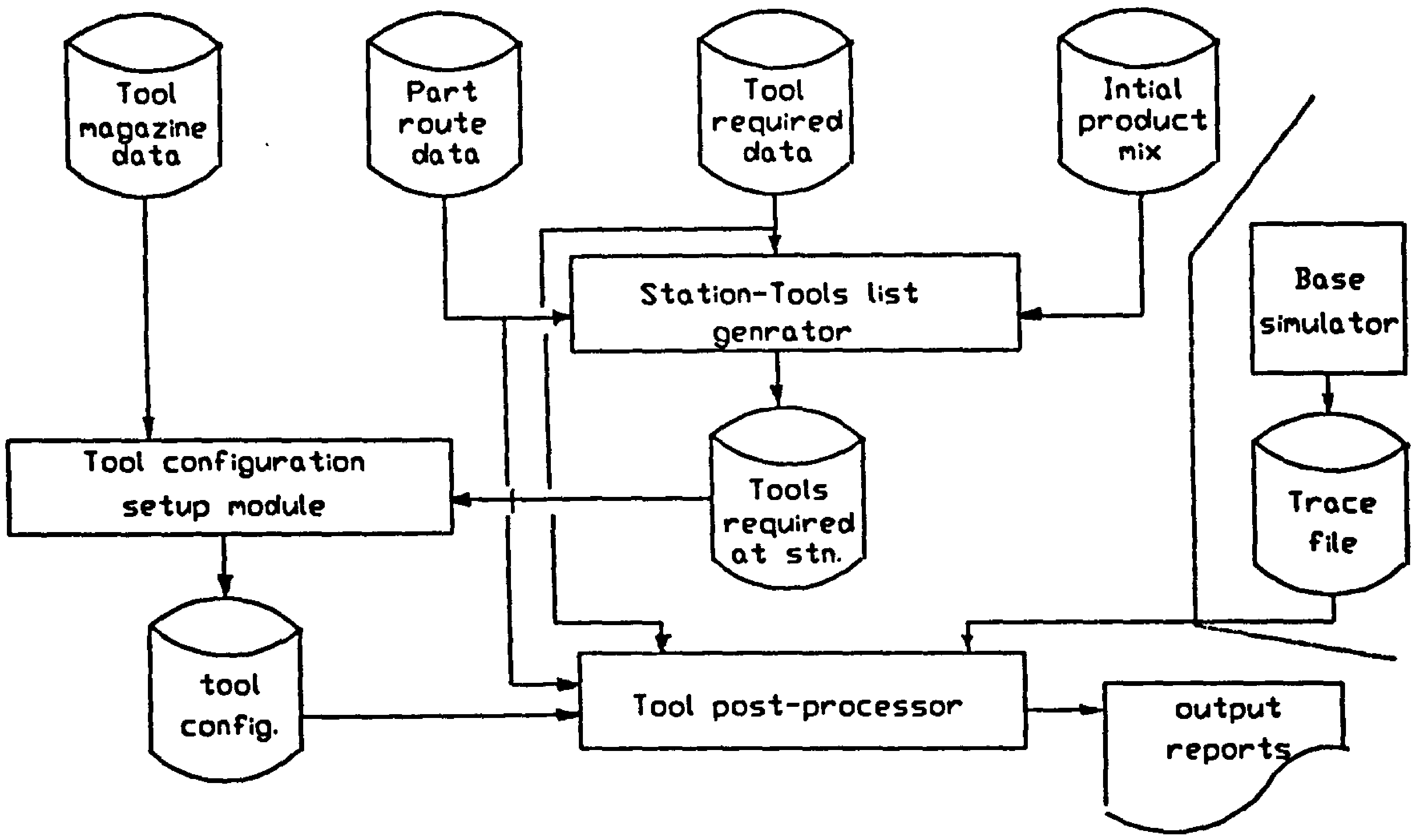


Figure 8.3 The Major Program Modules of the Tool Post-processor

Scenario 3

The required tool is not found. Tools have to be exchanged due to product variety. Perhaps it may be necessary to unload one or more tools to accommodate the new tool.

In all cases the direct tool exchange between the tool magazine and the central tool store is assumed. The program routines associated with tool post-processor were coded in FORTRAN 77. As in other programs two versions (VAX/VMS and IBM/PC) are available. More information about the IBM/PC version can be found in chapter 5 of volume 2. The Major modules of the tool post-processor are shown in Fig. 8.3.

8.7 IDENTIFYING THE SCALE OF THE TOOLING PROBLEM

The Main objective of this exercise was to identify the scale of the tooling problem. In the high tool variety environment of FMS, the complexity of the tool management problem may be best represented by the rate of tool exchanges due to product variety.

When the experiments were designed the tool variety index (TVI) (section 7.3.3) was taken as the control parameter. It takes different values for different product mixes. The part similarity indexes (section 7.3.1) were used to generate the initial product mixes of which the tool complements do not exceed the tool magazine capacity. Then more dissimilar parts (again using the product similarity indexes) were gradually added to the initial product set to create new product mixes with different values for the tool variety index.

A typical set of product mixes are shown below;

Part Types	The System Tool Variety Index
6,4,8,10	0.682
6,4,8,10,7	0.972
6,4,8,10,7,3	1.138
6,4,8,10,7,3,5	1.318

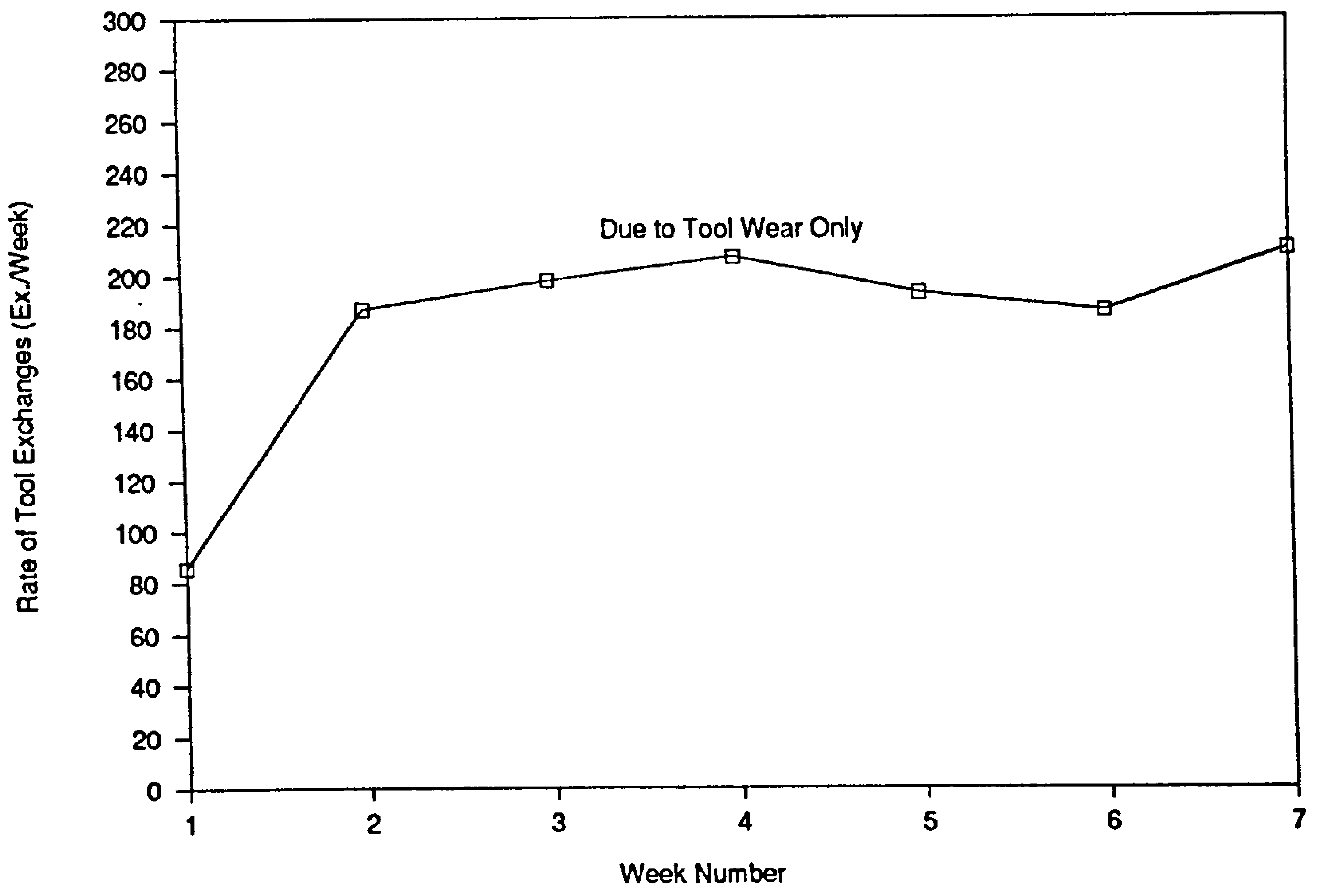


Figure 8.4 The Rate of Tool Exchanges (The System TVI = 0.682)

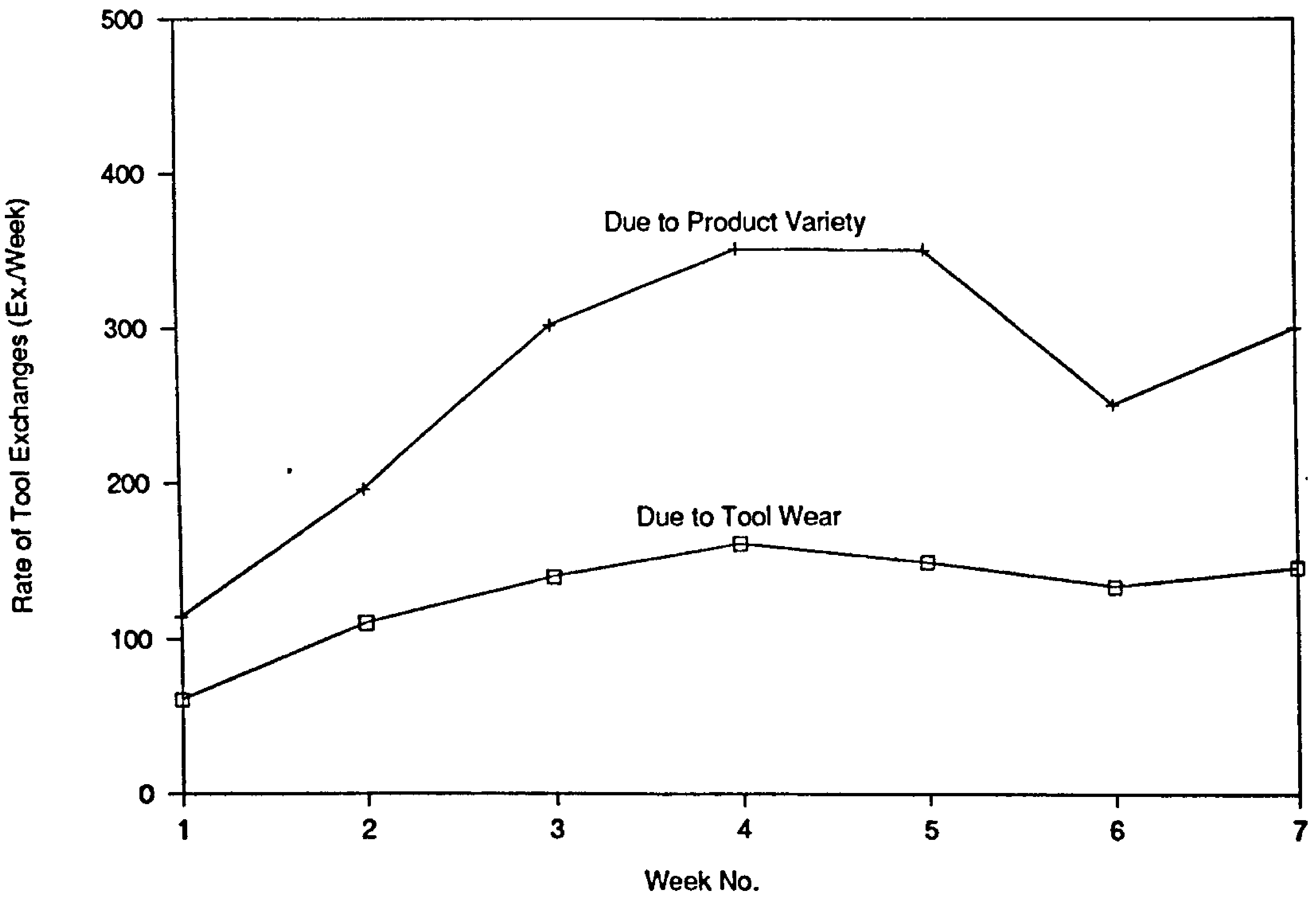


Figure 8.5 The Rate of Tool Exchanges (The System TVI = 1.138)

6,4,8,10,7,3,5,1	1.400

In this experimental setup, the part types 6,4,8 and 10 were selected as the initial product mix. In order to eliminate any effect of the initial product mix, the experiments were conducted with different initial product mixes.

The part flow simulator and the tool post-post processor were extensively used to estimate a number of tool management parameters which provide insight into the tooling problem.

8.7.1 The Rate of Tool Exchanges

The rate of tool exchanges for two different values of the tool variety index are shown in Fig. 8.4 and Fig. 8.5. In the first case (Fig. 8.4) the size tool complements at each workstation are less than the respective tool magazine capacities, therefore the rate of tool exchanges due to product variety is zero. The average tool exchange rate due to tool wear is very close to the value estimated (200 exchanges/week) in section 7.4.5.

Fig. 8.5 depicts the rate of tool exchanges when the system tool variety index exceeds 1 (in this case the system tool variety index is 1.138). The system tool variety index is the average of the tool variety indexes of workstations. In this system, the tool variety index vary quite significantly between workstations. For example, the system tool variety index of 1.138 was given by the following components;

Station No.	**Tool Variety Index**
4	1.08
5	1.08
7	0.84
8	1.48
9	1.21

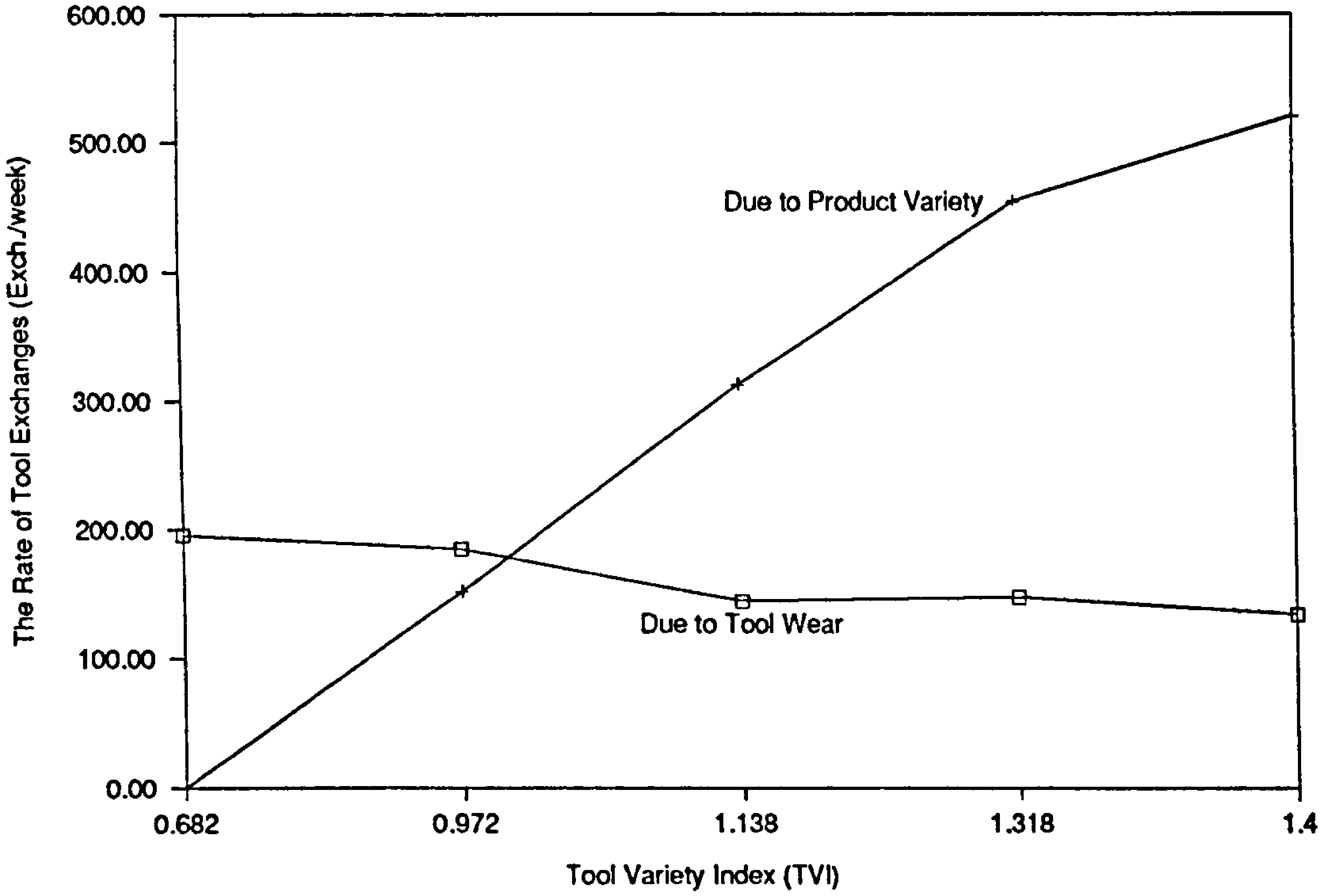


Figure 8.6 The Variations of Tool Exchange Rates with Tool Variety Index

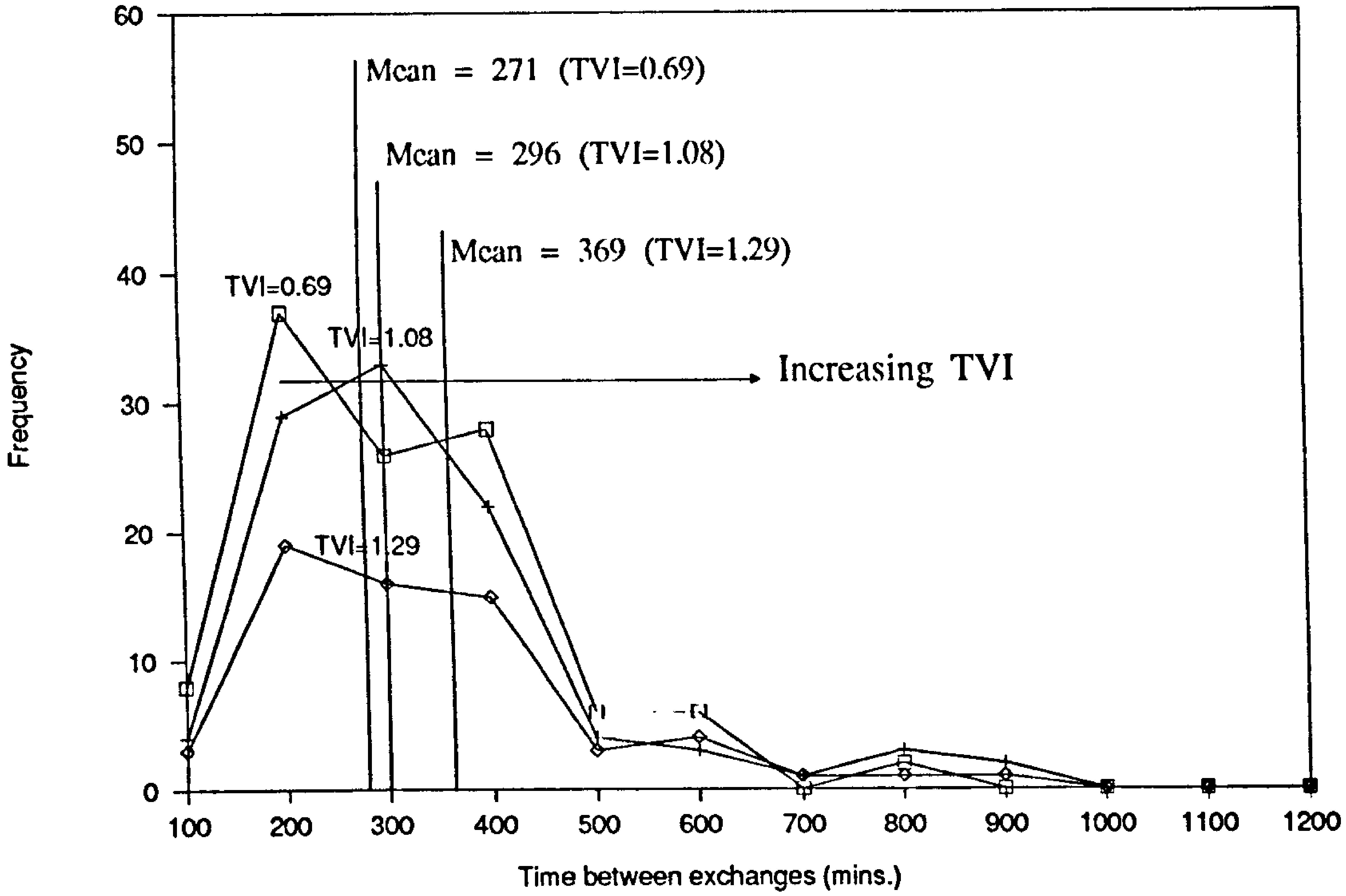


Figure 8.7(a) The Distribution of Time Between Tool Exchanges at Station 4. (Due to wear only)

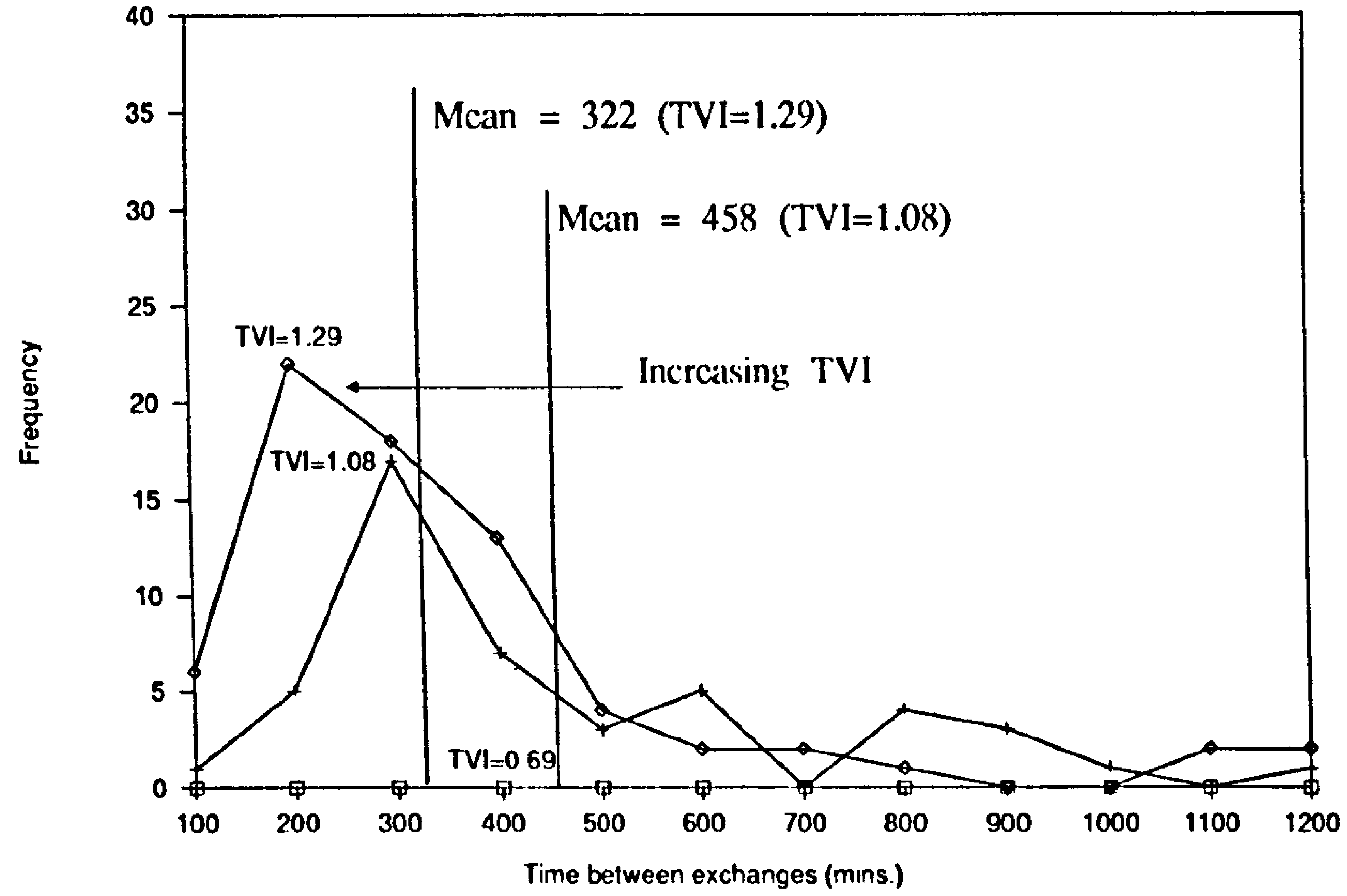


Figure 8.7(b) The Distribution of Time Between Tool Exchanges at Station 4 (Due to product variety only)

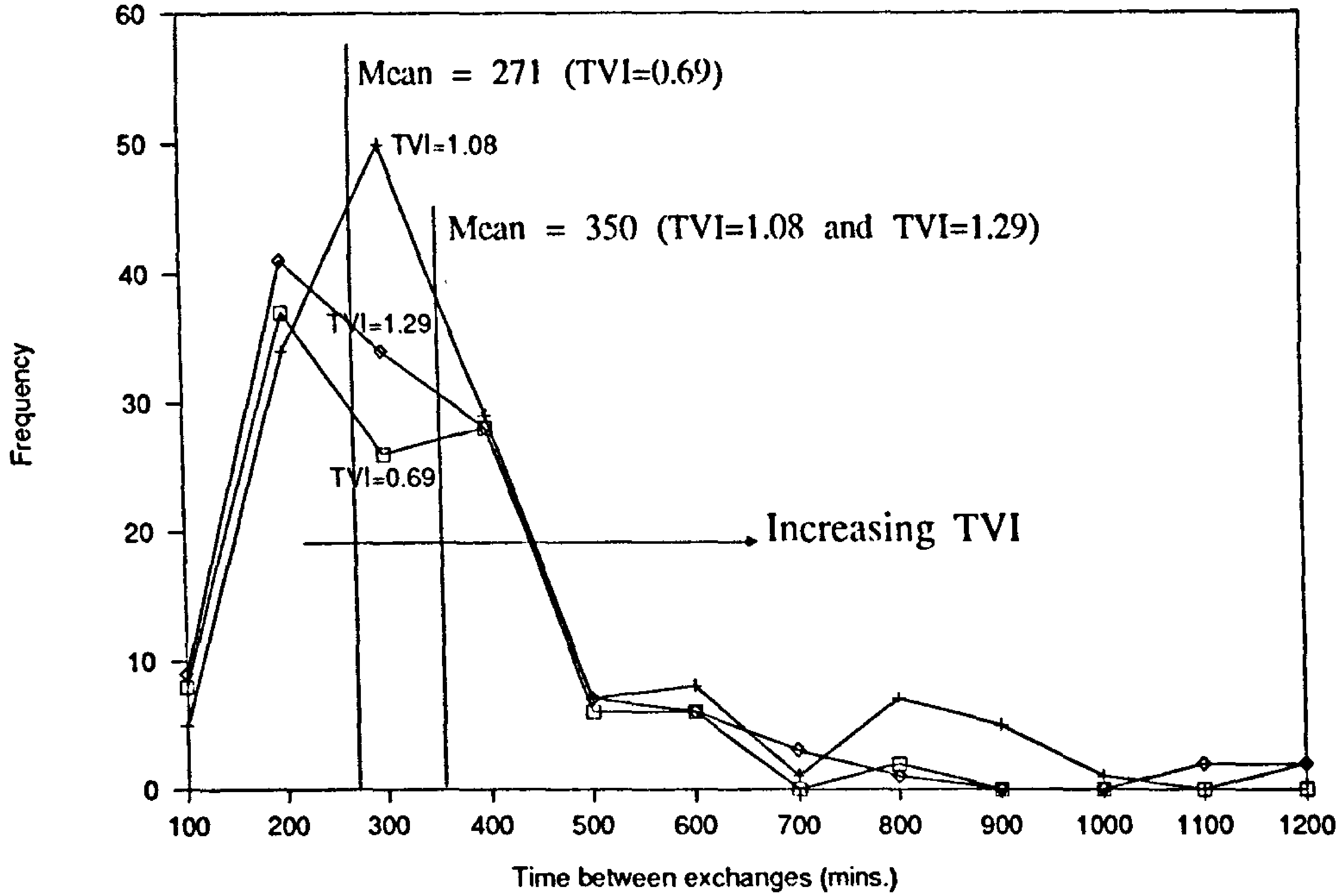


Figure 8.7(c) The Distribution of Time Between Tool Exchanges at Station 4 (Due to tool wear and product variety)

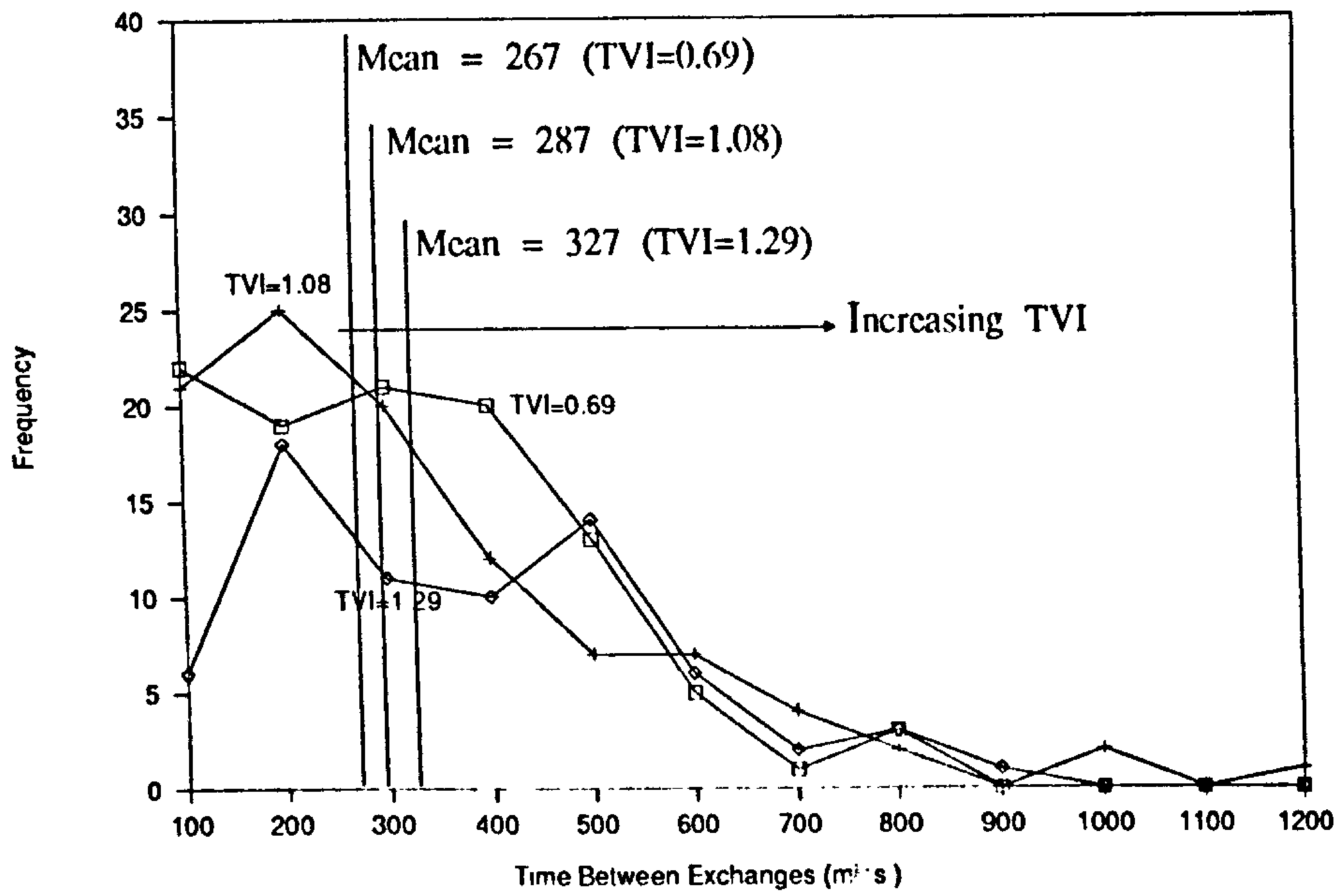


Figure 8.8(a) The Distribution of Time Between Tool Exchanges at Station 9 (Due to tool wear only)

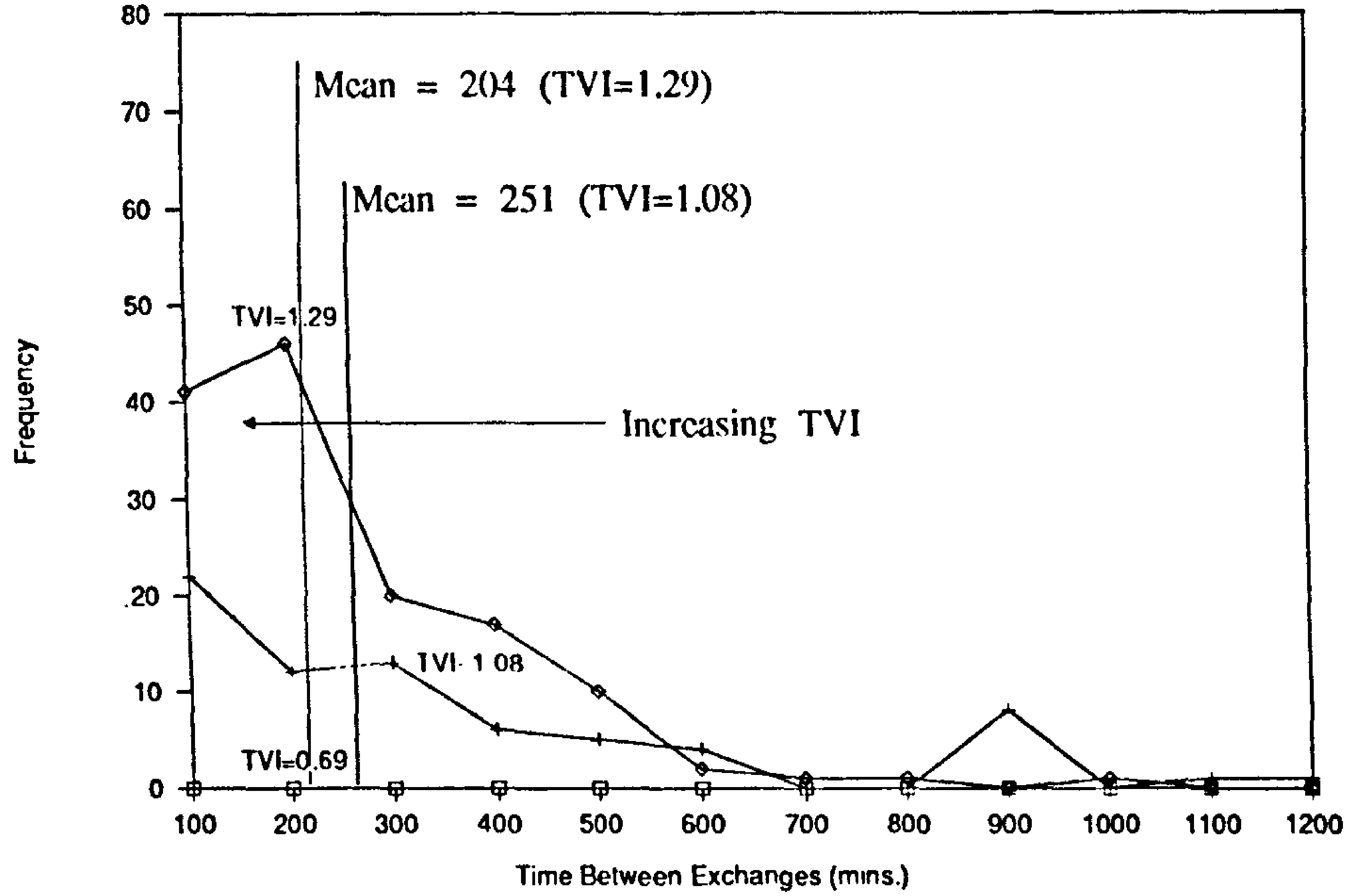


Figure 8.8(b) The Distribution of the Time Between Tool Exchanges at Station 9 (Due to product variety only)

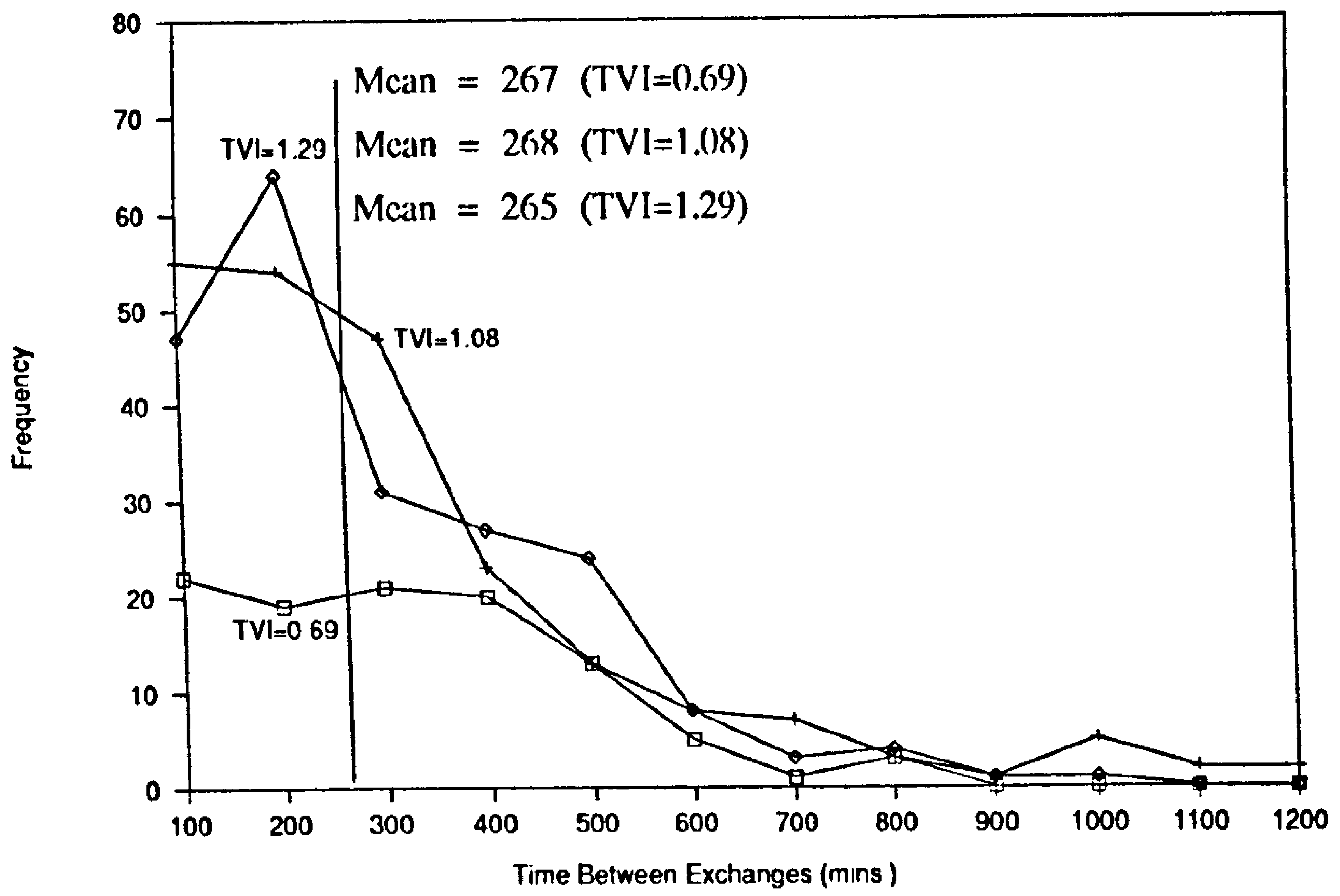


Figure 8.8(c) The Distribution of Time Between Tool Exchanges at Station 9 (Due to tool wear and product variety)

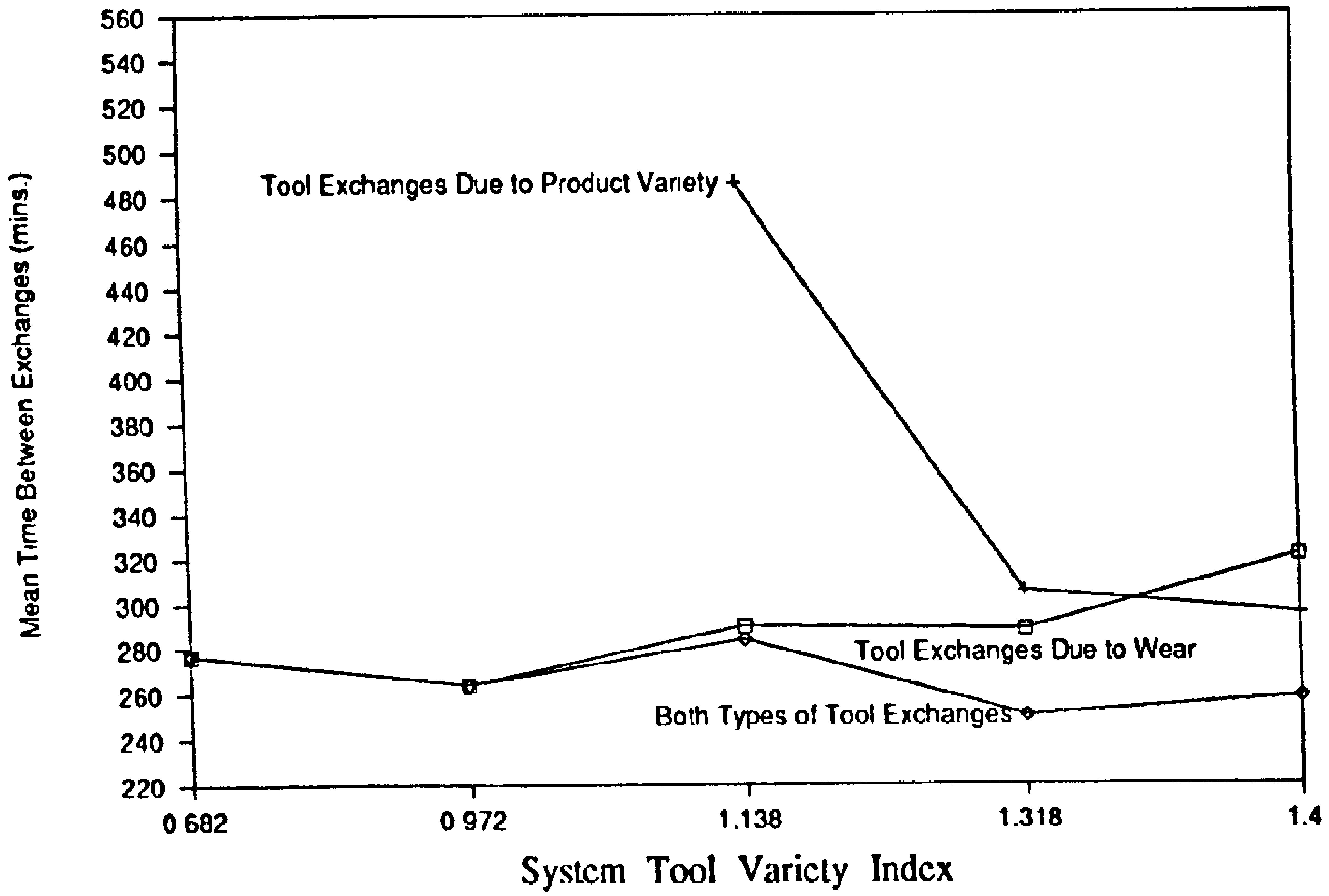


Figure 8.9 The Variation of Mean Time Between Tool Exchanges with Tool Variety Index (at station 4)

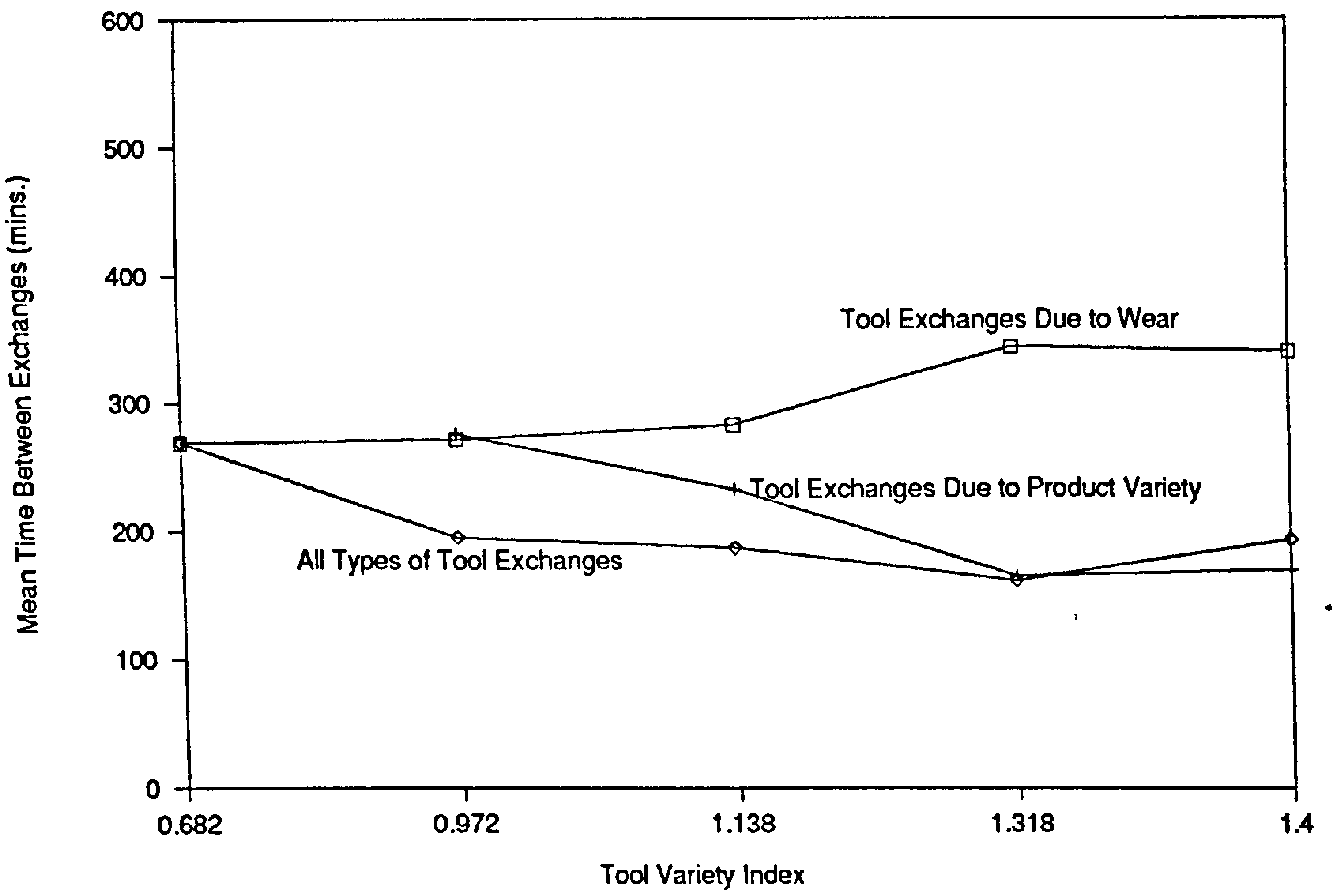


Figure 8.10 The Variation of Mean Time Between Tool Exchanges with Tool Variety Index (at station 9)

Therefore for some workstations, the rate of tool exchange due to product variety may be zero (in this instance, the station no. 7) although the system tool varirty index exceeds 1. However, in this case, the rate of tool exchanges due to product variety is much greater than the rate of tool exchanges due to tool wear.

The variation of the tool exchange rates with the system tool variety index is shown in Fig. 8.6. The rate of tool exchanges due to product variety rapidly increases with the tool variety index. Although the rate of tool exchange due to tool wear drops for the high tool variety indexes, its value is not large enough to counterbalance the increase in tool exchange rate due to product variety. Thus the total tool exchange rate rises quite significantly.

Therefore it is absolutely necessary to reduce the the rate of tool exchanges due to product variety to a manageable level.

8.7.2 The Time Between Tool Exchanges

This is one of the parameters which decides whether the unmanned (or lightly manned) operation of the system is possible. As in the above case, this parameter is also highly depend on the characteristics of the part mix being processed. To obtain a more comprehensive picture, the time between tool exchanges due to each case (i.e due to tool wear and product variety) were individually monitored. A set of distribution curves for two different stations are shown in Fig.8.7(a) to Fig 8.8(c).

The distribution of mean time between tool exchanges for different values of tool variety index are shown in Fig. 8.9 and Fig. 8.10. When the tool variety index increases, the mean time between exchanges due to product variety drops substantially (i.e. more frequent tool exchanges). However, it was found that the mean time between exchanges for all types of changes does not change significantly, due to increase in the mean time between tool exchanges due to tool wear.

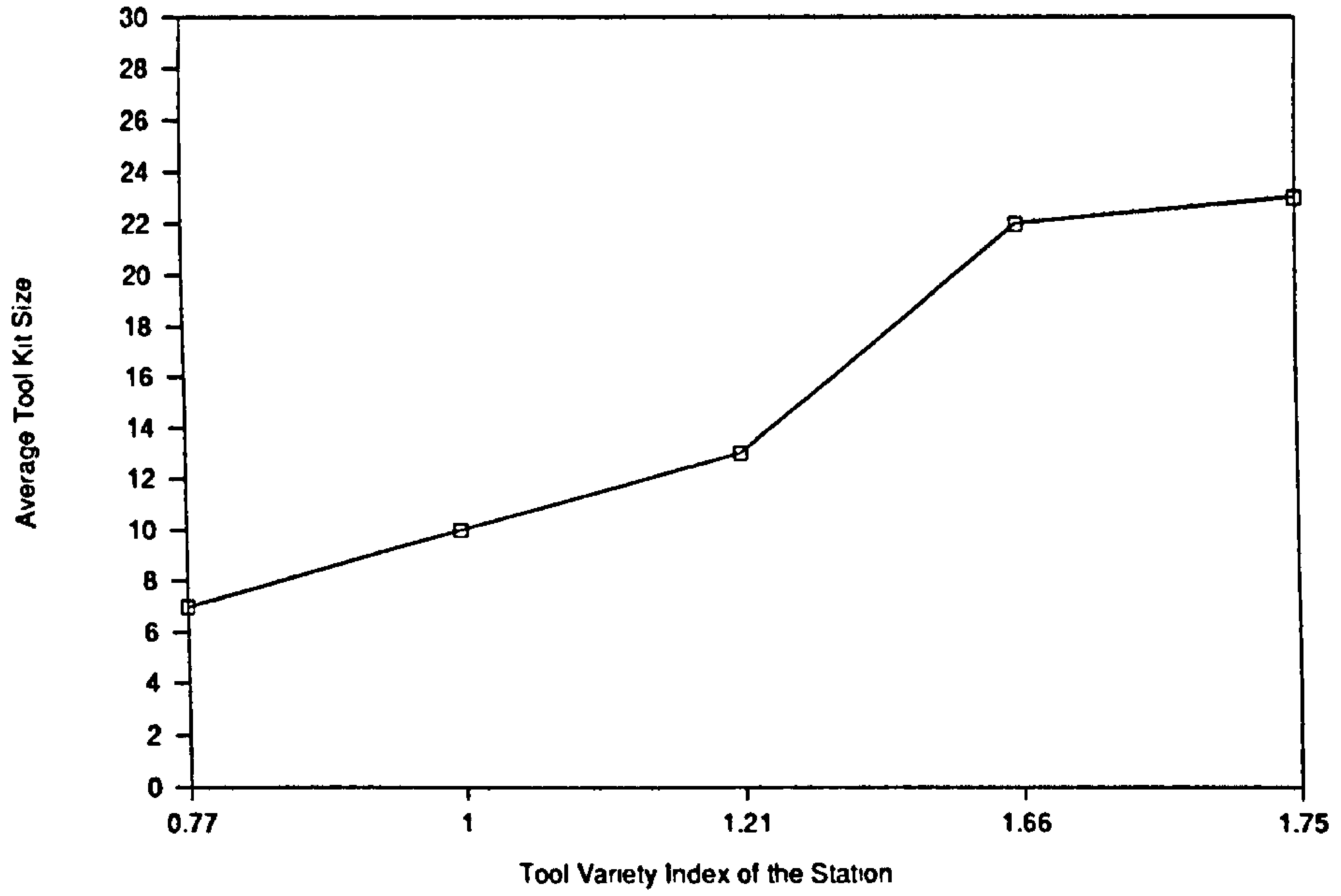


Figure 8.11 The Variation of Average Tool Kit Size with Tool Variety Index (at station 9)

```
**  Week No: 2  Day: 1  Shift: Day  **

    ** Station no: 4 **

    Tool type ID   Quantity
    132            1
    13             2
    4              1
    274            1
    135            1
```

Figure 8.12 Output from Tool Requirement Planning Module

It was noticed that for certain product mixes, the tools have to be exchanged about every two hours. Therefore unmanned operations seem to be a remote option for this system.

8.7.3 The Tool Kit Size

The average tool kit size also increases with the tool variety index. For certain product mixes, the tool kit size was about 30 tools. The increase in average tool kit size of station 9 is shown in Fig. 8.11.

8.8 TOOL REQUIREMENTS PLANNING

Apart from supplying information about tool exchange rates etc. the tool post-processor can help the management to plan tool requirements. In order to calculate the number of tool exchanges, the types of tool involved are identified within the processor. This information can be re-grouped on the basis of a time slot (say, a shift) and station numbers. Thus tool required at each station for a given period can be obtained from the tool post-processor. Fig. 8.12 depicts a typical output from this module of the post-processor.

The information provided by the tool requirement planning module may not be very accurate due to the following reasons;

- **a.** Some CNC controllers adjust cutting conditions to reduce the rate of tool wear therefore pre-determined wear increments may not be same as the actual wear increments.

- **b.** The base simulator cannot mimic all unpredictable events. Thus actual part flow may be slightly different from the flow patterns output by the simulator.

- **c.** Most simulators cannot emulate the system. Thus the results depend on the level of abstraction used in the model.

However it is expected that this approach provides a better estimation of tool requirements compared with the other static tool requirement planning packages.

8.9 A TOOL FLOW SIMULATOR

Although the tool post-processor can be useful in some applications, it suffers from a major drawback i.e. it cannot provide dynamic data related to the tooling system. But availability of real time data is essential when production planning problems are solved. For example, the selection of part types for immediate processing can be influenced by the current system tool configuration. Thus the part flow simulation model must be extended to capture tooling aspects of the system.

The information about modelling tool flow can hardly be found in literature. A small number of tool flow simulators have been developed by various research groups for specific applications. So far no commercially available package has emerged. In the following others modelling approaches are briefly explained;

> Elamaraghy [Elmaragy and Ho 1984] reports TOOLSIM program which can be used for designing and evaluating automated tool handling systems. The package has been written FORTRAN IV and GASP IV. It has some rudimentary graphical features to animate the tool flow.
>
> Crite and others [1985] discuss the capabilities of the PATHSIM package which uses SLAM simulation language. The tool and part handling systems within the model are independent and a dedicated tool handling system is used.
>
> Two simulation packages TOOLSIM1 and TOOLSIM2 have been developed at the Cranfield Institute of Technology [Kay 1985]. These packages can model tool exchanges between various tool stores (at workstation level) in detail. TOOLSIM1 is concerned with tool handling at a workstation whereas TOOLSIM2 can model tool exchanges in a multi-workstation system.

Bell and Souza [1987] reports a simulation system with tool flow modelling capabilities. This model has been developed in-house on an enhanced IBM AT microcomputer, using a high level programming language (Pascal).

All models described above use simulation as the underlying modelling technique. Two other noteworthy approaches have been reported in FMS literature.

Bruno and Biglia [1985] uses Petri Nets to model tool handling in FMS. In their model, conveyors are used to move tools within the system. Impact of the number of conveyors and the ratio (machining time)/(delivery time) on machine utilization has been investigated using this model.

Vinod and Sabbagh [1984] attempts to model tool handling systems using queueing network theory. It is used to predict system performance and to allocate spare tools to workstations in an optimal manner.

These non-simulation approaches however, have very limited applications in complex tool handling systems. Bruno and Biglia [1985] conclude that a system with several machines and tools cannot be handled in their model. A large number of unrealistic assumptions have been made in Vinod and Sabbagh model. Therefore this further strengthens the assumption that only simulation can model essential complexities of tool flow within an FMS.

Within the tool post-processor a simple flow of tools was assumed. However, real FMSs have more complex flow patterns but with different degrees of complexity. Therefore it was necessary to select a representative tool flow pattern.

8.9.1 Tool flow Management

In a review of literature on tool management [Zeleny 1981, Elmaragy 1984, Ber A and Falkenburg 1985, Zeleny 1985, Acaccia et al. 1987] the following emerged as the major activities of tool flow management;

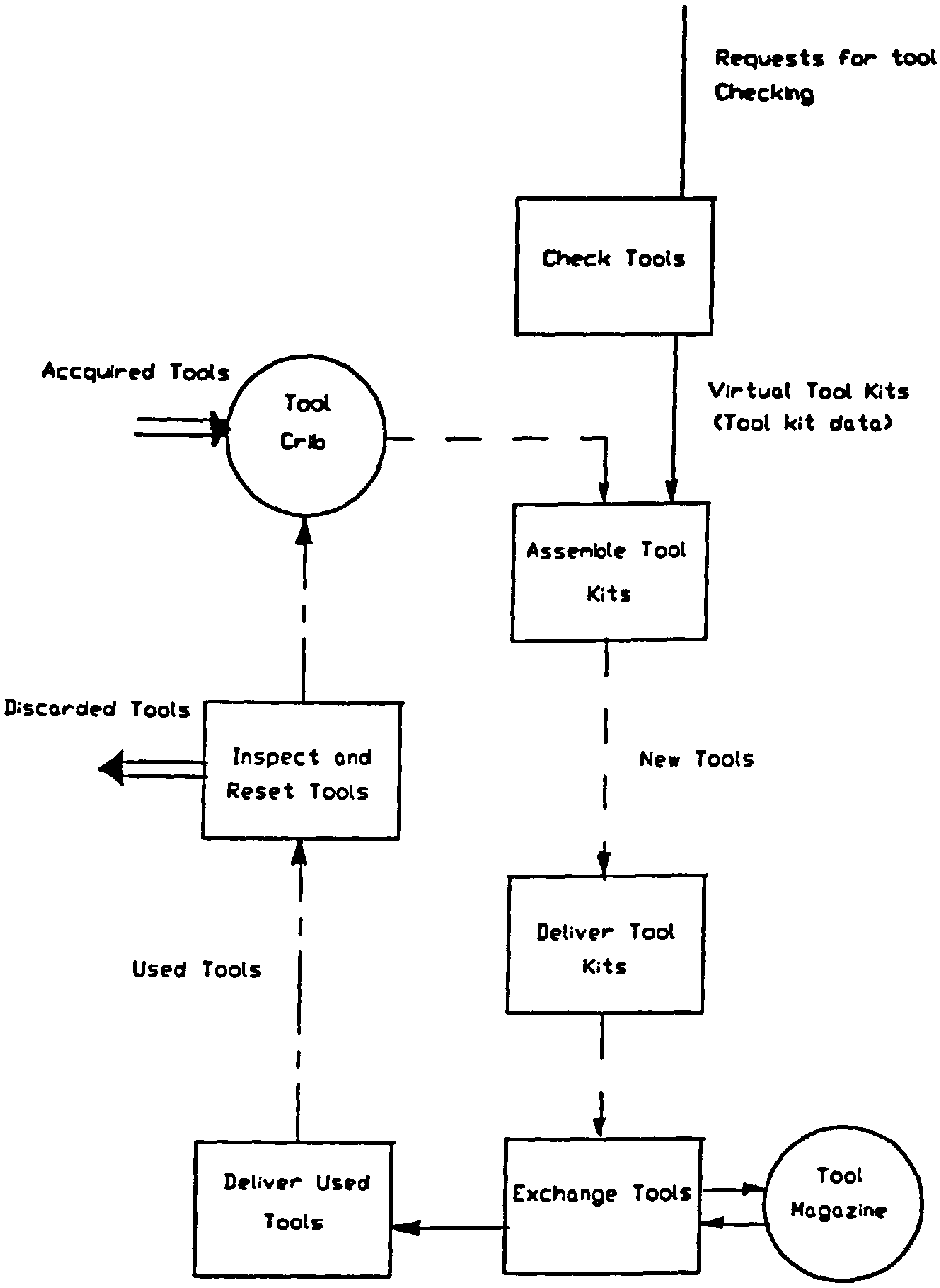


Figure 8.13 The Tool Flow in a Typical FMS

Tool Crib Management

This function is mainly concerned with tool management within the central tool stores. In respond to requests from the FMS and/or from any other planning activity, kits of tools are made. These kits are issued to the system when the tool handling devices are available. Tool inventory management is also a sub-task under this function. Several software packages have been developed to support these functions [Sandora 1984, Anon. 1985, WCI Controls and Data Systems, 1986, Mason 1986, Brohan 1986, Gayman 1987, ISIS 1987].

Tool Delivery Systems

In most systems tools are delivered to workstations by operators. A few examples of automated tool handling systems can be found in section [Zeleny 1981, Weimer 1983].

Tool Tracking and Monitoring

Positive identification of individual tools is an important feature in any FMS. The movements of tools are continuously monitored by the central computer. Various tool identification techniques have been develop to facilitate this activity [Murphy and Kay 1987].

Tool Inspection and Presetting

Used tools which returned from the system are inspected and preset. Nearly in every FMS, the presetting station is linked to the central computer and tool data are updated accordingly.

A typical flow of tools is depicted in Fig. 8.13. Although this sequence of activities appears to be common in many FMSs, the management of tools within the each activity widely varies. For example, the nature of tool delivery strategies highly depend on the type of tool handling system. When operators are used the tool handling seems to be very informal.

8.9.2. An Integrated Tool Flow Simulator

The program routines of the tool flow simulator were further enhanced and linked to the part flow simulator. The major improvements are that the tool flow simulator can handle several tool kits simultaneously and provide real time data.

8.10 CONCLUSION

The management of tool flow is much more difficult than that of the part flow due to the number of tools involved and the complexity of flow patterns. Consequently the modelling of tool flow is also a quite intricate task.

Although simulation is the most appropriate modelling tool in this case, existing simulation systems fails to provide the most needed ingredient, an integral data base management system.

CHAPTER 9

TOOL AVAILABILITY STRATEGIES FOR FLEXIBLE MANUFACTURING SYSTEMS

9.1 INTRODUCTION

In the high tool variety environment of FMS one of the major objectives is to reduce the number of tool exchanges due to product variety. It appeared that there are several ways of achieving this goal.

In this chapter these techniques are explored in detail. Various tool availability strategies are suggested and evaluated using the tool post-processor and the tool flow simulator.

9.2 REDUCING THE TOOL EXCHANGE RATES

As discussed in section 7.3.5, tool exchanges take place due to tool wear, breakage and product variety. The tool exchange rates due to first two causes can only be reduced by adjusting cutting tool conditions and/or using different types of tools. However, this requires a joint effort from part designers, process planners and supervisors (or operators) of machining systems.

By contrast reducing the number of tool exchanges due to product variety is purely a management problem. A variety of different types of actions can be taken to solve this problem [Perera 1988(a)];

9.2.1 Adopting an appropriate tool availability strategy.

This is concerned with the way tools are made available at workstations. For example, it may be sensible to hold a set of tools which are used by a large number of different part types, on a permanent basis. Different strategies are presented and evaluated in section 9.4.

9.2.2 Controlling the flow of parts.

This can be implemented at two levels;

a. Planning level

When parts are selected for immediate processing, their tooling requirements can be taken into account. For example, a part type which causes the minimum impact on the current tooling configuration can be selected. However, it is necessary to consider other management objectives such as achieving due dates, simultaneously. This approach is discussed in detail in chapters 10 and 11.

b. Control Level

When alternative workstations are made available, real time data of tools can be used to control the part flow. For example, when an alternative station is selected, the station which has the highest number of tools available for the required operation can be considered as the best option.

9.2.3 Expanding the tool magazine capacity.

This may be a part of a long term capacity planning strategy. Although this is theoretically possible, it is difficult to implement. Most tool magazines have a very closed architecture, i.e they cannot be expanded. In this case, however, a back up tool storage and a local tool handling device could be an alternative solution. More recently, a few machining centres have been introduced with modular tool magazine. The manufacturers claim that tool magazine can be expanded by adding modular units. However, this option requires a high investment and it must be considered as the last resort.

In the next few sections the first option is discussed in detail.

9.3 TOOL AVAILABILITY STRATEGIES

Various tool availability strategies have been suggested in the FMS literature [Crookall 1985, Tomek 1986, Mason 1986]. However no universal solution has emerged. The adaptation of an appropriate tool availability strategy would depend on the nature of production mission, the capability of the tool handling system and other management

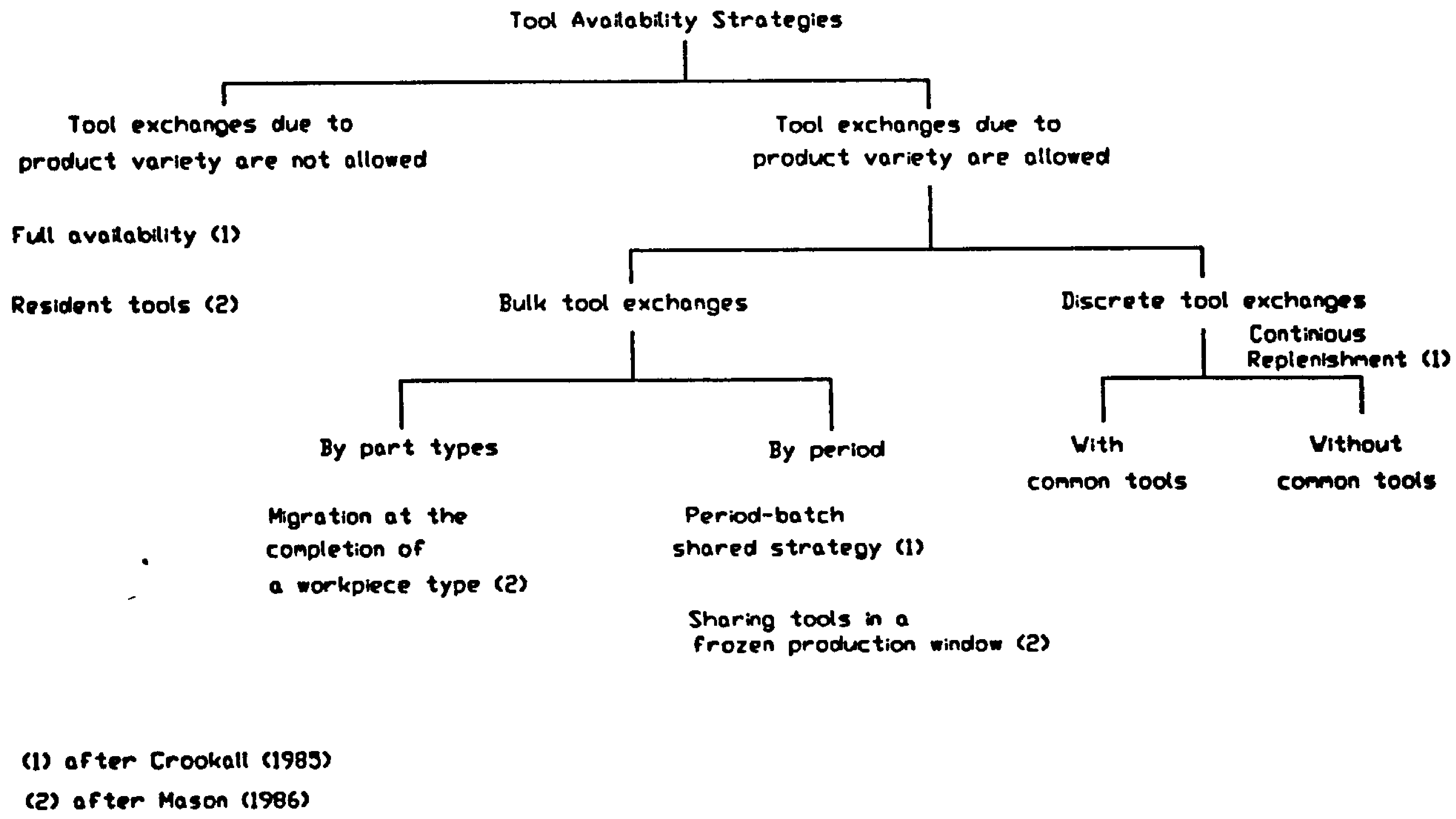


Figure 9.1 Tool Availability Strategies

objectives such as low tool inventory etc. It appeared that all these strategies are based on three key points;

a. Are tool exchanges due to product variety allowed?.

b. If so, how are they exchanged ?.

c. Are common tools taken into account ?.

In the following all possible strategies are suggested. The relationships between these strategies and the terminology used by others are shown in Fig. 9.1.

9.3.1 Tool exchanges due to product variety are not allowed.

The tools required by all part types are made available in the magazine. If parts have dissimilar tooling requirements then large tool magazines have to be used. However, this arrangement provides the highest part routing flexibility but at the expense of a high tool inventory. This is the simplest strategy among the alternatives and will be referred to as Strategy A in the discussion which follows.

9.3.2 Tool exchanges due to product variety are allowed.

This can be further categorized according the number of tools involved in the exchange.

a. Bulk Tool Exchanges

A large number of tools are exchanged. This can be grouped according to the nature of exchange.

1. By part types

The strategy is to provide a completely dedicated set of tools for each part set. At the completion of the current part types, all tools are taken out and a new set of tools are loaded for the next part type. This will be referred to as Strategy B.

2. By a fixed period

A set of tools are made available for a certain period of time. Part types which can use these tools are processed during this period. At the end of period the system is reconfigured for a different set of part types.This will be referred to as Strategy C.

b. Discrete tool exchanges

A small number of tools are exchanged. This can be further divided according to use of common tools.

1. No common tools

All tools may be exchanged due to product variety. This will be referred to as Strategy D.

2. Hold a set of common tools permanently

The tools shared by most part types are held permanently in the magazine. Other tools move in and out of the magazine as parts flow through the system. This will be referred to as Strategy E.

The selection of an appropriate tool availability strategy is an intricate task. The tool management parameters defined in chapter 7 can be useful in this case. No numerical comparison of these different strategies have been reported in the FMS literature.

9.4 TOOL AVAILABILITY STRATEGIES IN HIGH TOOL VARIETY ENVIRONMENT

In this section, the applicability of the above mentioned tool availability strategies are discussed with special reference to FMS with high tool variety.

9.4.1 Strategy-A: All required tools are made available at the tool magazine.

In high tool variety environment, most product mixes require a large tool complement at the workstation. Therefore this approach is rejected due to the following reasons;

a. A very high tool inventory.

b. Low usage of certain tool pockets.

c. High tool magazine cost.

9.4.2 Strategies B and C: Bulk tool exchanges

These are effective solutions when batches of parts are produced. However, due to variety of reasons (such as low volumes, long processing times) the parts cannot be grouped. Thus the bulk tool exchange strategies are not applicable.

Therefore, it can be concluded that the discrete tool exchanges due to product variety are unavoidable in high tool variety of environment. In the following, alternative options under this strategy are discussed and evaluated using data extracted from the FMS described in chapter 3.

A large number of experiments were carried out with different types of production requirements (i.e. different product mixes and/or different quantities). However, in the following the data from a single experiment is used to explain the performance of each strategy.

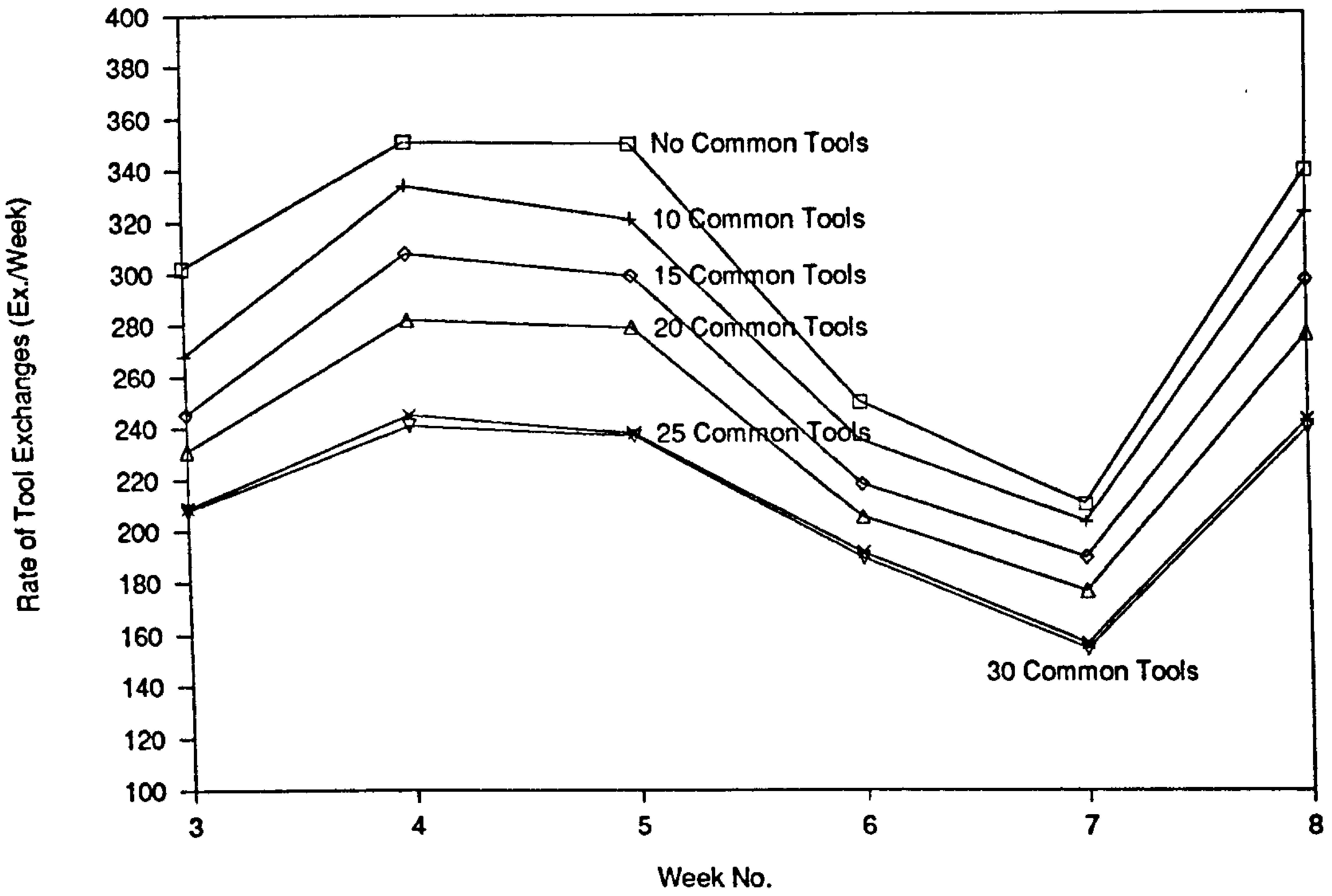


Figure 9.2 The Effect of the Number of Common Tools on the Rate of Tool Exchanges due to Product Variety

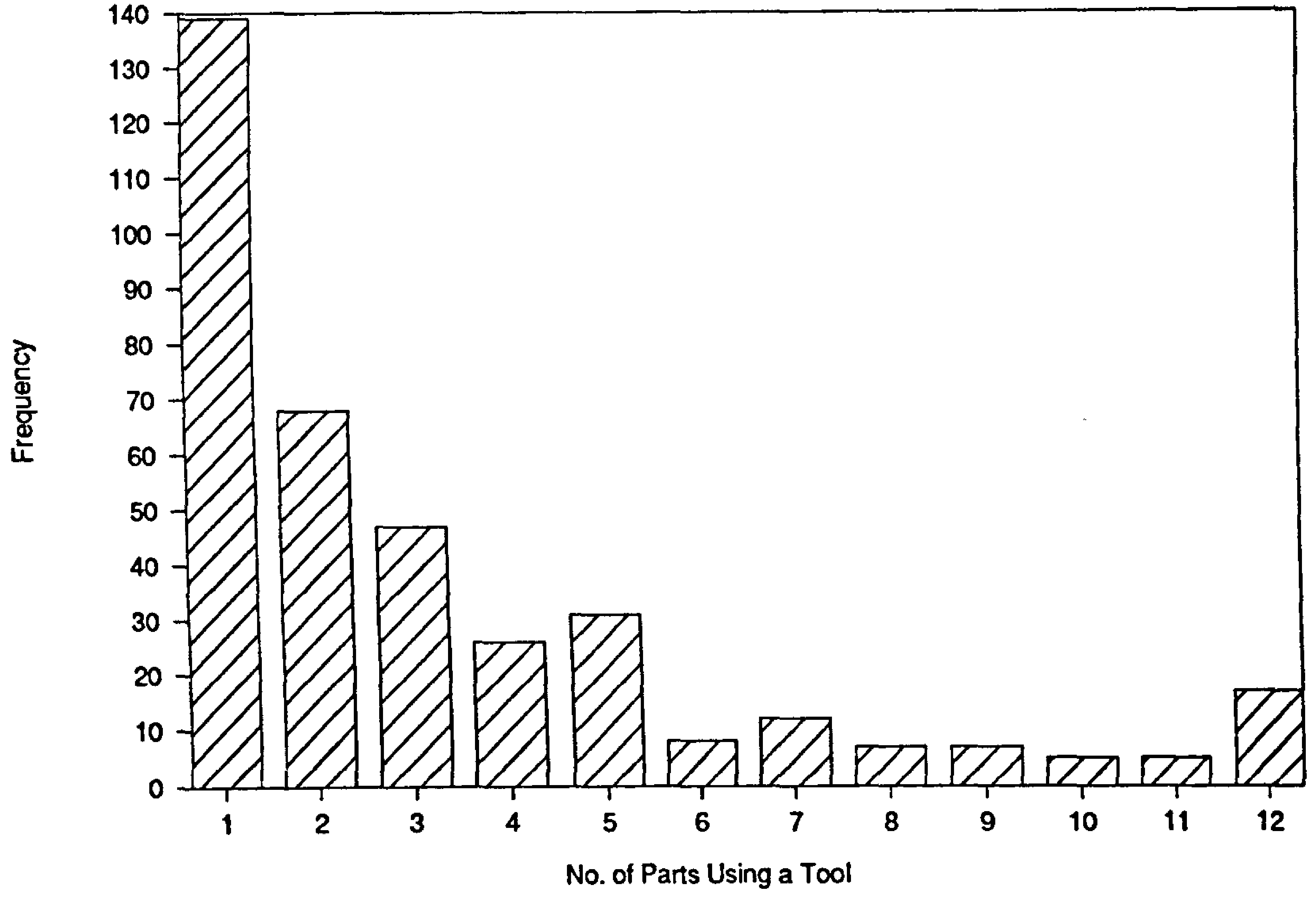


Figure 9.3 The Distribution of Demand for Tools Due to all Part Types

9.4.3 Strategy D: No common tools

When tool availability strategies were defined, the relative size of tools were ignored. However, when tools are placed in the magazine, constraints imposed by their sizes have to be considered.

Among the different classes of tools described in section 7.4.3, class III is the most difficult one to handle, as it need three successive empty pockets on the magazine. When tools are exchanged, it is easy to change a class III tool with another class III tool rather than a set of class I and class II tools. Therefore all class III tools are loaded first and remaining pockets are filled with class I and class II tools alternatively (note: class II tools cannot be placed in neighbouring pockets.).

A typical product set {part types: 4,6,8,10,7,3} is used here. This product set results in a system tool variety index of 1.183.

The distribution of the rate of tool exchanges due to product variety is shown in Fig. 9.2. As expected, the rate of tool exchanges due to product variety is very high.

9.4.4 Strategy E: A set of common tools

There may be some tools which are shared by many part types, therefore, it is sensible to hold these tool types permanently on the magazine. This can be implemented in two ways.

a. The product mix independent permanent tools

In this case, a set of tools are permanently held in the magazine, irrespective of the changes in product mix. In order to consider this option, the demand for each tool (i.e. the number of part types assigned to a tool) was estimated. The distribution of the demand for tools due to all part types are shown in Fig. 9.3. It is evident that a large number of tools (about 37%) are used only

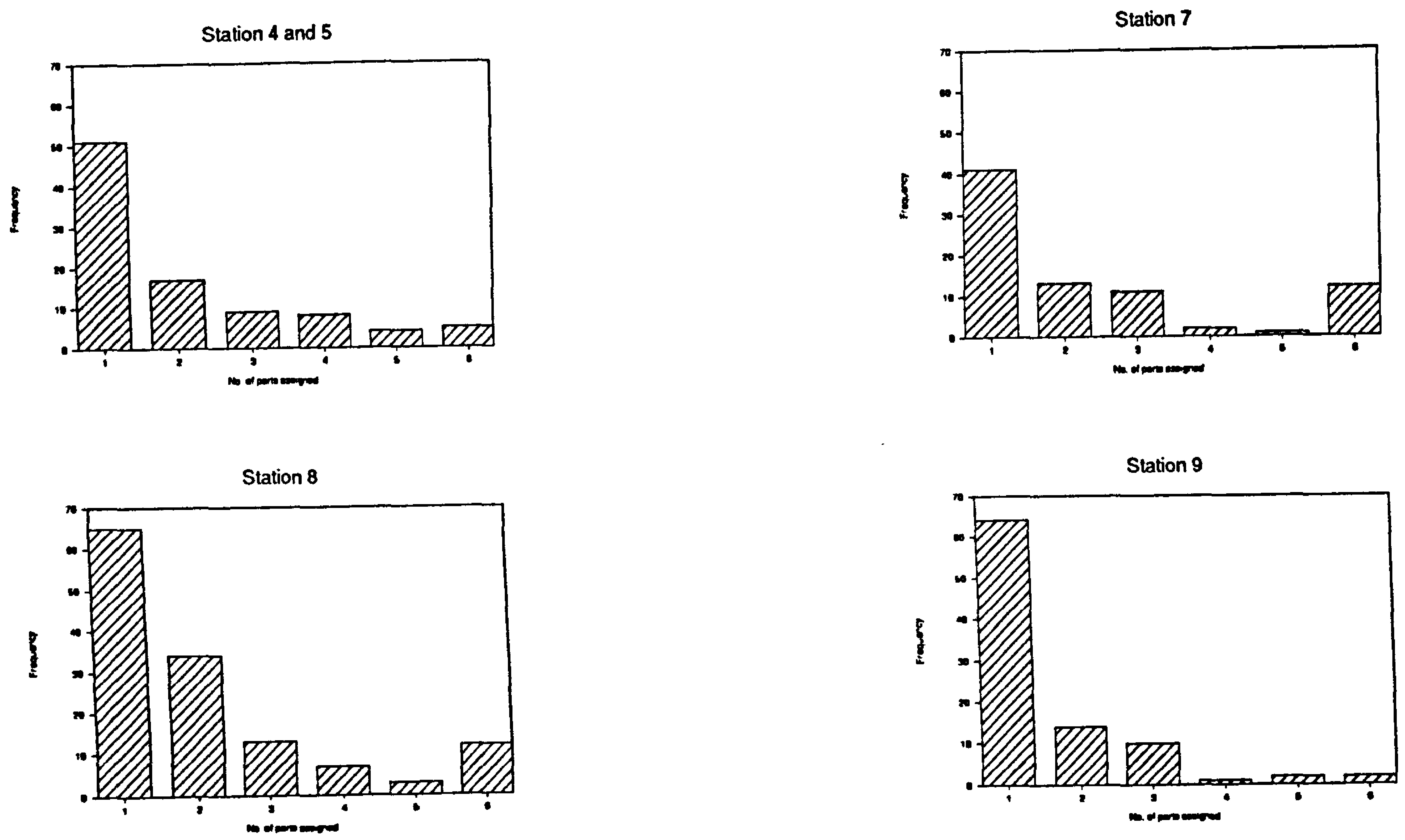


Figure 9.4 The Distribution of the Number of Part Types assigned to a Tool

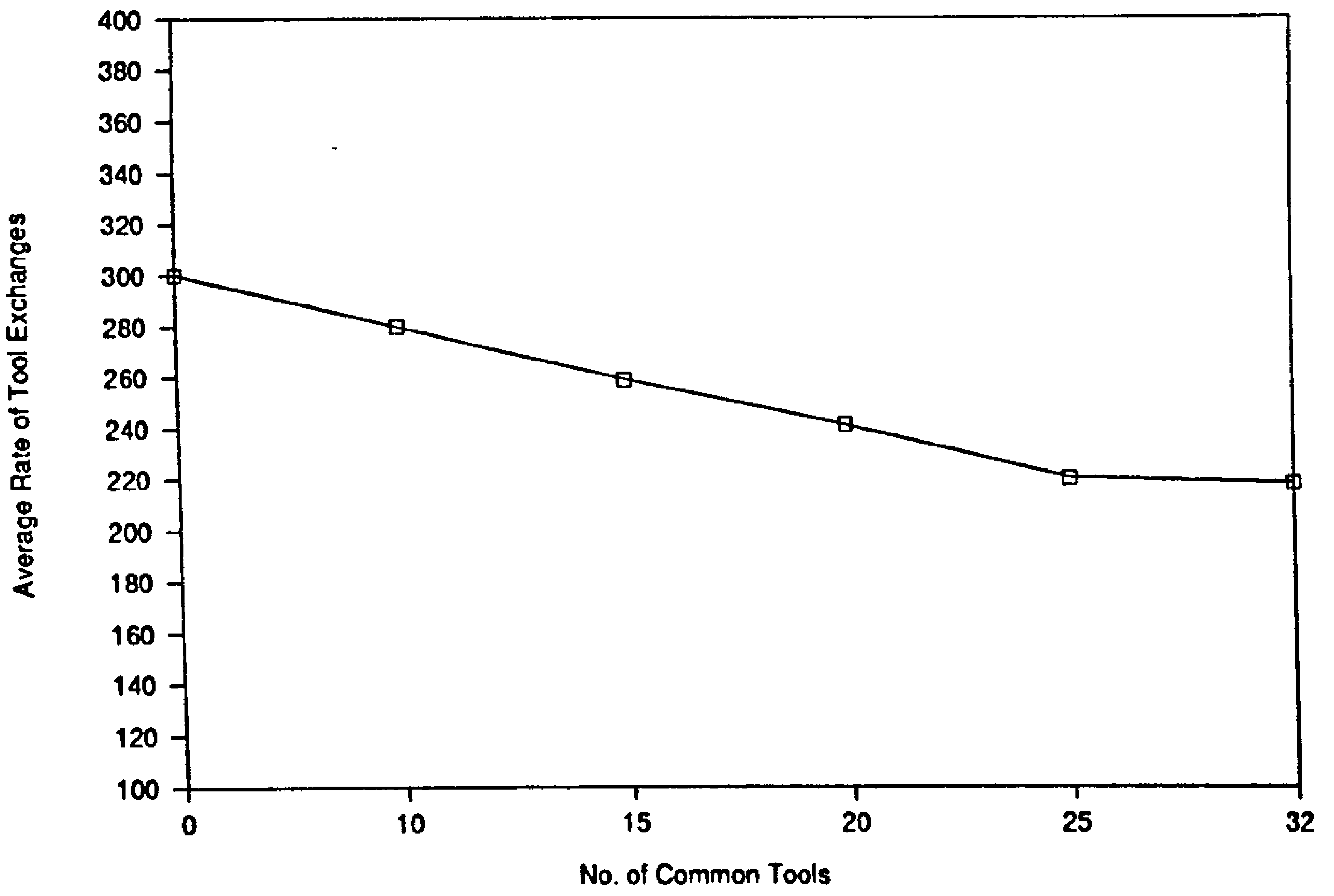


Figure 9.5 The Average Rate of Tool Exchanges Due to Product Variety Vs. The Number of Common Tools

by one part type. Only 17 tool types (out of 372, i.e. about 4%) are used by all part types. Therefore it was concluded that when tools are declared as common tools, they must be related to the current product mix [Perera 1988].

b. The product mix dependent permanent tools.

Instead of considering the entire product spectrum, the current product mix is used to generate common tools. The distribution of demand for tools for the above product mix is shown in Fig. 9.4. The tools with high demand are classified as common tools. A number of experiments were carried out with different amount of common tools per workstation.

A significant reduction in the rate of tool exchanges due to product variety was observed [Fig. 9.2]. However after a certain point the rate of reduction diminishes [Fig. 9.5]. Because, after this point, even common tools have to be taken out to accommodate new tool types. It is ineffectual to declare a large set of tools as common tools.

In strategies discussed so far, the relative sizes of tools were not considered. However, when there are a number of large tools, it may be possible to reduce the rate of tool exchanges due to product variety, by limiting the number of large tools present in the magazine.

9.4.5 Strategy F : A limited set of class III tools.

As class III tools take up three consecutive pockets in the magazine, there may be a quite number of pockets which cannot be used. Thus, if the number of class III tools held at the magazine is reduced, more tools from other classes can be loaded. However, in order to avoid a class III tool being changed with a set of class I and class II tools, a minimum number of class III tools have to be maintained in the magazine.

Station no.	Class I tools	Class II tools	Class III tools	No. of unloaded tools
4	70	17	7	4
5	70	17	7	4
7	70	8	2	0
8	116	11	7	46
9	73	6	14	21

Part Types = {4,6,8,10,7,3}
Tool Magazine Capacity = 100

Figure 9.6 Tool Requirements at Workstations

Station no.	Class I tools	Class II Tools	Calss III tools
4	36	7	4
5	36	7	4
7	33	3	2
8	39	4	5
9	35	3	8

Figure 9.7 The Maximum Number of Tools (by their class type) Used in Operations

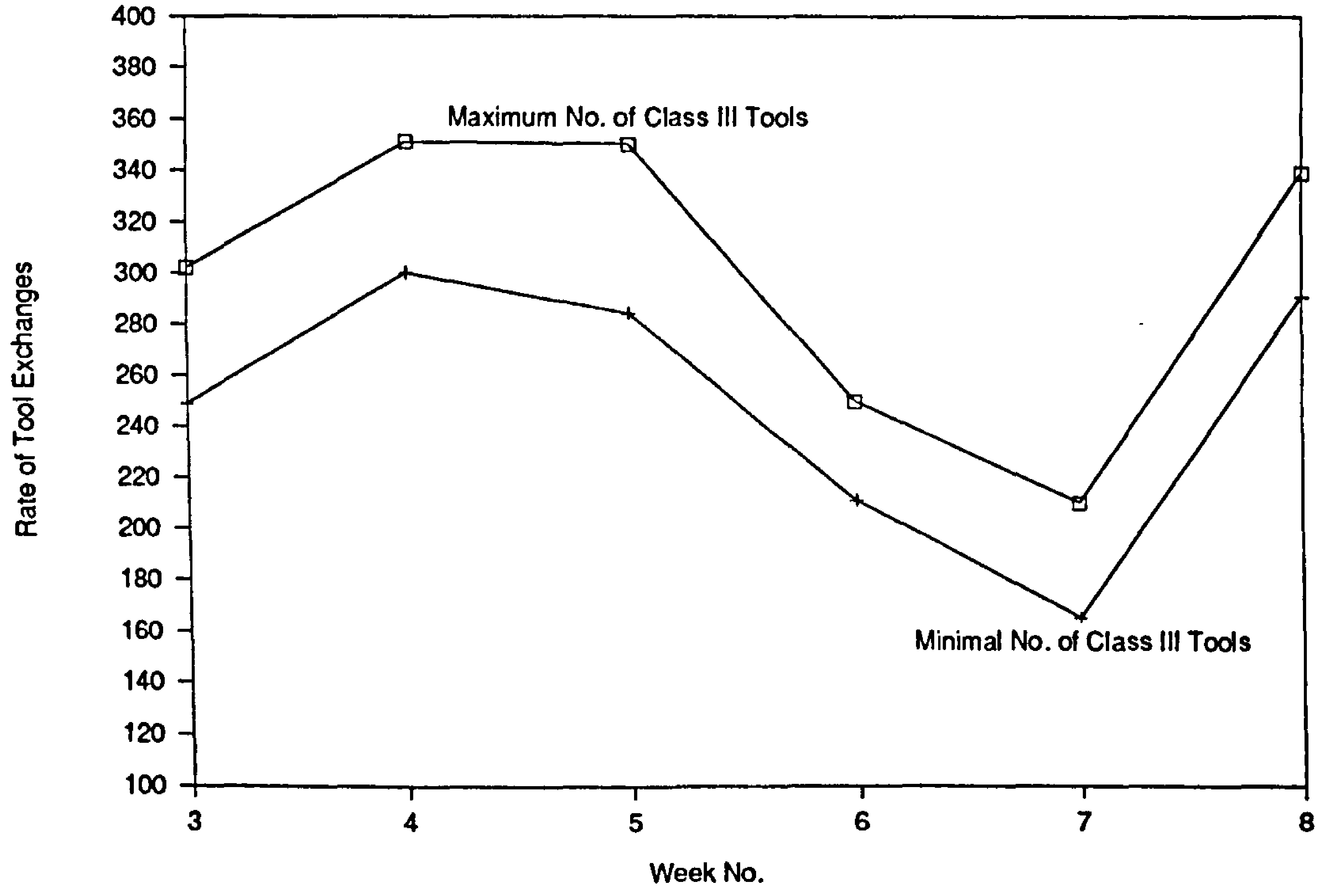


Figure 9.8 The Effect of Minimal Number of Class III Tools

Fig. 9.6 depicts the total tool requirements due to the above product mix. For example, 14 class III tools are required at the station 9 and they occupy more than 50 % (3x14 pockets out of 100). However all these class III tools are not used by a single operation. Therefore, tool requirements (by class type) were obtained for all operations of the product mix. Fig. 9.7 shows the maximum number of tools (by class type) used in a single operation. For example, at station 9, a maximum of 8 class III tools are used in an operation. Therefore a minimum of 8 class III tools would have to be maintained in order to avoid replacing a class III tools by a set of class I and class II tools when tools are exchanged due to product variety.

Therefore instead of loading all class III tools, the minimal number of class III tools are placed on the magazine. A significant reduction in the rate of tool exchanges was observed [Fig. 9.8].

9.5 A CRITICAL REVIEW OF EVALUATED TOOL AVAILABILITY STRATEGIES

It was shown that a significant reduction in the rate of tool exchanges due to product variety can be achieved by adopting a proper tool availability strategy. However the percentage of the reduction (15% to 25%) depends on the characteristics of the current product mix.

If the product mix remains stable over a long period, the above evaluated strategies provide an effective solution to the problem of exchanging tools due to product variety. However, when the product mix changes dynamically due to low production volumes, it is difficult to adopt these techniques. When this occurs, an approach which uses real time data is required to control the tool exchange rates due to product variety (Chapters 10 and 11 expand on this theme).

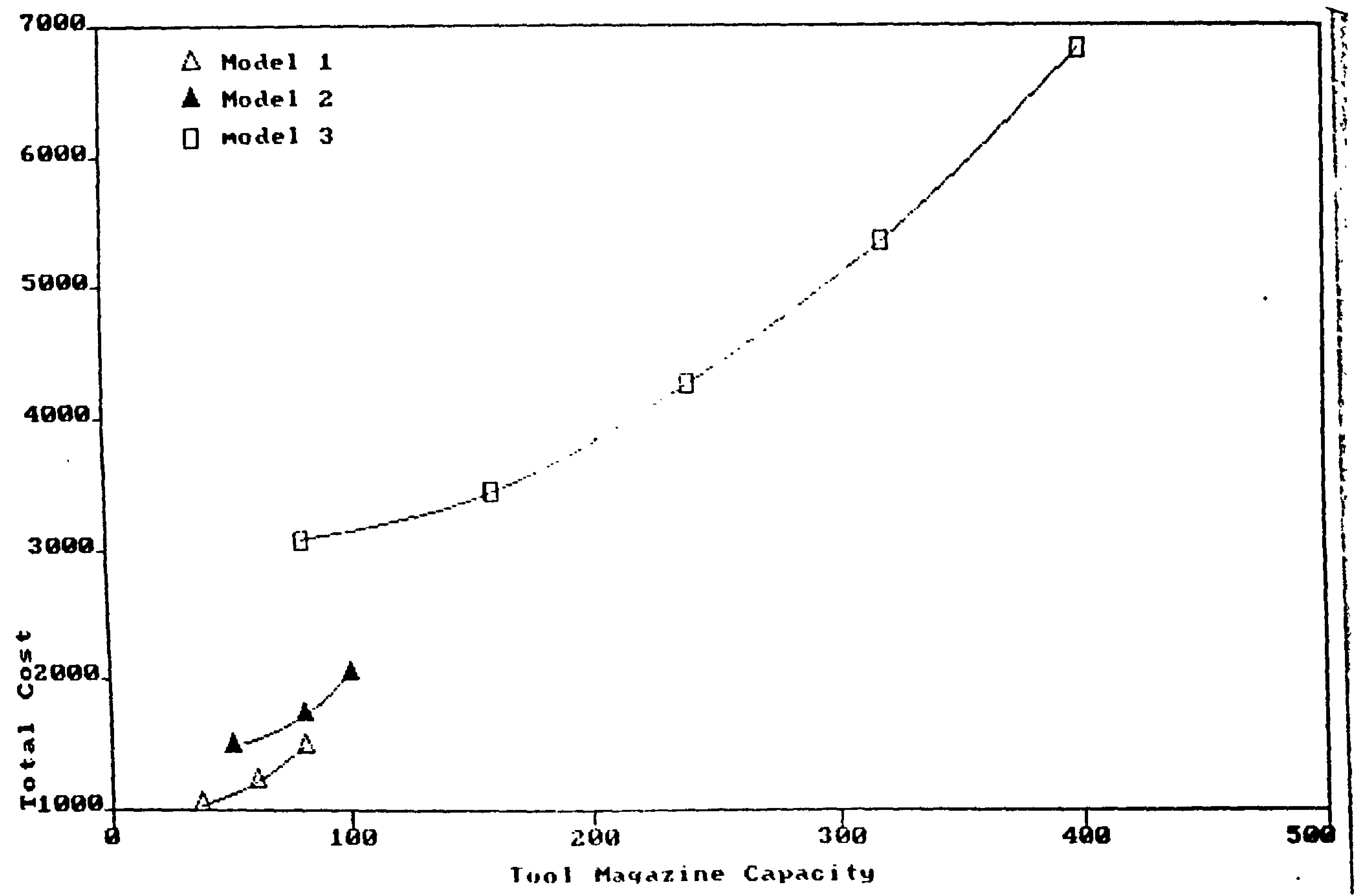


Figure 9.9 The Machine Cost Vs. Tool Magazine Capacity

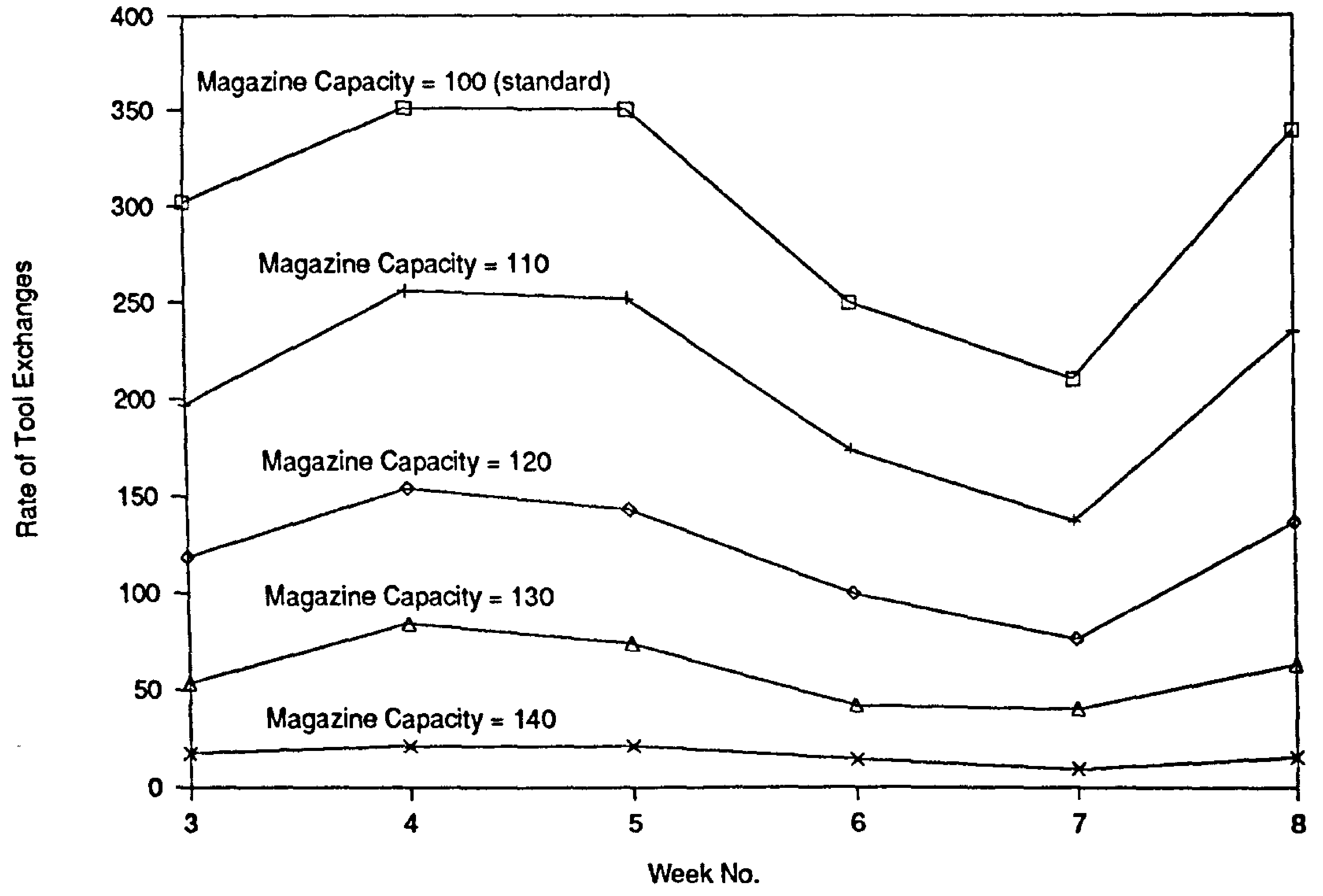


Figure 9.10 The Effect of the Tool Magazine Capacity on the Rate of Tool Exchanges due to Product Variety

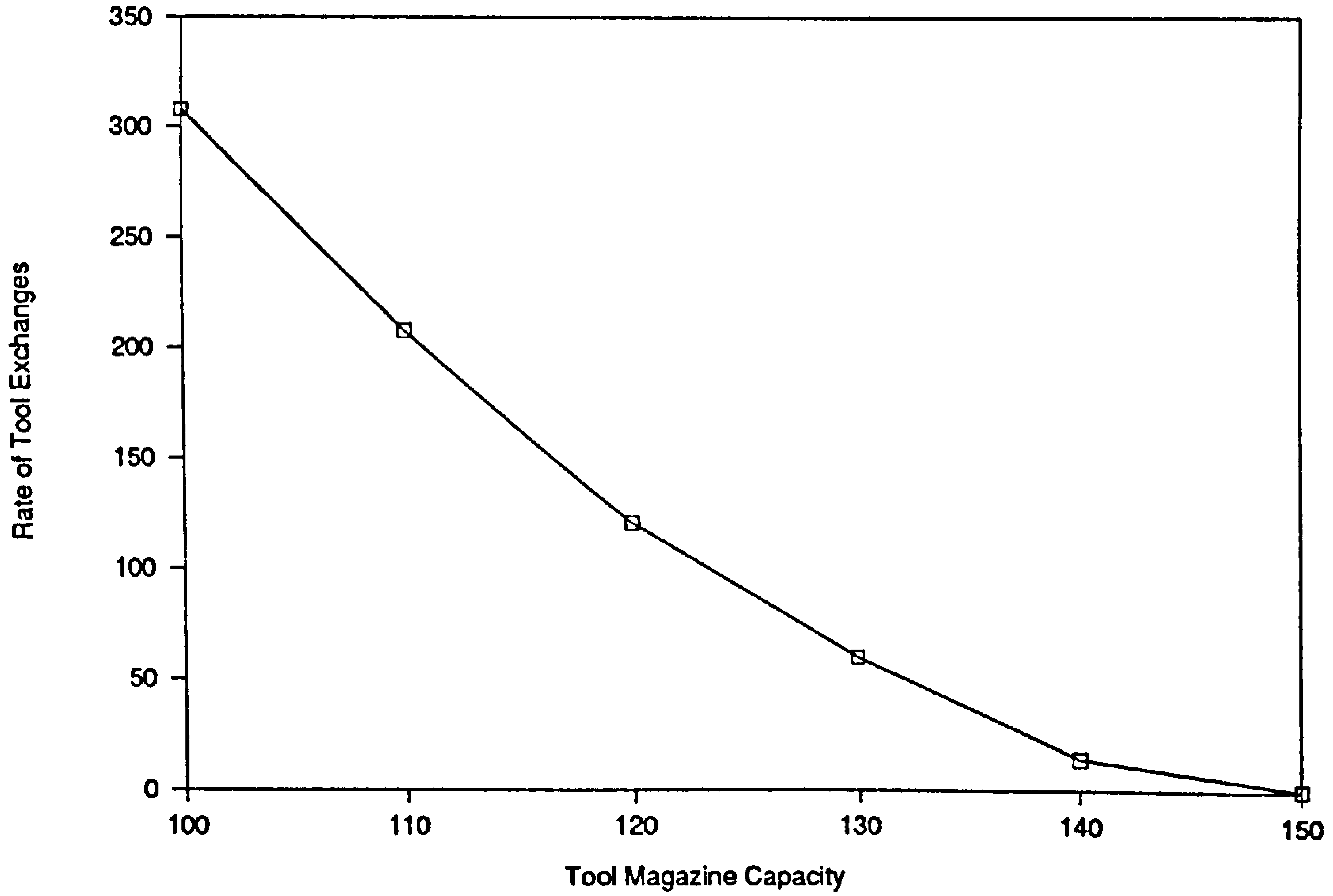


Figure 9.11 The Average Number of Tool Exchanges Due to Product Variety Vs. The Tool Magazine Capacity

9.6 EXPANDING THE TOOL MAGAZINE CAPACITY

As explained in section 9.2, an alternative strategy is to expand the tool magazine capacity. This option must be given an in-depth consideration at the system design stage rather than at the planning stage. Once the tool magazine capacity is decided, it is quite difficult to expand the magazine when the system is operational.

Generally, the machining centres are equipped with a standard tool magazine and optionally large tool magazines are available. A survey on machining centres indicated that the extra investment for a machine with a larger tool magazine can be as high as 30 - 40% of the standard cost of the machine tool [Fig. 9.9].

The tool post-processor can be used to investigate the effect of tool magazine capacity on the tool exchange rates due to product variety. For the product mix described above, a number of experiments were carried out with different levels of tool magazine capacities. Undoubtedly, any increase in the tool magazine capacity will reduces the rate of tool exchanges [Fig. 9.10 and Fig. 9.11].

Unless there is an upward trend in the rate of tool exchanges due to product variety, it is difficult to justify this approach. The tool requirements vary with the current product mix, therefore in certain periods the magazine is under-utilized and in other periods the magazine is over-loaded.

9.7 CONCLUSION

By implementing a proper tool availability strategy, the rate of tool exchanges due to product variety can be reduced. It was also shown that, by limiting the simultaneous presence of large tools, the tool exchange rates can be reduced.

However, when the product mix changes quite rapidly due to low volumes, the effectiveness of these strategies may diminish. Therefore the use of a technique which utilize real time data is imperative in high tool variety environment.

CHAPTER 10

THE PROBELM OF PART SELECTION FOR IMMEDIATE PROCESSING

10.1 INTRODUCTION

As discussed in chapter 1, the planning and control problems of FMS are reckoned to be major operational obstacles. Although the control of part flow within the system has been automated, the management of parts outside the system, in many cases, is left to the user.

Among the decision making processes which a user controls, the selection of part types for immediate processing presents a challenging problem.

In this chapter, the factors which inhibit the simultaneous processing of orders are identified. Approaches by other autohers to this problem are discussed in detail. The need for an alternative strategy in the case of high tool variety is pointed out.

10.2 THE PROBLEM OF PART SELECTION

The FMS research community uses the term part selection in two different stages of developing and managing an FMS;

10.2.1 The part selection at the design stage

This is concerned with the selection of a sub-set of parts from all part types which a company produces for flexible manufacture. It is regarded as the first step of the FMS design process. The characteristics of selected parts are used to decide the number of workstations, the type of material handling system, etc. Conventional Group Technology techniques have a great potential application in this area [Kochan, D. ,1985, Ham 1985]. Other markedly different approaches have been suggested by Whitney and Suri [1985] and Kusiak [1983].

10.2.2 Part selection at the planning stage

The acceptance of production orders by the system triggers a sequence of operational activities. The foremost activity is the selection of a sub-set of orders for immediate processing. Though simultaneous processing of all orders may be desirable, there are several reasons which hinder such parallel processing of orders [Suri and Whitney 1984].

a. The FMS as an up-stream feeder

In some systems, the parts are produced to feed a down-stream assembly line. A pre-determined ratio of part types has to be maintained to support un-interruptive assembly operations. When production orders are received, a subset of part types is selected for immediate processing to sustain this desired ratio of part types. An appropriate operating objective is to complete the selected part types at the same time. In this case, one of the operational problem is to assign available resources such as tools, fixtures, etc. to maintain this desired part type ratio.

b. Constraints imposed by production ancillaries

In most FMSs, the key feature is random processing of parts. But this may be severely constrained by the limited availability of production ancillaries;

The limited number of fixtures and pallets

The parts cannot be taken for immediate processing because required fixtures may not be readily available. These parts are held until required fixture types are released by previous parts.

The limited tool magazine capacity

In many systems, this is reckoned to be the major constraint against simultaneous processing of a larger part set.

As the part selection problem at the planning stage is constrained by a number of factors, it formulates a challenging problem. Furthermore it is the first problem to be solved at the beginning of the planning period. The solution to this problem has a great impact on subsequent operational activities (see chapter 1 for more information). Since this problem forms one of the main interests in this research work, the approaches of other authors to this problem are discussed in detail.

10.3 OTHERS APPROACHES TO THE PART SELECTION PROBLEM

There have been some research studies to date that address the part selection problem. In the following these techniques are explained in detail;

10.3.1 Linear programming formulations

Luca [1985] presents a set of linear programming models to solve general production planning problems and some of these models address the problem of part selection. In the following, all four models are described to provide better understanding of his approach.

Model 1: Optimum part route mix for minimum total production time

This formulation assumes that all part types can be processed simultaneously and the problem is not constrained by due dates and limited resources. He argues that the optimized performance is achieved by minimizing the total completion time. In order to create the solution space, alternative routes are considered. Given the production requirements, the model outputs the relative quantities of parts which take alternative routes.

Model 2: Optimum batching to satisfy given due dates for partial quantities of some parts

In this model due dates of certain orders (for example urgent orders) are considered. The objective is to minimize the total production time. The model works on the principle that the production orders can be grouped into distinct batches and it works out the duration of each sub-period (corresponding to batches) and average production rate for each part type within that sub-period. However he points out that for certain production schedules a solution may not exist due to conflits between due dates and the system capacity.

Model 3: Optimum batching with resource constraints

In this model due date constraints are relaxed but resource constraints such as a limited number of fixtures, are taken into account. As in the previous model, the duration of each sub-period and production rates are established.

Model 4: Optimum batching with resource constraints and with given due dates for partial quantities of some parts

This essentially blends the model 2 and model 3 i.e. due dates and resource constraints are jointly considered. The model outputs the same parameters described in model 2 and model 3.

10.3.2 Integer programming formulations

a. Menon and O'Grady [1984] present a planning framework which enables the selection of a subset of prospective orders which is compatible with the current configuration of manufacturing system resources and constitutes the best compromise solution in relation to a set of conflicting performance goals. The modelling approach includes concepts drawn from zero-one programming, boolean relationships and the weighted attainment function form of goal programming. The following constraints are modelled;

i. Special tool requirements.

ii. Concurrent processing of certain part types.

iii. Tool magazine capacity.

iv. Tool type availability.

v. Machine capacity.

vi. Alternative process routes.

vii. Due date achievements.

viii. Limited volumes of certain part types

ix. Expediting certain orders.

The weighted attainment function is formulated by considering potentially conflicting multiple goals in accord with the deviational weights.

b. Hwang [1986] aims to minimize the number of batches through reducing the number of tool re-configurations. Since this formulation is intractable, it attempts to maximize the number of part types in each batch as a reasonable approximation. The formulation to minimize the frequency of tool changeovers seems to select the part types with most number of required cutting tools as late as possible.

10.3.3 Heuristic methods

Whitney and Gaul [1985] use a sequential decision algorithm based on optimization of a probabilistic performance criterion to solve the part selection problem. This basically tries to minimize the number of distinct batches and then to balance workloads within each batch sequentially. The approach is iterative and uses estimated performance indices. This heuristic approach can handle special cases such as limited tool magazine capacity, tool sharing etc. A software system BATCH/BAL which implements this technique has been developed.

10.3.4 Coding systems

Kusiak [1985] suggests a technique based on code generation for parts, to solve the part family selection for short horizon planning. It basically uses the geometrical and technological attributes of parts to identify parts with similar processing requirements. This approach takes the advantage of information already stored in the CAD data base. The data concerned with part geometry and part technological parameters are extracted from the CAD database. The pattern recognition techniques are used to identify the part geometry which is blended with technological parameters to generate individual code for each part type. These codes are used to compute the distance between any two parts and resulting data are manipulated to generate batches of parts.

10.4 THE APPLICABILITY OF EXISTING TECHNIQUES IN THE SELECTED TYPE OF FMS

Most of the techniques described above work on the principle that the production orders can be partitioned in to separate batches with distinct planning horizons. However the batching strategy may depend on the type of constraint. For example, in the case of limited number of fixtures, the batches may consist of more dissimilar parts to reduce the demand for fixtures. In contrast, when tool magazine capacity constrains the simultaneous processing of parts, more similar parts are selected.

The system is configured for a selected batch and upon finishing the selected batch, the system is reconfigured to accept the next batch. However, this discrete batching can only be justified when batch sizes are large enough to reach the steady state and the time taken for reconfiguration is comparatively small.

As explained in chapter 2, the selected type of FMS processes continuously changing product mixes due to low volume. Consequently, the system may not approach a steady state, therefore batching of parts is not appropriate in this environment.

Among the techniques described above, except Menon and O'Grady [1984] model, all other approaches assume that the production orders can be split into discrete batches of parts and all tools required to support each batch can be made available within the each planning period. Among these batching approaches Whitney and Gaul approach seems to be the more appropriate. It considers realistic constraints of flexible manufacturing systems and have a greater application potential in real systems.

Menon and O'Grady take a different view of the problem. Instead of creating batches, a sub-set of parts is selected from the remaining orders to continue the production. This approach is more appropriate for the selected FMS type. However Carrie and Perera [1986] identify some drawbacks of the model. Observations concern;

a. Standard versus non standard tools. The model requires that tools are categorized as standard or otherwise. In reality in the FMS there is no such distinction and some arbitrary decision must be taken. It would be possible to to declare each tool which is used on only one part at each station as a non-standard tool, but there are other rational possibilities. It appears that some experience will be necessary to tune the definition.

b. The values given to the weighting factors. These are also arbitrary, although in principle it might be possible to give a financial measure to some of them. It appears that the experience is also required to tune weights. The situation is more complicated by the fact that different periods the schedule might well require different values of the weighting factors. This implies that there exists a higher level of planning which would set the overall objective for the period, from which the weights would be deduced.

c. Fixing the planning period. In the model the machine capacity and orders are given without reference to the period to which they apply. Obviously they must be consistent. If a short planning horizon is used there will be few orders to consider and a fewer non-standard tools to take into account, but less flexibility in selecting a subset of orders. If a long planning horizon is considered there will be more orders to select from, more tools to consider and greater choice of subset. However, the load on the system will commit it for a longer time during which the situation may change. Here again experience will suggest a suitable balance. Intuitively, it would seem that the period should be roughly equal to time taken to process parts through the system because that is the minimum period for which a decision commits the system.

d. Data collection. For the model to be useful as an operational tool it must be possible to inset the data easily into the model. The tableau of the model is rather large and it may be difficult to extract the data automatically from the FMS control system.

10.5 AN ALTERNATIVE APPROACH TO THE PART SELECTION PROBLEM

When the system states change rapidly, as in the selected type of FMS, techniques which use real time data instead of steady state data (or predicted data) are expected to produce better system performance. Therefore the formulation of a new strategy for the part selection problem must take the following into consideration;

a. The real time data must be used.

b. The batching of parts is not appropriate.

It was thought that an effective operational strategy could be developed, if production orders are sequentially selected for immediate processing. This approach allows the use of real time data such as the current tool configuration, work in progress etc. Batching strategies do not use real time data as the decision is taken at the beginning of the planning period.

When operational strategies are developed, one of the prime tasks is to identify appropriate goals. In this problem domain, the following are reckoned to be the most appropriate goals;

a. Minimize the number of tool exchanges due to product variety.

As pointed out in chapter 7, in the high tool variety environment the number of tool exchanges due to product variety may be excessively high, but it is a controllable parameter. For example, different part input sequences result in different number of tool exchanges and there may exist a sequence which gives the minimum number of tool exchanges.

Although it is desirable to eliminate tool exchanges due to product variety all together, what is more important is that it must be reduced to a manageable level, because in any case a certain number of tool exchanges have to be carried out due to tool wear and breakage.

It is difficult to predict the number of tool exchanges due to product variety in advance (section8.7.1) however it strongly depends on the excess number of tool pockets required at the workstation (i.e. difference between the number of tool pockets required and the tool magazine capacity.

It is also important to balance tool pocket requirements at workstations. For example, if tool requirements at one workstation are very high compared with requirements at other workstations, that workstation may become a bottleneck station due to excessive number of tool exchanges (generally, tools are not allowed to be exchanged while the machine is running).

b. Balance work loads

A fair distribution of work loads is also a desirable objective but difficult to achieve. A balanced work load system may reduce the bottlenecks and capital resources are equally utilized.

c. Achieve due dates

Undoubtedly, this is one of the major objectives in any manufacturing organization, but often, some orders are finished before due dates and others are delayed.

The solution strategy proposed in the next chapter will consider these goals jointly.

10.6 CONCLUSION

The part selection problem in high tool variety environment needs special attention as the number of tool exchanges due to product variety is high.

Other proposed approaches fail to model the essential characteristics of this problem. It is vital to use real time data in the solution strategy, as transient effects do not disappear due to rapid changes in product mix.

CHAPTER 11

AN ALTERNATIVE SOLUTION TO THE PART SELECTION PROBLEM

11.1 INTRODUCTION

As explained in the previous chapter, the problem of part selection in high tool variety needs a different approach which must take the advantage of the real time data available in the FMS.

The framework of the new approach is represented by an integer programming model. A heuristic approach based on the model is developed. The data extracted from the FMS described in chapter 4, is used to demonstrate the effectiveness of the novel approach.

11.2 AN INTEGER PROGRAMMING MODEL FOR THE PART SELECTION PROBLEM

A solution strategy is proposed to solve this problem based on real time data. Parts are drawn from a pool of waiting orders in a sequential manner [Section 10.5].

The part selection procedure can be invoked in the following instances;

- **a.** When work load assigned to the machine group with the highest utilization is less than a pre-determined work load level (a threshold value).
- **b.** When there are considerable number of empty pockets available at workstations.
- **c.** When urgent orders need to be processed.

Such time instant is defined as a *stage*. At each stage one or more orders can be selected. However when multiple order selection is possible at a given stage, the procedure is repetitively used for each selection. Therefore only one order is selected at a time.

It is assumed that machine capacity analysis has been carried out prior to the application of this procedure i.e. all remaining orders must be processed within the FMS.

The mathematical formulation uses the following notation;

t = time instant.

i = index for orders ($i=1,\dots n$).

n = number of orders

j = index for decision variables ($j=1,\dots 4$).

k = index for workstations ($k=1,\dots s$).

s = number of stations.

x_i = binary variable for ith candidate order.

$x_i = 1$ if ith candidate order is selected.

f_i = estimated flow time for ith order.

$T(t)_k$ = accumulated tool pocket requirement at workstation k at time t.

$(T)_{ik}$ = increment in tool pocket requirement at station k if ith order is selected.

$T_{avg}(t)$ = average tool pocket requirements at a workstation at time t.

$W(t)_k$ = assigned work load at station k at time t.

$(W)_{ik}$ = increment in workload at station k due to ith order.

$W_{avg}(t)$ = average work load at time t.

$(DT)_i$ = specified due date of ith order.

$(DT)_{i+}$ = expected positive deviation (delay) of due date of ith order.

$(TC)_k$ = tool magazine capacity of station k.

$(TC)_{k+}$ = excess tool capacity requirement at station k.

The decisions are constrained as follows;

a. Only one order is selected at a time.

$$\sum_{i=1}^{n} x_i = 1$$

b. Tool magazine capacity constraint (at kth station).

This constraint can be model as a hard or a soft constraint [Williams 1985]. If it is considered to be a hard constraint, then the total tool pocket requirement is not allowed to exceed the tool magazine capacity. This can be expressed mathematically as follows;

$$T(t)_k + \sum_{i=1}^{n} (\delta T)_{ik}.x_i \leq (TC)_k$$

However, in the case of high variety tool environment, it is unrealistic to model it as a hard constraint. since, it is difficult to eliminate the number of tool exchanges due to product variety altogether. Thus, the tool magazine capacity is modelled as a soft constraint, but the *over-shoot* of tool pocket requirement is minimized within the objective function. The modified constraint can be expressed as follows;

$$T(t)_k + \sum_{i=1}^{n} (T)_{ik}.x_i \leq (TC)_k + (TC)_{k+}$$

c. Due date constraints.

It is ideal if all orders can be finished on or before due dates. Generally, this objective is hardly achieved i.e. some orders are completed in well advance of due dates while others are delayed. Therefore as in the above case, it is treated as a soft constraint.

$$f_i.x_i \ =< (DT)_i + (DT)_{i+}$$

d. Mean values of variables

As explained in section 10.5, it is desirable to have a fair distribution of work load and tool pocket requirements. This can be achieved by minimizing the deviations from the mean values of these variables. The mean values are computed as follows;

Mean tool pocket requirement;

$$T_{avg}(t) = \frac{\sum_{k=1}^{s} \{ T(t)_k + \sum_{i=1}^{n} (T)_{ik}.x_i \}}{s}$$

Mean work load assigned to workstations;

$$W_{avg}(t) = \frac{\sum_{k=1}^{s} \{ W(t)_k + \sum_{i=1}^{n} (W)_{ik}.x_i \}}{s}$$

e. Objective function

The objective function includes four components. As explained, the deviations from mean values of work load and tool pocket requirements are considered. In addition the over-shoot in tool pocket requirements and due dates are taken into account.

These are normalized to convert into comparable units. In this generic model g_j functions are used to normalize the variables.

1. Normalized deviations from mean work loads.

$$y_1 = g_1\left[\sum_{k=1}^{s} \left| W_{avg}(t) - \left\{ W(t)_k + \sum_{i=1}^{n} (\delta W)_{ik}.x_i \right\} \right| \right]$$

2. Normalized deviations from mean tool pocket requirements.

$$y_2 = g_2\left[\sum_{k=1}^{s} \left| T_{avg}(t) - \left\{ T(t)_k + \sum_{i=1}^{n} (\delta T)_{ik}.x_i \right\} \right| \right]$$

3. Normalized deviations from specified due dates.

$$y_3 = g_3\left\{ \sum_{i=1}^{n} (DT)_{i+} \right\}$$

4. Normalized deviations from tool magazine capacity.

$$y_4 = g_4\left\{ \sum_{k=1}^{s} (TC)_{k+} \right\}$$

Weights (α_j) are used for trading off between decision variables, where;

$$\sum_{i=1}^{4} \alpha_j = 1$$

Therefore objective function is;

$$\text{minimize} \quad \sum_{j=1}^{4} \alpha j.yj$$

The order for which $x_i=1$ is selected.

11.3 SOLVING INTEGER PROGRAMMING MODELS

Unlike linear programming with the simplex algorithm no good integer programming algorithm has been found to solve integer programming models [Williams 1985]. Different algorithms prove better with different types of problem, often by exploiting the structure of special classes of problem. The most successful algorithm so far found to solve practical general integer programming problem is branch and bound method. However, in this case the complexity of the objective function inhibits use of any established technique.

The complexity of the planning problem for FMS encourages the consideration of heuristics methodologies which facilitate the determination of solutions which are feasible and acceptable with respect to the pursuit of the optimum solution. Taha [1982] offers the following description of heuristic in his discourse on production management techniques;

> *A heuristic procedure is an intuitively designed procedure capable of providing a good, but not necessarily optimum solution to a problem. Because of the complexity of many situations facing the production manager, rigorous methods providing optimum solutions are rarely available, hence heuristic procedures are of considerable importance.*

Stecke [1981] points out that although some integer programming models are solvable, they are in general, too large to be a computationally feasible procedure. A good heuristic should used instead.

11.4 A HEURISTIC APPROACH

A heuristic approach based on the above framework has been developed. This can be invoked at previously defined time instances (stages). Some additional notation must be defined.

Step (1)

Obtain cumulative work loads and cumulative tool pocket requirements at each workstation due to released orders which are being processed.

Step (2)

Compute total workloads and tool pocket requirements at each workstation due to each remaining order.

W_{ik} - Total workload at station k if ith order is selected.

T_{ik} - Total tool pocket requirement at station k if ith order is selected.

Step (3)

Compute slack time for each order.

s_i = estimated slack time for ith order

$s_i = (DT)_i - f_i$

Step (4)

Compute decision variables and normalize them.

a. The decision variable dependent on work load distribution.

MW_i = Mean workload if ith order is selected.

$$MW_i = \frac{\sum_{k=1}^{s} W_{ik}}{s}$$

$(DV)_{1i}$ = the first decision variable.

$$(DV)_{1i} = \sum_{k=1}^{s} \left| W_{ik} - MW_i \right|$$

b. The decision variable dependent on tool pocket requirement distribution.

TM_i = Mean tool pocket requirement if ith order is selected.

$$TM_i = \frac{\sum_{k=1}^{s} T_{ik}}{s}$$

$(DV)_{2i}$ = The second decision variable.

$$(DV)_{2i} = \sum_{k=1}^{s} \left| T_{ik} - TM_i \right|$$

c. The decision variable for due date achievements.

$(DV)_{3i}$ = The third decision variable.

$$(DV)_{3i} = s_i$$

Step (5)

Normalize the decision variables.

The decision variables are normalized by dividing individual values by the sum of respective values.

For l=1, ... 3

$(NDV)_{li}$ = The normalized decision variables.

$$(NDV)_{li} = \frac{(DV)_{li}}{\sum_{i=1}^{n} (DV)_{li}}$$

Step (6)

Calculate the composite decision variable and select the order with the minimum value of composite decision variable.

β_l = The trade-off coefficient for lth normalized decision variable.

$(CDV)_i$ =The values of the composite decision variable for ith order.

$$(CDV)_i = \sum_{l=1}^{3} \beta_l (NDV)_{li}$$

Select the order i for which $(CDV)_i$ is minimum.

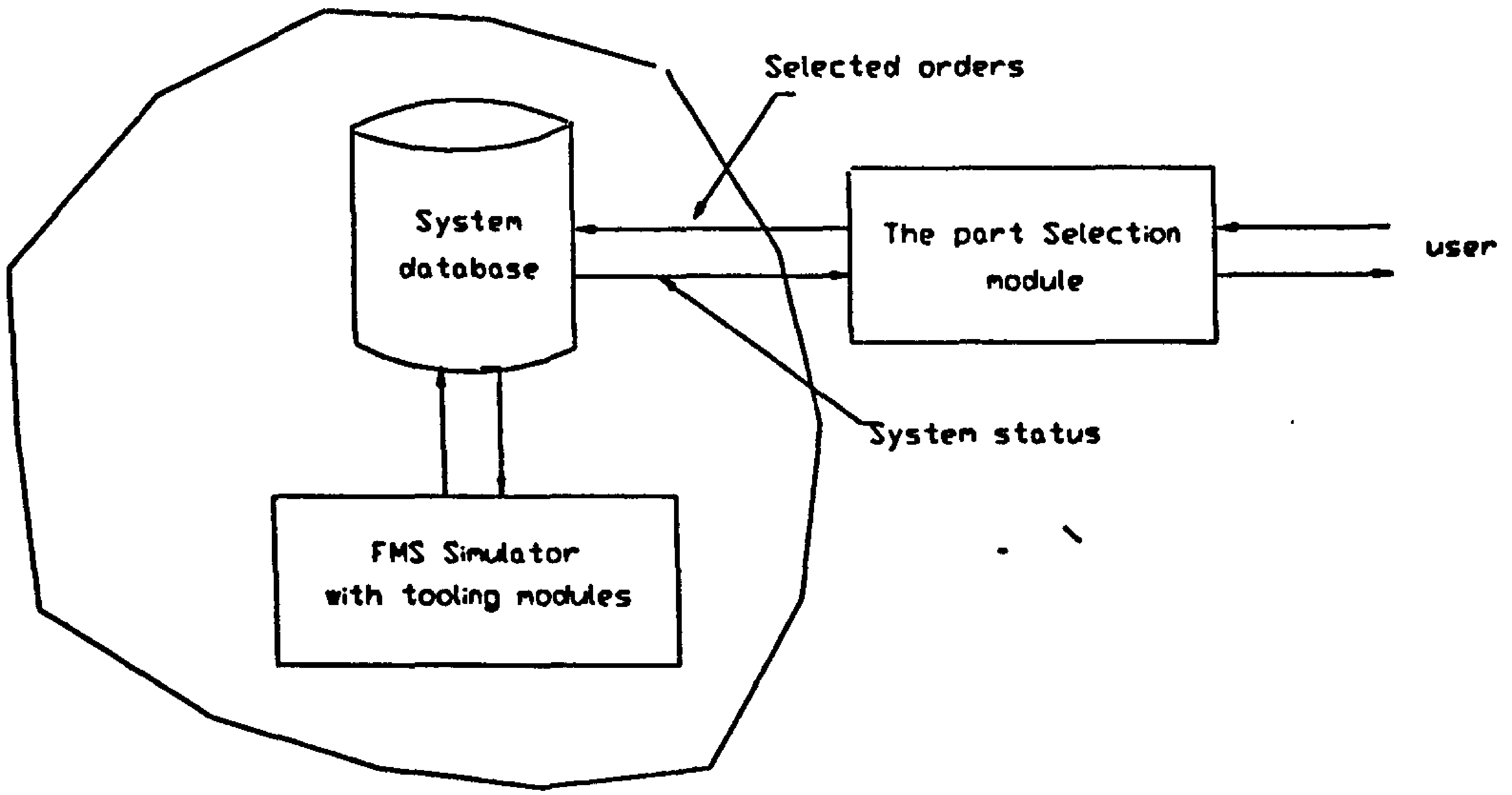


Figure 11.1 The Part Selection Program Module

In the following this heuristic is evaluated using the data extracted from the FMS described in chapter 3.

11.5 ESTIMATION OF BATCH FLOW TIMES

In order calculate the slack time of orders, some estimate of batch throughput time is required. The total flow time for a given batch of parts highlly depend on the number of fixtures allocated to it. The following formulae can be used to compute the approximate flow time;

nb = batch size.
nf = number of fixtures allocated to the batch.
$(ft)_1$ = average flow time of a single part on the first fixture.
$(ft)_T$ = average total flow time of a single part.

$$\text{Batch flow time} = \frac{(nb-1)*(ft)_1 + (ft)_T}{nf}$$

A simulation model of the system can be used to estimate the average flow times.

11.6 IMPLEMENTATION OF THE HEURISTIC APPROACH

This heuristic approach needs real time data, and in this kind of research work it is difficult to experiment with a real system. However, a simulation model which can mimic tool flow can be considered as the representative of the real system.

Therefore the heuristic procedure was coded in FORTRAN and linked to the tool flow simulator. The part selection module can access the database of the simulator to retrieve required data. The overall arrangement of the system is shown in Fig. 11.1.

When prescribed time instances are reached, the simulator pauses and allows the part selection module to access the required data. Then the part selection module will process the data, if prevailing conditions permit, an order is selected for immediate

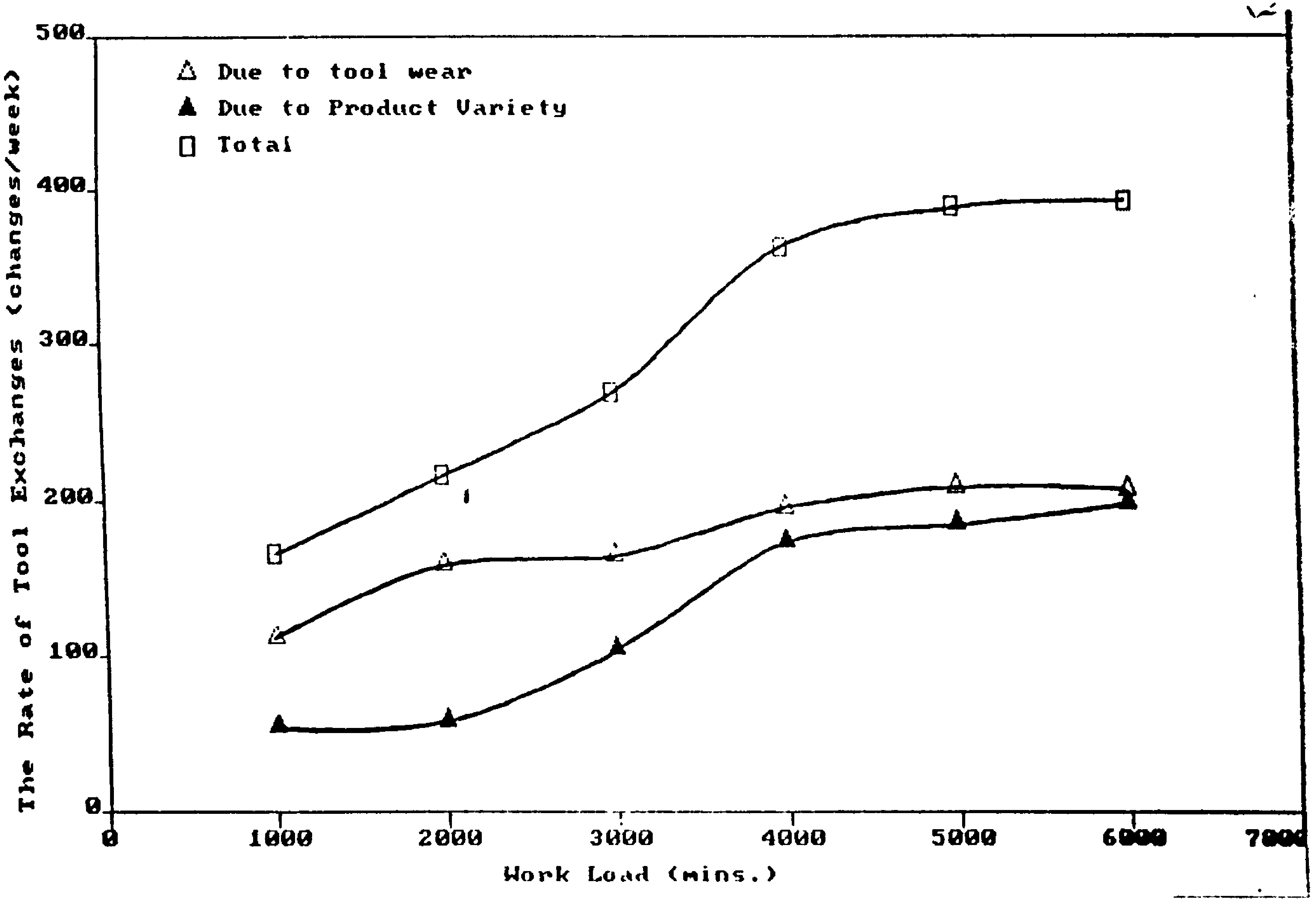


Figure 11.2 The Rate of Tool Exchanges Vs. Work Load

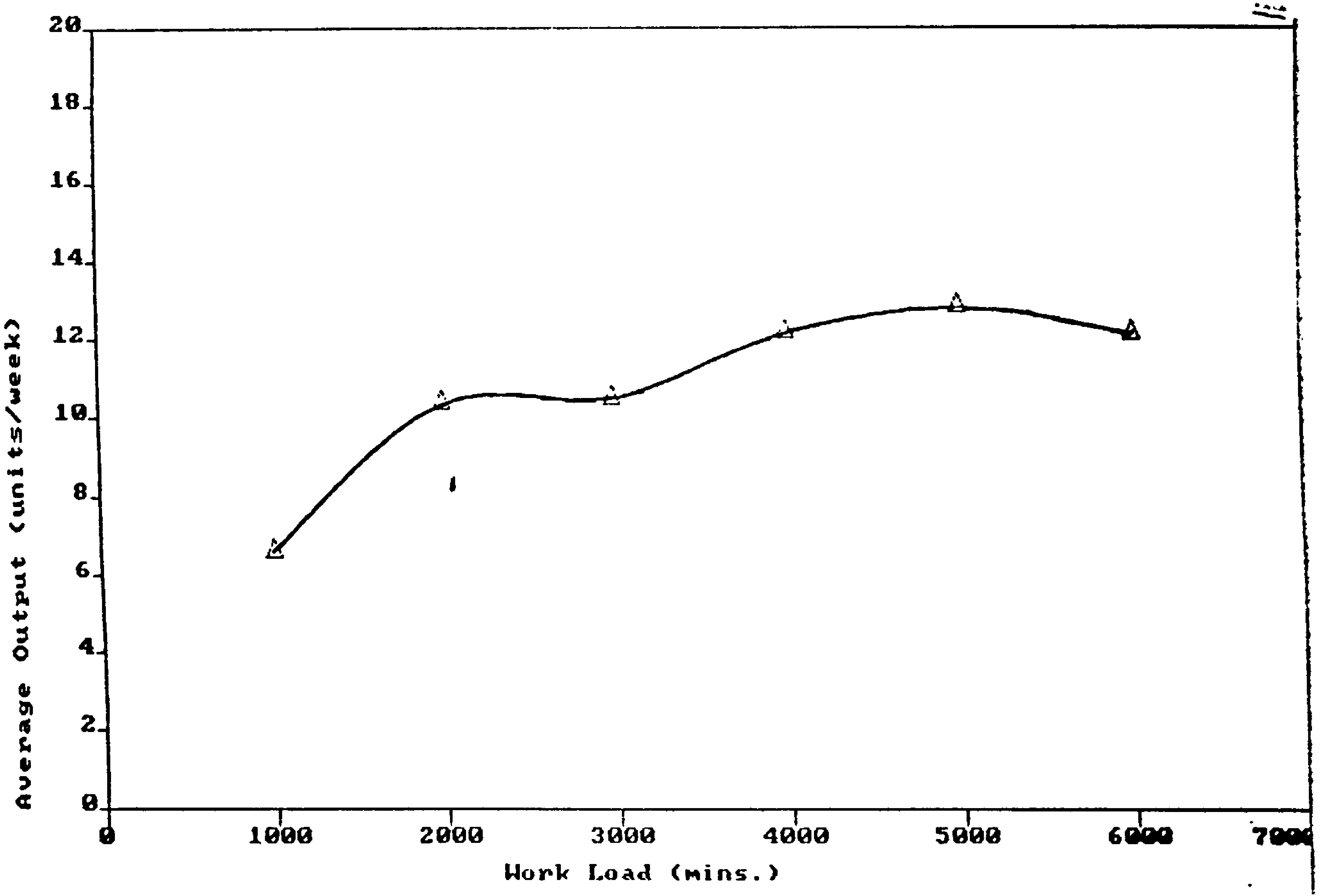


Figure 11.3 The Average Output Vs. Work Load

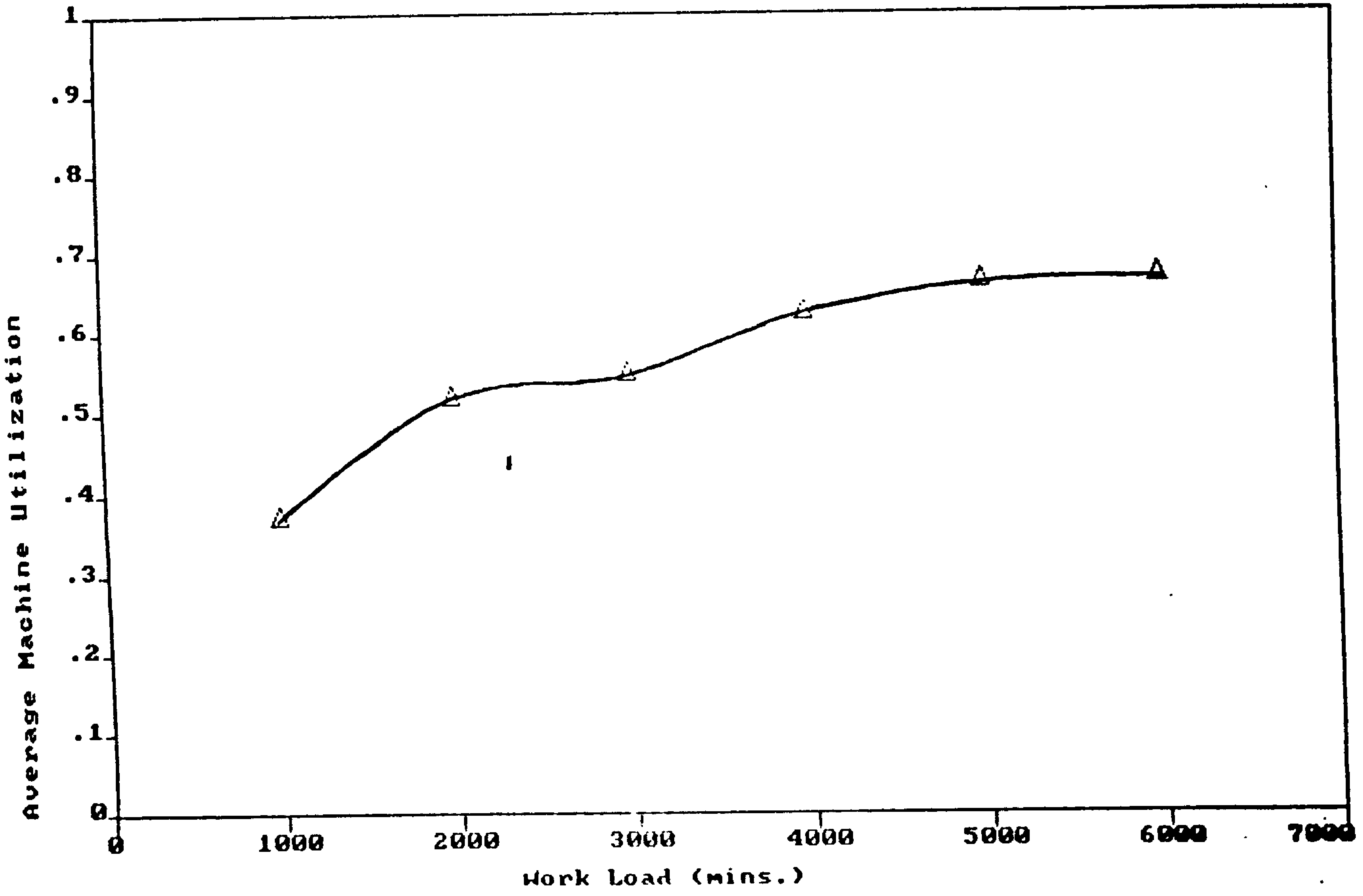


Figure 11.4 The Average Machine Utilization Vs. Work Load

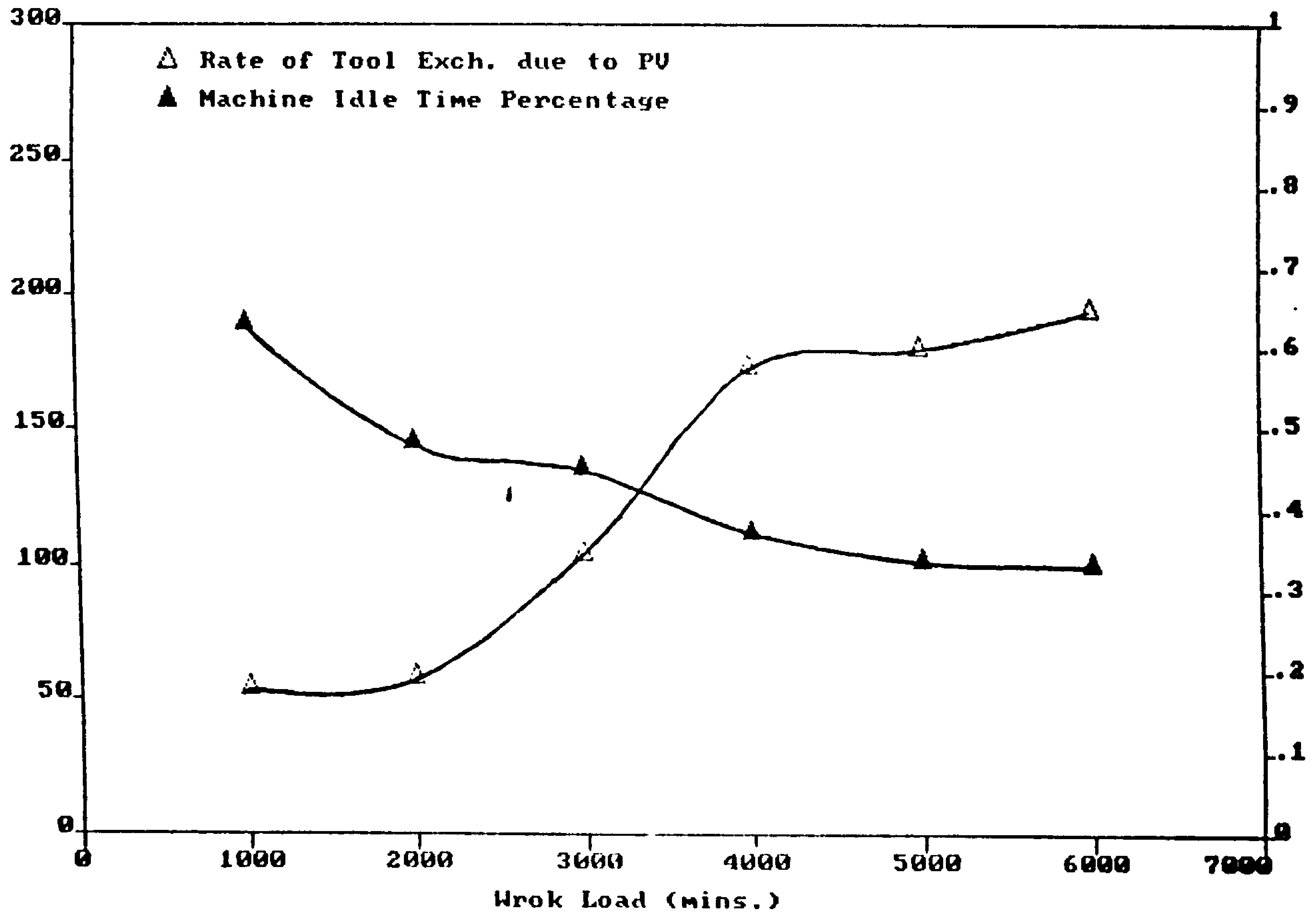


Figure 11.5 The Effect of Workload Variations on the Rate of Tool Exchanges and Machine Idle Time

processing. In order to handle special cases user is allowed to override the decision of the part selection module.

11.7 ESTABLISHMENT OF THE THRESHOLD VALUE

As explained above this procedure can be invoked when work load assigned to the workstation with highest utilization is less than a certain value. It is necessary to maintain a certain amount of work load in order to avoid possible work starvation. On the other hand excessive work load may result a large number of tool exchanges. This threshold value can be established, through simulation experiments, by changing the work load level assigned to that workstation.

11.8 A CASE STUDY

The data extracted from the FMS described in chapter 4 is used to demonstrate the effectiveness of this heuristic approach.

As explained in section 11.2, it is required to establish the threshold workload level for the machine group with the highest utilization. When the assigned workload level is less than the threshold value the heuristic procedure can be invoked. In order to estimate this value a number of experiments were carried out with different work load levels. In all experiments equal weights were given to the decision variables.

In this FMS, stations 4 and 5 are highly utilized, therefore the work load assigned to this machine group was taken as the control variable. The results due to a typical production run are shown in Fig. 11.2 to Fig. 11.4.

The average machine utilization and the output rate increases steadly with the workload up to a certain level, after that there is no significant improvement. By contrast, the rate of tool exchanges due to product variety rises continuously [Fig. 11.5]. This lead to the conclusion that the workload must be maintained about a specific value to avoid the excessive tool exchanges and starving at workstations. For this experimental setup, the threshold value appeared to be about 5000 mins.

Week No.	Output (units/ week)	Average Machine Utilization	Tool Exchange Rate (due to wear) (changes/wk.)	Tool Exchange Rate (due to PV) (changes/wk.)
3	12	0.583	163	280
4	10	0.655	176	296
5	13	0.691	226	264
6	13	0.681	192	301
7	11	0.605	170	304
8	12	0.708	197	315

The system performance when the part selection algorithmis not used.

Week No.	Output (units/ week)	Average Machine Utilization	Tool Exchange Rate (due to wear) (changes/wk.)	Tool Exchange Rate (due to PV) (changes/wk.)
3	11	0.622	190	41
4	15	0.699	218	246
5	10	0.576	165	101
6	10	0.520	168	131
7	13	0.689	246	235
8	14	0.648	187	286

The system performance when the part selection algorithm is used.

Figure 11.6 The System Performance with or without the Part Selection Algorithm

Parameter	Without the Part Selection Algorithm	With the Part Selection Algorithm	Percent Change
Output (units/week)	11.8	12.6	+6.77 %
Average m/c Utilization	0.653	0.625	-4.28 %
Rate of tool exchanges due to product variety	293	173	-40.95 %
Mean tardiness (mins.)	876	464	-47.03 %

Figure 11.7 The Effect of the Part Selection Algorithm on the System Performance

A number of experiments were carried out with different production runs and for all experiments, the threshold value was found to lie between 4840 mins and 5120 mins (approximately) with average of about 5000 mins. Therefore the threshold workload value for this system is 5000 mins.

Having established the threshold value, a new set of experiments was carried out without the part selection algorithm to find out its effect on the parameters such as the rate of tool exchanges, machine utilization, etc. The results due to a typical production run are shown in Fig. 11.6 and average values of the parameters are compared in Fig. 11.7. A very significant reduction in tool exchange rate due to product variety and a substantial improvement in due date achievements were observed.

11.9 CONCLUSION

A new heuristic procedure was proposed and evaluated. In thehigh tool variety environment of FMS, it leads to a better system performance with a significant reduction in tool exchange rates and throughput times.

This heuristic procedure takes the advantage of the real time data available in FMS. Since the computational time is very low (in seconds), this heuristic procedure can be used as effective management tool in the high tool variety environment of FMS.

CHAPTER 12

SUMMARY OF RESULTS, CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

12.1 SUMMARY OF RESULTS

The contribution of this research are summarized as the following list of results;

12.1.1 The characteristics of high tool variety environment have been defined.

Flexible manufacturing systems represent a wide variety of automated production facilities with different system configurations and operating policies. An area of FMS which has not received enough attention from the FMS research community has been identified. The main characteristics of the environment are low volume production and high tool variety. The production planning and control problems of the this type of FMS are severely constrained by tooling aspects of the system.

12.1.2 Simulation has been identified as the only technique available for modelling of tool flow.

A variety of different modelling techniques, such as closed queueing networks, perturbation analysis etc., were critically reviewed to identify their application potential in tool flow modelling. Although an attempt has made to model tooling aspects using queueing theory, all techniques other than simulation fail to model essential complexities of tool management systems.

Major limitations of some of the existing simulation software have been identified. As an alternative solution, with tool flow simulation in mind,a GASP based simulator for a complex FMS has been developed.

12.1.3 A graphical post-processor has been developed.

At the first phase of the research programme, simulation systems with powerful graphical animation capabilities were limited and expensive. A low cost graphical post- processor which could be linked to different simulation systems has been constructed.

This suite of software has been extensively used to identify some specific operational problems of a real FMS. In contrarst to what had been suggested by several researchers, it was shown that *look-ahead* features may not always provide better operational tactics. It was also shown that the control strategies need to be enhanced in order to react to changes in the production environment.

12.1.4 Parameters of tool management systems have been defined.

For the first time, the parameters associated with tool management systems were formally defined. It was shown that different values and different mixes of these parameters have a created a wide variety of tool management systems with different degrees of complexity. It was also pointed out that the tool variety index and the rate of tool exchanges can decisively set the way in which the system is operated.

12.1.5 A tool post-processor and an integrated tool flow simulator have been developed.

As a consequence of the negligence of tool management aspects of FMS, most simulation studies have been confined to modelling of part flow and no proven tool flow simulator is available to the research community.

Firstly, a tool post-processor was developed. It can be used to estimate parameters related to tool management systems. It was also shown that it can help the management to plan tool requirements. Secondly, an integrated tool flow simulator was constructed by linking the part flow simulator with routines developed for the tool post- processor and some other auxiliary routines.

12.1.6 Several tool availability strategies have been defined and evaluated.

The different tool availability strategies have been suggested with the view of reducing the number of tool exchanges due to product variety. Traditional techniques such as holding a set of tools permanently in the tool magazine appears not to be effective in high variety tool environment. It was shown that when different sizes of tools exist, tools which impose location constraints must be given a special attention. It was also concluded that tool availability strategies alonemay not reduce the number of tool exchanges due to product variety.

12.1.7 The need for a new approach to the part selection problem has been identified.

When production ancillaries constrain the part selection problem, conventionally it has been solved by creating batches of parts for sequential processing. It was pointed out that in low the volume, high tool variety environment a new approach is required since the system does not reach a the steady state. The need for technique based on real time data was highlighted.

12.1.8. The part selection problem in high tool variety environment has been solved.

Finally, a novel solution strategy to this planning problem was presented within a framework of an integer programming model. Several objectives were jointly considered. A heuristic was developed due to the complexity of the objective function. The time instances at which the part selection procedure can be invoked have been defined. The heuristic approach has been evaluated in a simulated environment.

12.2 IMPLICATIONS AND APPLICABILITY OF THE TECHNIQUES DEVELOPED

This discussion is confined to two major areas which are addressed in this research work.

a. Tool management system parameters and tool flow simulation.

At present the design and operation of tool management appears to be taking informal approaches. The defined parameters provide an opportunity to develop a structured technique to address these problems. The values of these parameters direct designers and users to develop appropriate operational strategies for tool management. These parameters can be evaluated for any type of FMS irrespective of their operating differences.

The tool flow simulator can play a major role in all phases of developing a tool management system. At present, the tool flow simulator has certain limitations i.e. it can be used only with a certain class of FMS with a specific hardware configuration. However it can be easily enhanced to model a wider variety of FMSs.

b. The heuristic procedure for the part selection problem

Application of this heuristic can improve the system performance dramatically in the high tool variety environment. Specifically it can reduce the rate of tool exchanges due to product variety without any significant loss of machine utilization.

It is necessary to evaluate the scale of the tooling problem before the application of this technique. In particular, it is vital to identify at which stage tool exchange due to product variety will strain the tool handling system and/or causes machine idle time due to tool starvation.

It is also necessary to decide the relative importance of conflicting objectives such as low tool exchange rates and high machine utilization. This heuristic technique provides a flexible framework to solve the part selection problem. However it has to be tuned to meet users specific requirements.

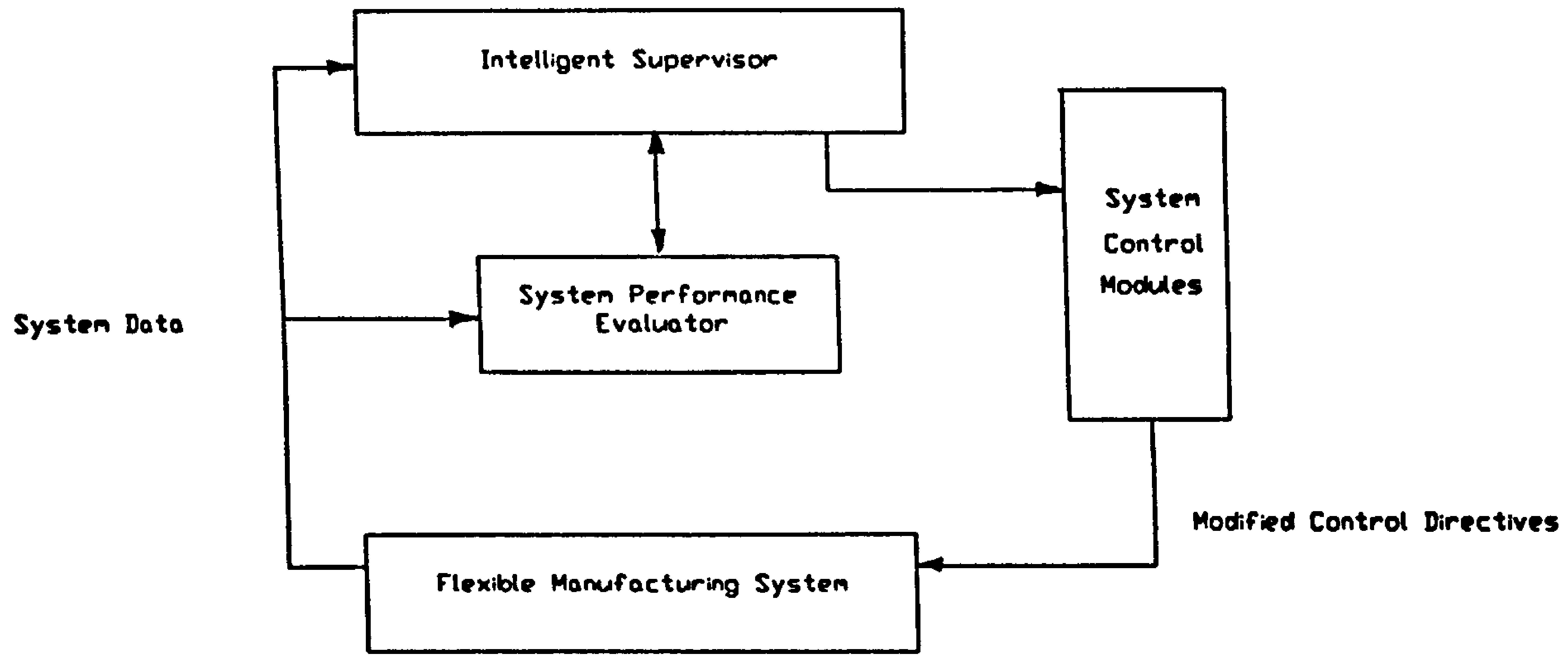


Figure 12.1 An Intelligent Tool Management System

The threshold value described in the solution process will have different values for different systems. Therefore, the value given in this research work should not be regarded as a universal value.

12.3 DIRECTIONS FOR FUTURE RESEARCH

This research can be extended in several interesting ways;

a. An Intelligent Tool Management System

It appeared that the dynamic nature of the production environment hinders the development of a generic solution procedure for a given problem even in a specific FMS. For example, the proposed part selection algorithm is more effective when the tool variety is high. However, the tool variety within a given planning period depends on the product mix which is dynamic. Therefore, it may be required to develop different strategies to solve the same problem at the different level of operational complexity.

It may be possible to classify the complexity of the system operation using the proposed tool management parameters. For example, the tool variety index is a representative of the tool requirements for a given product mix. Perhaps a series of threshold values can be established to identify the different operation zones. However, within these major zones there may be other parameters to which the system may be sensitive. For example, for a fixed tool variety index (i.e. for a fixed product mix) the rate of tool exchanges may be sensitive to the relative production quantities.

Therefore whenever there is a change in the production environment, its effects must be evaluated and appropriate operational strategy must be invoked. Fig. 12.1 depicts the major modules of such intelligent system.

The intelligent supervisor tracks the changes in production environment and when a significant change occurs (decided by built in rules), it fires the system performance evaluator which in turn passes the expected performance to the supervisor for further analysis. Based on previously established threshold and/or rules. If required, the supervisor will invoke the most appropriate solution procedure.

The efficiency of this type of system largely depends on the system performance evaluator. At present computer simulation is the only modelling technique which can be used to mimic the tooling aspects. Perhaps it may be possible to develop techniques to estimate the approximate values of the parameters concerned quickly.

b. A Simulation System with Database Management Facilities

As discussed earlier, the major drawback of existing simulation software is that they cannot handle a large amount of data effectively and efficiently. Thus it is essential to provide database management facilities within the simulation system. This can be achieved in two different ways;

i. Linking the existing simulation system with a database management package.

ii. The fourth generation languages have improved data handling facilities therefore it may be possible to develop a new simulation system based on one of these languages.

c. The Balance between the System Flexibility and the Complexity of the Control System

It was realized that in many cases, the system flexibility can be improved by providing new types of tools, fixtures, etc. However, it may have some impact on the system operations. It may be interesting to find out to what extent the system flexibility can be improved without making a major impact on the system control aspects.

12.4 CONCLUSION

There are several main conclusions of this work.

a. Tooling aspects must be given more attention when FMSs are designed and operated. Computer simulation of tool flow is highly recommended at the design stage.

b. Existing simulation systems do not provide essential ingredients to develop a flexible tool flow simulator. The main drawback is poor database management facilities.

c. All parameters related to tool management systems must be evaluated prior to operation of FMS. A flexible control strategy may be required to respond to variations in these parameters.

d. The part selection problem of FMS with high tool variety needs different strategies as the tool exchanges due to product variety is high.

e. The heuristic approach developed in this research work provides a better operational strategy than conventional techniques.

This research work addressed the operational problems of FMS with high tool variety which has not been a subject of the FMS research community. This work made a substantial contribution to the FMS research field by highlighting and and solving operational problems in the high tool variety environment.

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Work Scheduling in FMS

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WORK SCHEDULING IN FMS

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SUMMARY

This paper presents some of the problems in planning and operating Flexible Manufacturing systems. The main context is one particular FMS, but the general situation is also considered. The problems discussed include the number of pallets and fixtures which should be provided, congestion in the system, handling empty pallets, job sequencing and tool and workpiece scheduling. A major conclusion is that most of the approaches in the literature which consider tools are invalid. It is suggested that Operational Research methods have had little impact, and that OR practitioners might like to take a closer look at the problems.

INTRODUCTION

Flexible Manufacturing Systems present many new problems in operations management, and a new environment in which established approaches should be re-examined. Since most FMS have certain individual characteristics some problems have to be addressed in the context of the particular FMS, while others are quite general. Operational Research techniques have had little impact on the design of FMS, although analysis of queueing networks have been found useful, (Solberg, 1980, Suri and Hildebrandt, 1984). Several some mathematical programming models have been formulated (Stecke, 1983, Kusiak, 1984, Wilhelm and Shin, 1985), but there are few reports of their application.

This paper will present several problems in the context of an FMS which the authors have been examining in detail and also in the general context. We hope to encourage O.R. practitioners to consider whether decision rules may be formulated.

A brief review of the problems in planning FMS may be helpful to set the scene. Carrie and Perera (1985) described them thus:

> When an FMS is being planned initially decisions are required on the following problems:
>
> 1. The Product Range Problem: Of the parts which potentially could be produced on the system which should actually be produced on it?
> 2. The Process Planning Problem: What operations are needed on the parts? What tools will be needed? How should the operations be allocated to machines?
> 3. The Machine Capacity Problem: What types of machines are required? How many machines of each type are required?
> 4. The Transport Problem: How should the parts be moved around the system? What should be the capacity of the transport system?
> 5. The Fixturing Problem: How should the parts be clamped? How many fixtures of each type need to be provided?
> 6. The Pallet Problem: Are the parts to be palletised? How many pallets are needed? Will all pallets be of the same type? How many parts should be carried on one pallet?

These define the overall structure of the FMS, its methods and operating principles. Once the FMS exists they define a framework within which day to day decisions are made. Stecke (1981) gave an hierarchy of the operational problems:

1: The Part Type Selection Problem: From the set of part types that have production requirements determine a subset for immediate and simultaneous processing.
2: The Machine Grouping Problem: Partition the machines into machine groups in such a way that each machine in a particular group is able to perform the same set of operations.
3: The Production Ratio Problem: Determine the relative ratios at which the selected part types will be produced.
4: The Resource Allocation Problem: Allocate the limited number of pallets and fixtures of each fixture type among the selected part types.
5: The Loading Problem: Allocate the operations and required tools of the selected part types among the machine groups subject to technological and capacity constraints of the FMS.

In the discussion which follows aspects of these problems will be encountered many times.

THE FMS

Carrie et al (1984) described an FMS for the manufacture of complex castings. It comprises six machines, five similar CNC horizontal machining centres and one special horizontal machining centre with a facing head. All of the machines have a tool magazine with a capacity of 100 tools. Castings are located in fixtures and mounted on pallets. The pallets are moved by an Automatically Guided Vehicle (AGV). At each machine there are two pallet stands acting as buffers between the AGV and the machine table. One nominally serves castings queuing to go on to the machine, while the other serves castings coming off the machine. There are also two pallet stands at the load/unload area. There are 13 pallets. Initially seven part types were to be produced on the system.

When the initial plans were made the operations on the castings were categorised as roughing, semi-finishing and finishing operations, as well as facing head operations. Taking the forecast requirements and operation times into account the following initial solution to the machine grouping and loading problems had been proposed:

Machine Group	Operation type	Machine Numbers
1	Facing Head	1
2	Roughing	2 and 3
3	Semi-finishing	4 and 5
4	Finishing	6

The sequence of operations on the castings is illustrated by the following representative example (which omits the facing head machine since its commissioning had been delayed and full information was not available):

Operation Number	Operation Type	Machine Group	Operation Time (min)
1	Load	L/UL	10
2	Rough	2	156
3	Finish	4	18
4	Semi-finish	3	65
5	Refixture	L/UL	20
6	Rough	2	130
7	Finish	4	103
8	Reclamp	L/UL	20
9	Rough	2	203
10	Refixture	L/UL	20
11	Semi-finish	3	40
12	Semi-finish	3	40
13	Finish	4	67
14	Semi-finish	3	168
15	Unload	L/UL	10

This sequence involves three stages in different fixtures - operations 1 to 5, 5 to 10 and 10 to 15 - involving roughing operations followed by semi-finishing and/or finishing operations, and normally facing head operations. During one of the stages most of the parts will be brought back to the load/unload area for re-orienting within the same fixture, in this example at operation 8. This can be done on a pallet stand at the load/unload area. Otherwise, when parts are placed in a fixture on a work bench at the load/unload area before being mounted on a pallet, and when a part is to be taken out of a fixture they are first removed from the pallet. The successive semi-finishing operations, 11 and 12, are necessary because machines 4 and 5 do not have identical tool sets.

Simulation studies

Simulation studies of the system have been carried out over a few years, from the initial proposal to commissioning of the system. During this period two different system configurations were proposed and there were several sets of workpiece process plans as detailed planning proceeded and methods were proved out. Initially the objective was to verify or otherwise the supplier's predictions of the system's capacity. Later it was to assess the effects of method changes and to examine work scheduling aspects. A major result of the studies was the prediction that the system could become blocked and much of this paper deals with this and associated problems. As a result of the simulation work proposals were put to the supplier for revisions of software to deal with blockages and empty pallets.

FMS variations

In the discussion which follows alternative arrangements of the FMS will be mentioned. It may be helpful to review here the principal variations which may be possible in FMS.

Some systems have several load/unload positions, often one position for each type of part. This would be appropriate when operation times on the machines are relatively short, and loading times relatively longer than in the system described above. This arrangement also provide some buffer storage since parts can queue at their load/unload position both before being machined and afterwards. Another popular variation is to have a central buffer store in the system where parts which are waiting to go to a machine can be held, or where parts which have been machined can be held while waiting to be unloaded. This arrangement would facilitate three shift machine operation while the load/unload stations are manned only one or two shifts. Both of these variations provide a place to store unloaded pallets until the next workpiece of the appropriate part type arrives for processing.

More complex systems may have several AGVs and quite complicated track layouts, with junctions and sidings. They will normally have many machines of several types.

NUMBER OF PALLETS AND FIXTURES

The resource allocation problem mentioned above refers to the numbers of pallets and fixtures in the system. How many should there be? In practice the number of pallets is usually decided by some very simple arbitrary rule. In this FMS the number is 13, which allows for one pallet on each machine with a job being processed, one pallet on a pallet stand at each machine with a job awaiting processing and one at the load/unload area. Intuition suggests that the more pallets in the system the more work that can be supplied to machines with increased utilisation and output. However this notion is not normally supported by experiment.

When the initial simulation model of the system was developed details of pallets and fixtures were not available, so they were omitted from the model, and no limit was put on the number of castings which could be in the system. Congestion problems were encountered. The model was revised to include limits on the total number of castings which could be in the system, reflecting the limited number of pallets, and the number of parts of each type at each fixture stage, reflecting that only one fixture of each type would be purchased. Also the AGV's priorities were modified to reduce the congestion. The following results were obtained:

Number of castings of each type	1	1	1	no limit
Total number of castings:	6	9	13	no limit
Production rate (parts/week)	28.4	28.4	28.4	28.2
Mean time in system (minutes)	935	1151	1276	2006
Mean utilisation (percent) of				
Roughing Machines	78	78	78	78
Finishing Machines	64	64	64	64
AGV	64	65	65	64
Load/unload station	37	41	47	37
Number of "take-offs"	6	68	185	808

This suggests that the fewer pallets the better, since the castings will pass through the system quicker without loss of output or utilisation! In fact, this semms to be a fairly general result in FMS.

Since pallets are costly items a company will not wish to invest in more than necessary. What is the minimum number without sacrificing output? Obviously, when the number of pallets is reduced below the number of machines output must suffer. Is there any analytical model relating system performance to the number of pallets which can be solved to find the optimum number?

The number of fixtures is a similar problem, but perhaps more amenable to simple arithmetic. Carrie et al (1984) reported that the output of the system would rise by almost 20% if an additional set of fixtures were available.

BLOCKAGE OF THE SYSTEM

Simulation experiments found that the system could become blocked, - no pallet could be moved because the destination of each was already occupied. This problem is quite well known in computing circles as the "deadly embrace" or "circular wait" problem, Kuszzlow et al, 1975. In the early models this event always involved the load/unload area, which for simplicity had been assumed to act like any other workstation, i.e. it had two pallet stands and a single working position. The simple solution was to lift off the casting at the load/unload work position so that the one waiting there could be processed, and so on. This explains the "Take-offs" entry in the table, which shows that the frequency of this activity is highly dependent on the number of pallets allowed in the system. The model was revised to provide detailed modelling of the load/unload area in case simplifying assumptions had contributed to the problem. The problem was found to recur, and was not limited to the load/unload area. Blockage could occur among the pallets at two machines. In this case the same simple remedy cannot be used, and more complex logic, involving taking one pallet to some other location, was introduced. Logic also had to be added to the system control software. Logic to try to prevent blockages occurring was also added to the model, but was not totally effective. It was discovered that, although we thought we had covered all the possibilities, when changes were made to the sequence of operations the problem re-appeared. These again involved the load/unload area and the takeoff remedy had to be reintroduced, in a slightly different form.

We seek to know under what conditions blockages might be expected to occur. Ideally this should be expressed in terms of product mix, operation sequence, operation times and perhaps schedule. At present all we know is that one set of data did not cause the problem, while another did. Clearly, if no part visits any station more than once, so that there is a form of linear flow, there will be no blockages. Can this thinking be extended? Alternatively, is the maximum information to be deduced that if any part visits a machine more than once then blockage may occur (as opposed to will occur). In the computer field the subject has been taken further and some propositions have been formulated concerning deadlock detection and prevention. It seems however that these cannot be transfered easily to the FMS field, especially in complex FMS.

Can OR techniques come up with a solution?

EMPTY PALLET MOVEMENTS

The initial models and control system software assumed that empty pallets would be taken out of the system at the load/unload area. However, the Company did not wish to do this to avoid the risk of damage to locating surfaces, but move them to vacant stands within the system. New logic was added to the model to handle four new types of movement. These were i) taking an empty pallet away from the load/unload area to free the pallet stand for another pallet; ii) bringing an empty pallet to the load/unload area so that a new part could be mounted on it; iii) moving a pallet from the on-shuttle pallet stand of a machine so that a loaded pallet can be moved there; iv) moving a pallet from the off-shuttle stand of a machine so that a pallet can be moved out from the machine's working position. The simulation results showed that the AGV would be some 25% more utilised, output was reduced by almost 10%, throughput times were longer, and machine utilisation declined.

The logic in the model became quite complex since one does not want to move a pallet to a position which will soon be needed by a loaded pallet thereby causing yet another empty pallet movement. A "look-ahead" rule was introduced to identify when it would be necessary to move empty pallets a few minutes ahead of the need arising and to select suitable destinations. This was found to cause a large number of apparently unnecessary movements of empty pallets, indicating that it is difficult to predict the effects in a complex system of intuitively sensible heuristics. Curiously, the real system appeared to suffer similar effects. The inclusion of empty pallets in the system brings new scope for blockages to occur due to the increased complexity of possible pallet moves. The interaction of empty pallets and new routings for the parts lead to new blockage situations. These were studied when a graphics post-processor for the simulation model was written. By showing pallet movements preceding a blockage greater insight was obtained. A human observer could see readily what move would resolve the conflict, but find it very difficult to formulate a decision rule to prevent the situation occuring.

In describing FMS variations we referred to buffer storage and multiple load/unload areas. In this sytem it is likely that either of these would solve the blockage problems and provide an easy means of handling empty pallets. Perhaps those responsible for the design of our system have been shortsighted in not investing in additional pallet stands to eliminate the blockage problem?

We consider that much work needs to be done on scheduling AGV movements for both loaded and empty pallets, in both simple systems such as this and even more so in systems with several AGVs and more complex track layout. Although there is a substantial literature on vehicle scheduling in the OR field it does not seem to have been applied to this problem.

SEQUENCING AND DESPATCHING

Since the blockage problems appeared to depend on the operation sequence and times of the parts Carrie and Petsopoulos, 1985, performed a number of simulation experiments to evaluate the dependence of the system's performance on these details:

1. Part launch sequence. Seven different launch sequences, five of which were based on the relative magnitudes of operation times, were constructed. When parts were launched into the system according to these rules it was found that the differences between results could not be attributed statistically to the launch sequence.

2. Selection from internal queues. No significant difference was found in runs where the selection from queues within the model was on one hand by first-in-first-out or on the other, by minimum processing time rules.

3. Operation balancing. The substantial literature on job sequencing shows that the performance of a production line depends on sequence of loading jobs and on the relative magnitude of operation times. Would the performance of the FMS be affected if the operations were redefined so as to give some specific relative operation times? The operations on each part were redefined to give finishing operations which were of i. successively shorter

durations, ii. successively longer durations, and iii. equally balanced durations. No significant differences were observed.

4. Product mix. It was conceivable that results with one product mix would not hold true under other mixes. Four different mixes, selected in a way which should show up differences, were evaluated, but no significant differences in performance could be detected.

5. Allocation of machines to operations. Since the two roughing machines had the heaviest load, experiments were carried out in which one of the semi-finishing machines could also do roughing operations. The output of the system rose approximately 40%, although no account of tool changes was taken. When this machine was dedicated to roughing operations only, the semi-finishing machines became the bottleneck and output fell back to the previous levels.

Carrie and Petsopoulos concluded that, since travel times were short relative to operation times, on few occasions would there actually be a choice of part for the AGV to handle, and that, since only one fixture of each type was available, output was constrained by fixture availability rather than by the different launch rules, queue disciplines, operation time balances or product mixes. The fifth result was directly due to the increased flexibility. Some increase in output was expected, but a 40% increase is very substantial.

TOOL AND WORKPIECE SCHEDULING

A part can only be processed if all the tools required are present in the tool magazines of the machines. Since the tool capacity is limited, as more parts are loaded into the system the tool magazines will reach their capacity and no more parts can be loaded without tools being changed. The question then arises as to which of the parts which are to be processed should be launched immediately onto the system and which tools should be loaded into the magazines?

Menon and O'Grady (1984) have put forward a linear programming model which takes tools required, machine capacity, tool availability and due dates into account and selects which jobs should be loaded. The model's objective function is an summation of the weighted deviations from the desired level of these parameters. By varying the weighting factors different solutions can be obtained. Our assessment of this model is that it is somewhat limited on three counts. Firstly, we have no scientific means of establishing suitable values of the weighting factors. Secondly, we have no rigorous means of establishing the length of planning period. Thirdly, it ignores the need for tool changing between planning periods.

This last point leads to the question of whether there is a product launch sequence which would minimise the number of tool changes. In view of the results of Carrie and Petsopoulos given above it would seem that this idea must be rejected.

A tooling post-processor was written for the simulation model to examine the question of tool changes. This examined the record of events of a simulation run and computed the number of tool changes which would be required. These included not only the changes needed due to the limited magazine capacity and product variety but also on changes needed due to tool wear. Carrie and Perera, 1985, found that tool changes due to wear were an order of magnitude greater than those due to product variety. They concluded that it is much more important to achieve an efficient means of tool changing for whichever cause, rather than to construct scheduling rules which assume that mimimising them is a primary objective. This implies that scheduling rules which seek to minimise changes due to product variety but ignore changes due to wear are invalid. This renders most of the literature on the subject invalid! We are now considering how tool changes due to wear can be included in LP models, but have as yet no results to report.

A number of general questions are raised by these points. Since machines are normally offered with tool magazines of several possible capacities, how large a tool magazine should be selected? We see wide variations between systems in the ratio of tools needed in the system and magazine capacity. While some systems are constrained in the way described, other systems have tool magazines large enough to have spare tools of many or most types. Is it a simple matter of cost versus flexibility? If so, how is flexibility to be costed? Are more fundamental issues involved? Is the system control software a limiting factor on tool management? For example, does it require the tools for all operations on a part to be on the machines before it can be loaded on the system, or is it necessary only for the tools for the immediate next operation to be present? Is it necessary to stop a machine to change tools, or can tools be changed while another tool is cutting metal? Should buffer storage areas be provided to enable partly processed parts to be stored while awaiting tools to be loaded into the system for their next operations?

CONCLUSION

We have drawn three major conclusions from the above sections:

1. Congestion and blockage problems can be serious in FMS. We are unable to define the conditions under which they will occur. Blockage can be reduced or eliminated by introducing additional buffer storage, either at the load/unload area or elsewhere, thereby increasing the flexibility in the system.

2. Tool changes due to tool wear cannot be avoided, and models which attempt to minimise tool changes due to product variety fall short of practical needs. If tool changes due to wear are a high proportion of the total then changes due to product variety could be ignored.

3. There are substantial gains in output to be obtained from the most flexible assignment of operations to machines and machine grouping.

Taking these conclusions together we suggest that a somewhat radical reconsideration of the machine grouping and loading problems is required. Two possible strategies for work scheduling can be put forward, which we can refer to as the fixed and dynamic machine grouping strategies. The FMS considered has fixed grouping, in that machines are dedicated to particular types of operation. The variable strategy permits grouping to be adjusted every scheduling period. Fixed grouping has the advantage of simpler planning, but reduced flexibility and requires swapping of tools. Variable grouping has improved flexibility and may not require tool swapping during a period, but involves a more complex scheduling problem. It could be postulated that the best performance would be obtained and blockages avoided by redefining the operations on a part so that all operations on one fixture are done at one visit to one machine, subject to the number of tools needed for each part being less than the capacity of the magazine.

This would combine maximum flexibility in routing parts to machines and simplify work flow avoiding the interactions of routings which seem to cause blockages. Since tool changes due to wear predominate, very few additional changes might be needed for product variety.

Finally, may we return to our theme of suggesting problems possibly amenable to the O.R. approach. Work scheduling in FMS is a rather complex problem, and one which cannot satisfactorily be subdivided. Is it possible to formulate a model which combines tool changes, operation definition, machine grouping, allocation of work to machines, buffer provision and period-by-period scheduling? Could such a model be solved sufficiently quickly to be useful in practice?

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Work Scheduling in FMS Under Tool Availability Constraints

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Work scheduling in FMS under tool availability constraints†

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Various of the planning problems in FMS are introduced and the impact of tooling considerations observed. The effect of tool variety, product variety and product similarity on the frequency of two types of tool change, due to product variety and due to tool wear, are identified. It is shown that when variety is great tooling availability constrains scheduling decisions.

The problem area is illustrated with reference to an example FMS, for which it is shown that tool capacity constrains scheduling decisions. The possibility of developing some part launch sequence which would minimize the need for tool changes is considered but found ineffective. Dynamically selecting jobs from queues so as to minimize tool change is also found ineffective. A linear programming mode. due to Menon and O'Gradey (1984), is described, but found to require further evaluation.

A tooling post-processor for a simulation model is presented which computes the number of tool changes in any work schedule. For the FMS considered it is found that the number of tool changes due to product variety is small compared to those due to tool wear. It is concluded that the assumptions underlying some of the FMS planning problems must be reconsidered in view of this result.

Introduction

When a flexible manufacturing system (FMS) is being planned initially, decisions are required on the following problems:

(1) The product range problem. Of the parts which potentially could be produced on the system which should actually be produced on it?

(2) The process planning problem. What operations are needed on the parts? What tools will be needed? How should the operations be allocated to machines?

(3) The machine capacity problem. What types of machines are required? How many machines of each type are required?

(4) The transport problem. How should the parts be moved around the system? What should be the capacity of the transport system?

(5) The fixturing problem. How should the parts be clamped? How many fixtures of each type need to be provided?

(6) The pallet problem. Are the parts to be palletized? How many pallets are needed? Will all pallets be of the same type? How many should be carried on one pallet?

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These define the overall structure of the FMS and its operating principles. Once the FMS exists, they set the framework which constrains the day-to-day operating decisions. The operational decisions have been arranged in a hierarchical scheme by Stecke (1981):

(1) The part type selection problem: from the set of part types that have production requirements determine a subset for immediate and simultaneous processing.

(2) The machine grouping problem: partition the machines into machine groups in such a way that each machine in a particular group is able to perform the same set of operations.

(3) The production ratio problem: determine the relative ratios at which the selected part types will be produced.

(4) The resource allocation problem: allocate the limited number of pallets and fixtures of each fixture type among the selected part types.

(5) The loading problem: allocate the operations and required tools of the selected part types among the machine groups subject to technological and capacity constraints of the FMS.

Stecke and Solberg (1981) state that any solution to the loading problem must comply with certain constraints, namely:

(1) each required operation and all associated tools must be assigned to at least one machine.

(2) an operation can be assigned only to those machines capable of performing it, and

(3) the tools required for the entire set of operations assigned to any machine must not exceed the capacity of the tool magazine of that machine.

and that to improve system performance:

(1) the workloads assigned to each machine should be balanced (in some sense) to avoid unnecessary bottlenecks,

(2) when feasible, consecutive operations should be performed on the same machine to minimize the number of part movements required, and

(3) tool space permitting, operations should be assigned to more than one machine to increase flexibility when routing parts in real time.

Tooling is clearly a major consideration in these decisions, in particular the machine grouping and loading problems. Strictly speaking, an operation is a collection of mini-operations by various cutting tools which, for reasons of fixturing or part orientation, are to be done together on one machine. The way operations are defined is to some extent arbitrary, and will affect the machine grouping and loading decisions, but for the present they will be considered to be predetermined. The basic data in an FMS will therefore include a list of the operations needed on each part, the machine or machine group where each is to be done and its duration. For each operation there will be a list of the tools required and the cutting time of each tool.

In order to consider the scheduling implications of tooling, some terms should be introduced. *Tool variety* describes the number of different tools required by a part in its manufacture. ***Product variety*** measures the number of different parts in the system at any time. If ***tool complement*** is the set of tools needed to be present in a machine's magazine to carry out a specified set of operations on some set of parts, then it will increase with the product and tool variety. On the other hand, the tool complement will by reduced by increasing ***product similarity***, the extent to which the different parts require the same tools. For large tool and product variety the complement may exceed the capacity of the tool magazine. Once this situation arises it will be necessary to change tools from time to time as different parts arrive at the machine. We will refer to these changes as ***tool changes due to product variety***.

This paper deals with the constraints this situation places on work scheduling decisions.

In addition to tool changes due to product variety there will be ***tool changes due to tool wear***. Since the life of each tool is measured in terms of cutting time, it follows that, for any given level of production, the number of tool changes due to wear within any production period will be approximately constant. However, the interval between changes of each individual tool will increase with tool variety and product variety, but decrease with product similarity.

An example FMS

Carrie *et al.* (1984) have described an FMS for the manufacture of complex castings. It comprises five similar CNC horizontal machining centres and one special horizontal machining centre with a facing head. All of the machines have a tool magazine with a capacity of 100 tools. Castings are fixtured and moved on pallets by an automatically guided vehicle (AGV). At each machine there are two pallet stands acting as buffers between the AGV and the machine table. There are also two pallet stands at the load/unload area. There are 13 pallets. Initially seven part types were to be produced on the system.

When the initial planning decisions were made, the operations required on the castings were categorized as roughing, semi-finishing and finishing operations, as well as facing head operations. The operation times vary from around 15 minutes up to four hours. Taking the forecast requirements and operation times into account the following initial solution to the machine grouping and loading problems had been proposed in Table 1.

Commissioning the facing head machine was delayed and since information is not yet available it has been omitted in the rest of this paper. The sequence of operations on the castings is illustrated by the following typical example in Table 2. This sequence involves three stages in different fixtures, involving roughing operations followed by semi-finishing and/or finishing operations, and nor-

Machine group	Operation type	Machine numbers
1	Facing Head	1
2	Roughing	2 and 3
3	Semi-finishing	4 and 5
4	Finishing	6

Table 1.

Operation number	Operation type	Machine group
1	Load	L/UL
2	Rough	2
3	Finish	4
4	Semi-finish	3
5	Refixture	L/UL
6	Rough	2
7	Finish	4
8	Reclamp	L/UL
9	Rough	2
10	Refixture	L/UL
11	Semi-finish	3
12	Semi-finish	3
13	Finish	4
14	Semi-finish	3
15	Unload	L/UL

Table 2

mally facing head operations. During one of the stages most of the parts will be brought back to the load/unload area for re-orienting within the same fixture, in this example at operation 8.

At the initial design stage it had been decided that the two roughing machines would have similar tool sets, but the two semi-finishing would have slightly different sets, because it was expected that more than 100 tools would be needed for the semi-finishing operations. This would permit some semi-finishing operations to be done on either machine 4 or machine 5, while some operations could be done on only one or other of the machines. (This explains the successive semi-finishing operations, numbers 11 and 12, in the operation sequence in Table 2.) Notice that this implies a more complex definition of the machine grouping problem than given by Stecke (1981). It was found when detailed planning was done that the total number of tools for the initial seven parts was 288, some tools being needed on more than one type of operation. The number of tools needed for each type are: roughing operations—107 tools, semi-finishing operations—115 tools, and finishing operations—89 tools.

This gave the following number of tools used by each part on each machine, see Table 3. Ignoring common tools, the number of tools which would be added to the magazines for each successive part is given in Table 4.

Part number	Number of tools required on machine 2	3	4	5	6	System total
1	56	56	28	67	28	235
2	40	40	50	55	35	220
3	39	39	55	36	36	205
4	43	43	24	55	22	187
5	40	40	43	33	30	186
6	34	34	21	28	17	134
7	19	19	27	31	9	105

Table 3.

Part number	Number of tools added to machine 2	3	4	5	6	System total
1	56	56	28	67	28	235
2	18	18	29	13	23	111
3	13	13	15	3	18	62
4	7	7	0	4	3	21
5	6	6	8	3	9	32
6	6	6	3	7	6	28
7	1	1	3	5	2	12
Total	107	107	86	102	89	491

Table 4.

Because the number of tools required exceeds the magazine capacity tool changes due to product variety will be unavoidable. The situation is complicated by the fact that tools vary in size. Some have a diameter greater than the spacing of the tool pockets in the magazine, and therefore neighbouring tool pockets cannot be used. In fact there could be four types of tool:

(1) single tools, which take only one tool position;

(2) centre tools, which take up three positions, the pocket the tool is placed in and the positions on either side;

(3) fat tools, which take up only one position, but because of their size cannot be positioned in the pocket next to another fat tool; and

(4) handed tools, which are assymetrical and take two positions, the one the tool is in and the adjacent one on its left or its right depending on the handing of the tool.

This means that the nominal magazine capacity, 100, is not the actual number of tools which can be held, but larger by some amount which depends on the positioning of the tools in the magazine. In this FMS there are 28 centre tools, 32 fat tools and 228 single tools, distributed among the machines. If we assign all the centre tools, then intersperse single and fat tools until all fat tools are assigned, and then fill the magazine with single tools the following situation will be found, see Table 5. The problem of tool changes due to product variety may be quite serious on machines 2, 3 and 6.

Machine number	Centre tools	Fat tools	Pockets used	Tools assigned	Single tools unassigned
2	11	13	100	78	29
3	11	13	100	78	29
4	0	11	86	86	0
5	0	12	100	102	2
6	17	9	100	66	23

Table 5.

Part launch sequence for minimum tool changes

Sequence technology is based on the principle that it is possible to work out a sequence of processing parts on a machine which will minimize the required changeover time, given data on the changeover time between each pair of parts. Perhaps it would be possible to apply this principle to an FMS with the objective of minimizing the number of tool changes due to product variety. The tool lists for each part on each machine were examined and the similarity between each pair of parts on each machine calculated as the ratio of the number of tools common to both parts, to the total number of tools used by either part. Best sequences of processing the parts were worked out. Unfortunately, different sequences were obtained for each machine and yet another sequence for the system as a whole, although there was some similarity between them.

Carrie and Petsopoulos (1985) evaluated several part launch sequences but found that none made any noticeable difference to the system performance. They concluded that this was due to two factors. Firstly, the operation sequences require parts to return to the load/unload area and the roughing and semi finishing machines several times during processing, so that very soon after launching parts the initial priorities have little influence on the progress of parts. Secondly, since only one set of fixture of each type was available, after the first part of each type had been launched on the FMS the launching of subsequent parts depends on fixtures being released by previous parts of the same type, rather than by some externally determined priority.

Consequently we must reject the idea of some part launch sequence for minimum tool changes.

Dynamic priority decision making

If a launch sequence does not seem feasible perhaps it would be possible to select parts from queues within the model so as to minimize the required tool changes dynamically. Carrie and Petsopoulos (1985) investigated various rules, and again concluded that none made any significant difference to system performance. In addition to the possible reasons mentioned above they suggested that since transport times are short in relation to the operation times there were few occasions when the AGV had any choice of part to move. Consequently, although the matter is being examined further, this possibility does not appear fruitful.

A linear programming model

In view of the above it would seem that a more explicit control of product variety and tool variety will be required. Menon and O'Grady (1984) have formulated a linear programming model which selects from a list of orders to be processed a subset of orders to be launched to comply with tool and machine capacity, and possibly other constraints. They seek to minimize an attainment function defined as the summation of the products of deviation from some desired level and a weighting factor for each parameter. The parameters which they include are: the machine hours available at each machine; the capacity of each machine's tool magazine; the number of 'standard' tools at each machine; the number of 'non-standard' tools required by each part at each machine; the due date of each order; and the number available of each type of tool.

By applying appropriate values to the weighting factors the selected subset can be adjusted to emphasize machine hours, tool availability, tool capacity or due dates. The model is being evaluated and looks promising, although it is too early to say if it will be successful. Observations concern:

(*a*) Standard versus non-standard tools. The model requires that tools are categorised as standard or otherwise. In reality in the FMS there is no such distinction, and some arbitrary decision must be taken. It would be possible to declare each tool which is used on only one part at each station as a non-standard tool, but there are other rational possibilities. It appears that some experience will be necessary to tune the definition.

(*b*) The values given to the weighting factors. These are also arbitrary, although in principle it might be possible to give a financial measure to some of them. It appears that experience is also required to tune the weights. The situation is complicated by the fact that different periods' schedules might well require different values of the weighting factors. This implies that there exists a higher level of planning which would set the overall objective for the period, from which the weights would be deduced.

(*c*) Fixing the planning period. In the model the machine capacity and orders are given without reference to the period to which they apply. Obviously they must be consistent. If we use a short planning horizon there will be fewer orders to consider and fewer non-standard tools to take into account, but less flexibility in selecting a subset of orders. If we take a long horizon there will be more orders to select from, more tools to consider and greater choice of subset. However, the load on the system will commit it for a longer time during which the situation may change. Here again experience will suggest a suitable balance. Intuitively, it would seem that the period should be roughly equal to the time taken to process parts through the system because that is the minimum period for which a decision commits the system.

(*d*) Data collection. For the model to be useful as an operational tool it must be possible to insert the data easily into the model. The tableau of the model is rather large, and we foresee difficulties in extracting the data automatically from the FMS control system.

A tooling simulation post-processor

Simulation models of the system (Carrie *et al.*, 1983, Carrie and Adhami 1983) did not include tools. Because of the numbers involved tools could not be added to the models and a post-processor was written which would examine the history of a simulation run and compute the tool requirements.

The post-processor reads a file of work flow data and by referring to the part routing and tool requirement files maintains a list of the tools which would be present in each tool magazine. Hence the occurrence of tool changes due to product variety can be deduced. By aggregating the cutting time of each tool on each operation performed the program computes the occurrence of tool changes due to usage.

Clearly, the number of tool changes will be highly dependent on the work schedule being followed, but some representative results will be of interest. In any period, the number of operations performed by each tool will follow a characteristic distribution. For example, in one simulation experiment the figures for one week on a roughing machine were:

Operations:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Tools:	21	21	20	14	6	5	5	2	4	1	1	2	3	1	0	0	1	2	1

Since 21 tools out of 107 were not required that week, perhaps it would have been possible to operate that week without any tool changes due to product variety. The number of tool changes of both types observed in five-week simulation runs were:

Week number:	1	2	3	4	5
Changes due to product variety:	45	9	17	7	0
Changes due to tool wear:	52	95	145	128	162

Allowing for transient effects due to the initial conditions in the model, this shows that the number of tool changes due to product variety is not large, and that the number of changes due to wear is an order of magnitude greater. A rough estimate of the number of tool changes due to wear in the system as a whole in any period can be obtained from the relation: number of tool changes = total spindle cutting time/average tool life, which may be expressed as number of tool changes in system = number of spindles × working period × % spindle cutting time/average tool life.

Using very rough estimates of the spindle cutting time, which varies considerably between machines, say 30%, and of average tool life, say 30 minutes, this would give for a two shift week: number of changes = 5 × 4000 × 0·3/30 = 200, which is of the order of the figures given above.

These results suggest that concentrating on tool changes due to product variety and the associated scheduling decisions may be misguided, and that instead consideration should be given to the methods of tool change, for whatever cause.

The machine grouping and loading problems reconsidered

Carrie and Petsopoulos (1985) investigated the sensitivity of the system's performance to the machine grouping and loading decisions. During simulation studies of the system it was observed that the utilization of the two roughing machines was very high. They examined the effect of allocating additional capacity to these operations by allowing machine 4 to perform roughing as well as semi-finishing operations. Their experiments showed an increase in output of almost 40%, but since they did not take into account the limitations of the tool magazines, the need for additional tool changes would have to be set against this gain. The conclusion that tool changes due to product variety are small in number suggests that this would be a worthwhile alternative.

The results also bring into question the initial allocation of tools and operations to machines. The allocation reported above was made by the supplier's engineers after examining drawings of a range of parts. When detailed methods were developed by the user's staff perhaps the initial decision should have been reconsidered. Indeed it might be worthwhile reviewing the composition of the operations themselves.

One objective would be to provide alternative machines for every operation. For example, it might be wise to give machines 4 and 5 identical tool sets instead of about 70% common as planned. Relatively few additional tool changes would be introduced. This would not be possible as well as allowing machine 4 to do roughing work, and the roughing work is more of a bottleneck. It might be possible to balance the loads between machines better.

Carrie and Adhami (1983) reported that the system suffered from congestion and blockage problems, partly due to the number of times the parts return to the various machines in their operation sequences. Perhaps it would be possible to relieve these problems by a different allocation of work to machines.

Conclusion

Various aspects of work scheduling under tool availability constraints have been considered and illustrated with reference to a particular FMS. No optimal formula has been proposed, rather it has been shown that the problem is one with many parameters, and it is most unlikely that such a formula would exist. The nearest approach to that ideal is a model such as that of Menon and O'Grady (1984), although several aspects of that model require further assessment.

A tooling post-processor has been described which shows that tool changes due to product variety are only a small part of the total number of changes. Therefore devoting excessive effort to the product variety aspect of the problem is unwise, and initial operation definitions and machine grouping and loadings may need to be reconsidered. Applying the just-in-time principle it would be better to devote attention to efficiently performing tool changes for whichever cause, rather than evolving a scheduling method which assumes they are an immutable constraint.

Finally it must be emphasized that, as Stecke and Solberg (1981) and Carrie and Petsopoulos (1985) have pointed out, each FMS tends to have its own individual characteristics and therefore results related to one system may not be generally valid.

Divers problèmes de planification dans les systèmes de fabrication flexible (FMS) sont présentés et l'influence des considérations relatives à l'outillage est observée. Le rôle joué par la variété des outils, la variété et la similarité des produits sur la fréquence de deux types de modification d'outillage, due à la variété des produits et à l'usure des outils, est identifié. Il est démontré qu'en cas de diversité importante, la disponibilité d'outillage représente une contrainte par rapport aux décisions de programmation. La zone problématique est illustrée par rapport à un modèle de FMS, pour lequel il est démontré que la capacité d'outillage représente une contrainte pour les décisions de programmation. La possibilité de développer une séquence qui n'imposerait qu'un minimum de changements d'outils est examinée et jugée inefficace. La sélection dynamique de travaux à partir de files d'attente, destinée à minimiser les changements d'outils est également jugée inefficace. Un modèle de programmation linéaire, dû à Menon et O'Grady, est décrit et nécessite une évaluation complémentaire.

L'article présente un post-processeur d'outillage pour modèle de simulation qui calcule le nombre de changements d'outils dans tout programme de travail. Il est démontré que pour le FMS examiné le nombre de changements d'outillage dû à la variété de produits est réduit par rapport au nombre de changements dus à l'usure des outils. Etant donné ce résultat, l'article conclut qu'il est nécessaire de ré-examiner les hypothèses qui sous-tendent certains problèmes de planification des FMS.

Einige der Planungsprobleme, die bei flexiblen Fertigungssystemen (FMS) auftreten, werden vorgestellt, und der Einfluß der Werkzeugbestückungsfaktoren wird untersucht. Es wird ermittelt, welche Auswirkung die Vielfalt von Werkzeugen, die Vielfalt an Erzeugnissen und die Ähnlichkeit der Erzeugnisse auf die Häufigkeit zweierlei Arten Werkzeugwechsel haben: die eine, die durch die Erzeugnisvielfalt bedingt ist, die andere, die dem Werkzeugverschleiß zuzuschreiben ist. Es wird nachgewiesen, daß beim Vorliegen einer großen Erzeugnisvielfalt die Verfügbarkeit der Werkzeuge zu einer Zwangsbedingung der Ablaufplanungsentscheidungen wird.

Der Problembereich wird an Beispiel eines flexiblen Fertigungssystems erläutert, bei dem nachgewiesen wird, daß die Werkzeugverfügbarkeit eine Zwangsbedingung für Ablaufplanungsentscheidungen ist. Die Möglichkeit wird erwogen, eine Werkstück-Anlaufbearbeitungsfolge zu entwickeln, die es ermöglichen würde, den Werkzeugwechsel zu minimieren. Das erweist sich jedoch als unwirksam. Auch die dynamische Wahl von Aufträgen aus der Warteschlange erweist sich für eine Minimierung des Werkzeugwechsels als wirkungslos. Dann wird ein von Menon und O'Grady entwickeltes Linearprogrammierungsmodell beschrieben, doch zeigt sich dabei, daß es einer weiteren Überprüfung bedarf.

Es wird ein Werkzeug-Postprozessor für ein Simulationsmodell vorgestellt, der die Anzahl der Werkzeugwechsel in jedem Ablaufplan errechnet. Bei der erwogenen FMS-Anlage zeigt sich dabei, daß die Gesamtzahl der Werkzeugwechsel, die der Erzeugnisvielfalt zuzuschreiben ist, im Verhältnis, zu der, die durch den Werkzeugverschleiß erzwungen wird, nur klein ist. Als Schlußfolgerung ergibt sich, daß die manchen FMS-Planungsproblemen zugrunde gelegten Annahmen angesichts des obigen Ergebnisses neu überprüft werden müssen.

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Work Allocation in Flexible Manufacturing Systems

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Work allocation in flexible manufacturing systems

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SYNOPSIS This paper describes the problem of allocating operations and tools to machines in FMS. It discusses some of the important characteristics of the parts to be produced, and illustrates them with reference to FMS in Scottish industry. Systems exhibiting simple, moderate and complex allocation problems are described. Models in the literature are reviewed and their shortcomings noted. The magnitude of the problem in the complex system is discussed and the approaches being explored described. Some general observations are offered.

1 INTRODUCTION

The literature contains many comments on the nature and measurement of flexibility in FMS, eg Buzacott (1), Yao and Buzacott (2), Warnecke and Steinhilper (3). Yet most FMS incorporate decisions which explicitly limit their flexibility, often concerning the allocation of work to machines and associated scheduling problems, whether due to workload, tooling, data-processing or other considerations. The planning and operational problems in FMS design and management have been enumerated by various writers, eg Stecke (4), Stecke and Solberg (5), Carrie and Petsopoulos (6), Kusiak (7). The problem involves a set of parts to be produced to a program which specifies the quantities required in each time period; each of the parts requires a number of operations; each operation requires a set of tools, takes time to perform and must be done on a machine. Alternative machines may be available. There is usually a limit to the number of tools which can be held in the tool magazine of any machine. Parts are usually mounted in fixtures on pallets. Some parts may share the same fixture type. The numbers of pallets and fixtures available are limited.

This paper is concerned with the problem of allocating operations and the necessary tools to the machines to enable production to proceed in the most effective manner. Part of this decision is grouping the machines into groups such that all the machines in a group are capable of performing the same set of operations. Another facet of the problem is the assignment of fixtures to pallets and to parts. Depending on time and technical capacities it may not be possible to produce all the required parts in any period. The problem therefore includes deciding how parts are to be selected for production in the current period.

Among the objectives to be considered in making these decisions are:

1. Every operation on the selected parts must be allocated to at least one machine group.
2. The work content of the operations allocated to the machines of a group must not exceed the time capacity of the machines of the group.
3. The tools needed for each operation must be present in the machines of the group to which the operation is allocated.
4. The number of tools required for the operations allocated to the machines of a group should not exceed the tool magazine capacity of the machines of the group (many researchers take this as an absolute constraint).

In addition, as observed by Stecke and Solberg (5):

1. the workloads assigned to each machine should be balanced (in some sense) to avoid unnecessary bottlenecks.
2. when feasible, consecutive operations should be performed on the same machine to minimise the number of part movements required.
3. tool space permitting, operations should be assigned to more than one machine to increase flexibility when routing parts in real time.

It is the purpose of this paper to examine how these problems manifest themselves in systems in Scottish industry and how they have been tackled in these systems. It will also review some of the approaches in the literature and make some general observations and recommendations.

2. WORKPIECE CHARACTERISTICS

The nature of the workpieces is of paramount importance. Characteristics influencing the work allocation problem will now be discussed and examples from Scottish industry identified.

2.1 Diversity of operations

If workpieces require two distinctly different types of operation it may be wise to have separate FMS for each type. For example, if components require both rotational and non-rotational operations, separate systems could be built to avoid potentially difficult workpiece re-orientation problems. Caterpillar have two FMS adjacent to each other; the Scheiss line performs vertical turning operations and the Scharmann Solon line drilling and milling operations (8). Components are manually unloaded from the first and manually re-loaded in the second system. This seems to be implementing the advice of Schmoll and Popplewell (9) to 'take strides but don't stumble'. However with improving technology, linking the two stages with a robot re-orientation station would now be possible.

2.2 Complexity

Simple components may be completely machined in a single setup. More complex components will require two or more setups in different fixtures. The FMSs in Caterpillar mentioned above complete the work in one fixture. However, in the FMS at Anderson Strathclyde's Motherwell factory, supplied by Giddings and Lewis-Fraser, most of the parts require three stages of fixturing and also need to be re-positioned in one of the fixtures making at least four passes through the machines (10). A complex process routing greatly complicates the problems of work allocation and balancing loads on the machines, and can lead to blocking or deadlock of the system.

2.3 Size

If the parts are small then fixtures for several parts can be mounted on a single pallet. This is a straightforward application of the materials handling principle of large unit loads and reduces the load on the transporter. In some systems this may be extremely important. In Caterpillar's Comau line the transporter priority rules had to be carefully tuned to ensure that the vehicle would not be the system bottleneck (11).

Small parts requiring two or more stages of fixturing can be arranged in two ways. Either different pallets are used for the different stages so that each pallet has parts at one stage only, or parts at different stages are be mounted on different faces of a basic pallet/fixture combination. Both arrangements are used in the Makino FMS in Cummins Engines plant at Shotts.

With large parts these tactics are not available. Each stage of fixturing must be done on a different pallet, or after changing fixtures on a single pallet, as is done in Anderson's FMS.

2.4 Family relationships

If the parts have a family relationship in the sense that they are mating parts of a common assembly and are small then a further option is available. It may be possible to put a set of parts on a single fixture. This arrangement was selected for the FMS supplied by Olivetti (12) to Cessna in Glenrothes in Fife. In this way balanced sets may be produced for delivery to the assembly department. The alternative is to control the relative output of the parts by system software. The hardware solution avoids build-up of work in progress and achieves just-in-time production. It may even be possible to incorporate an assembly station in the FMS.

2.5 Production requirement

If parts are required in relatively small quantities the options of placing sets of parts or parts at different stages of production on a single fixture are appropriate. When quantities are larger additional fixtures, pallets and machines will be required. At high volumes different methods of machining may be desirable. In principle there is no reason why flexible computer controlled manufacturing techniques may not be combined with sequence controlled machining cells. The Comau line at Caterpillar is of this type.

2.6 Variety

When a large variety of parts are to be machined in an FMS the problems of scheduling and of allocating fixtures to parts and of tools to machines becomes more complex. The number of tools which are needed for the range of parts increases as more parts are programmed for FMS production, and the magazine capacity of the machines may soon be exceeded. When this point is reached tools and parts must be scheduled jointly and the work allocation problem becomes less tractable. This is a major consideration in Anderson Strathclyde's FMS and also occurs in Cummins' Makino FMS.

2.7 Similarity

Similar parts will require similar tool sets. This reduces the effect of part variety. Grouping parts according to the commonality of tools is a useful technique in work scheduling, discussed further below.

2.8 Workpiece material

The machinability of the material affects the work allocation problem in two ways. Hard materials will be cut at slower speeds and therefore operations take longer to perform. Long operations are less easy to balance than short ones. Also the rate at which tools wear will be more rapid, tools lives will be shorter and tool changes more frequent. This aspect is ignored in many of the models in the literature, but may be important, as in Anderson's FMS.

2.9 Work content

The work content on a part is influenced by several of the factors above.

For simple parts it will be possible to complete the work at each fixturing in a single operation. If the number of tools and the work content are not large and the operations are of basically one type then the FMS may consist of a number of identical machining centres each of which can process any workpiece. The Solon and Scheiss FMSs at Caterpillar are of this type.

If the tool variety is large (in relation to machine tool magazine capacity) or the operation times are large then it will be necessary to split the operation between more than one machine. In the Anderson Strathclyde system, because of the numbers of tools involved, workpieces have between two and five operations per fixture stage. This greatly complicates the work allocation problem. A further complication is that if there is only one fixture for each stage on a part there can be only one part in process at any time. Production of any part may be constrained by fixture availability rather than by machine capacity. This applies in Anderson's FMS, where Carrie (10) found that having duplicate fixtures permitted output to be raised by about 20%.

3 EXAMPLES OF WORK ALLOCATION PROBLEMS

In the Glasgow area there are systems exhibiting very simple, moderate and complex work allocation problems.

3.1 A simple problem

The Caterpillar Solon line is an example of a simple system. It consists of four machining centres, a washing machine and load/unload stations served by a rail car. The workpieces can be processed in a single operation and the machines can hold all the tools needed for the entire set of parts. In these circumstances the work allocation problem disappears.

3.2 A moderate problem

Cummins' Makino line is of moderate complexity. It consists of three machining centres, pallet storage racks, load/unload stations and rail car. The parts are of three basic types and require two fixture stages. The number of tools is too large to allow any machine to process any part. The solution adopted was to tool up each machine to process two out of the three part types. The parts are small and normally four can be loaded on a pallet. Among the questions being investigated are whether it is preferable to have fixtures for only one stage on a pallet or alternatively fixtures for both stages, and whether the allocation of work and tools to machines substantially constrains the system performance.

3.3 A complex problem

From the comments above it will be apparent that a complex work allocation problem is presented by the Anderson Strathclyde system. It consists of six machining centres served by an AGV on a single path track. The parts generally require three fixture stages with around 4 operations per stage. The total work content is of the order of 20 hours, about 6 hours per stage. In excess of 200 tools may be required for a part. Of the six machines five are similar and one is slighlty different from the others. Two of the five are assigned to roughing operations, two to semi-finishing and one to finishing operations. This allocation provides a framework for NC programmers, and it was hoped, when the system was being planned, that the number of tools needed on each machine would not exceed the magazine capacity of 100 tools. When the first seven parts were loaded onto the system the number of tools needed were 107, 115 and 89 at the roughing, semi-finishing, and finishing machines respectively. A further 5 parts are being planned for FMS operation and the numbers are approaching 200. The problem of jointly scheduling tools and parts exists in earnest.

4 REVIEW OF MODELS

Stecke and Morin (13) show that work loads should be balanced in machine groups of equal numbers of machines, whereas Stecke and Solberg (14) show that in unequal sized groups loads should be unbalanced so that large groups have slightly proportionately more work and small groups less work. Stecke and Talbot (15) present loading algorithms which ensure that loads are properly balanced in machine groups of equal size and properly unbalanced in groups of unequal size. Unfortunately they did not take tool capacity into account. Stecke (16) formulates certain non-linear integer programming models which do take tool capacity into account. They operate on a one-time basis and do not account for tool changes between one period and the next, or of inventory costs due to making parts in advance of the scheduled period. Kusiak (7) presents a model which does take these costs but omits tool considerations. Wilhelm and Shin (17) analyse the value of alternate operations, while Kimemia and Gershwin (18) tackled the problem of flow optimisation. Most of these models are based on mathematical programming, and purport to provide optimal solutions. However, as Stecke (16) indicated there are data processing problems in solving them, and to date they have had little impact in practice.

Menon and O'Grady (19) have formulated a linear programming model which takes tools required, machine capacity, tool availability and due dates into account and selects from the total list of orders those jobs which should be loaded into the FMS. The objective function is a summation of the weighted deviations from the desired level of the parameters. They were supplied with data for the Anderson's system and it was hoped that their model would be useful in practice. However as Carrie and Perera (20) have reported it suffers from several deficiencies. It did not take the period by period nature of the problem into account; by varying the weighting factors a wide variety of solutions could be obtained, and there was no scientific basis for establishing values of the weighting factors; in common with many such models the data requirements are significant and unless the model can be built into the system software the problems of extracting data are prohibitive.

5 MEASURING THE SCALE OF THE PROBLEM

It is all too easy to embark on elaborate mathematical models of a problem, only to discover later that what had been thought a significant factor was in reality of minor concern, or that important factors had been overlooked. To measure the scale of the problem in the Anderson Strathclyde system a tooling post-processor was written for the models of the system developed earlier (10). This examined the record of events in the simulation model and computed the number of tool changes which would have been necesary. It maintained a list of the tools which were present in each tool magazine and deduced whenever tool changes due to product variety would have been necessary. By aggregating the cutting time of each tool on each operation and comparing this with the life of each tool the program computed the occurence of tool changes due to tool wear.

The results when applied to the initial set of parts have been reported by Carrie and Perera (20). They found that on typical production schedules the number of tool changes due to part variety averaged between 10 and 15 per week. The

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number of tool changes due to wear was an order of magnitude greater, usually around 130 per week. They concluded that models which excluded tool changes due to wear overlooked the main problem, and that to develop complex algorithms which minimised what were only a small proportion was misguided. Much more attention should be paid to developing efficient means of changing tools. As Hutchison (21) has stated 'most FMS have done a rather good job of supplying the machine with all of the production requirements apart from the tools.'

A rough estimate of the number of tool changes due to wear in the system as a whole in any period can be computed from the number of spindles, the average tool life and an estimate of the proportion of spindle cutting time. For the Anderson FMS this could be as large as 200 per week, reflecting the short tool lives and large work content when machining complex steel castings.

Recently a further five parts have been planned for FMS production. In some cases they bring into the system several dozen new tools. Simulation experiments with various part mixes show that the number of tool changes due to wear is fairly stable at about 170 per week. The number of tool changes due to part variety will vary from near zero to over 400, depending on the part mix. Clearly a problem of some magnitude exists.

6 DEVELOPING HEURISTICS

Study of the problem and the development of heuristics for managing the system is part of on-going work, and it is not possible to put forward solutions. Full details of the new parts are still in preparation. To date several approaches have been looked at, mainly on the original set of parts. The possibility of computing a part launch sequence to minimise the number of tool changes was explored. the tool lists for each operation were examined and best sequences obtained. Inevitably there were different sequences for each machine and for the system as a whole. Experiments on the effect of different launch sequences were carried out, Carrie and Petsopoulos (6), and found to have no significant effect on system performance. They concluded that the nature of the operation sequences, the duration of the operations in relation to transport times and restriction on number of fixtures for each part quickly overshadowed externally determined priorities between parts.

Carrie and Petsopoulos (6) also investigated the sensitivity of the system's performance to the machine grouping and loading decisions. During simulation studies of the system it was observed that the utilisation of the two roughing machines was very high. They examined the effect of allowing one of the semi-finishing machines to perform roughing operations as well as semi-finishing operations. The results showed an increase in output of almost 40%, although tool changes were not taken into account. This figure is similar to those quoted by Wilhelm and Shin (17) for the gain in output when rules which permitted dynamic selection of alternate operations relative to rules which permitted no alternate operations. These results suggest that the static allocation of operations to machines reported above (which was made by the supplier's engineers after examining drawings of a range of parts) may be limiting system performance. Since each operation may take up to four hours and require several dozen tools there is clearly scope for further subdivision of operations. On the other hand attempting to provide a means of dynamically allocating work and tools to machines could cause problems in the tool supply room and has important implications for the way in which part programs are defined. Any such approach would also have to guard against compounding the blockage problems from which the system was found to suffer (10). Work continues on various fronts.

7 CONCLUSION

In this paper factors influencing the work allocation problem in FMS have been considered and related to systems in Scottish industry. The problem was shown to be particularly complex in the FMS at Anderson Strathclyde. Some of the models in the literature were reviewed, and all were found deficient in some respect. Some of the approaches being examined were described.

The following general observations are offered:

(1) The problem of work allocation in FMS is a significant one.

(2) Because tool changes due to wear are unavoidable it is unwise to concentrate only on those due to part variety.

(3) The most effective solution is through improved engineering and machine design to facilitate tool change without loss of production.

(4) Significant gains in output can be obtained by maximising the dynamic flexibility of the system.

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A Simulation Tool for Real Time Scheduling of FMS

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A Simulation Tool for Real Time Scheduling of FMS

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1.0 INTRODUCTION

It is recognized that the production planning and control problems of Flexible Manufacturing Systems are the major operational problem [Carrie and Perera, 1986]. Although some functional strategies (such as next station selection) are embeded into control software, many decisions relating to day-to-day operating policies are left to the user. Furthermore users are continually affected by disturbances such as machine breakdowns and schedule changes

Computer simulation has been widely accepted by users in evaluating alternative approaches to problems. In most cases off-line simulators are used. However, the quality of the decision can be improved if real time data are used and in some operating enviroments the use of real time data is essential. For an example, in a high variety, low volume environment, it is reckoned that the system may never reach a steady state due to constant changes in product mix. Thus in evaluating management decisions, the current status of the system must be taken into account.

This paper presents the design and implementation of an on-line FMS simulator and its application.

2.0 A FLEXIBLE MANUFACTURING SYSTEM

The system [Carrie, et el, 1984] consists of five identical machining centres and one special machine. These workstations and two load/unload stations are served by a single automated guided vehicle. Identically tooled machine groups provide alternative routes for the parts which have complex processing characteristics. Every part type requires two or more fixtures. Processing times spread from a few minutes to several hours.

In this system, fixtures and tools impose severe constraints on management decisions. The waiting time for fixtures is considerable especially in the case of dedicated fixtures. Of course this depends on the product mix. At present a modular fixturing system is being implemented which generates the new problem of fixture sharing. Furthermore the parts demand a large number of cutting tools at all workstations. Aggregrate tool requirements exceed the tool magazine capacity. Some control over the part release is imperative to avoid excessive number of tool changes [Carrie and Perera, 1986].

An operating feature is that empty pallets are not taken out of the system, hence two types of pallets are routed through the system, pallets with parts on them and empty pallets.

3.0 OPERATIONAL PROBLEMS ASSOCIATED WITH FMS

As mentioned in above day to day operational problems are tackled by the user. In the following some of these and other associated problems are discussed in detail.

a. Due date achievement evaluation.

When customer orders are accepted for flexible manufacture it is necessary to evaluate whether due dates can be achieved. In this system manufacturing lead time heavily depend on fixture availability. Thus any technique used to evaluate this should include fixture constraints as well.

b. Fixture allocation

At present a modular fixturing system is being implemented. Thus it is possible to use some fixture elements for different part types with minor changes in configuration. At present 'accquired experience' is casually used to solve this problem and therefore it is necessary to evaluate effectiveness of the user's strategy in this context.

c. Introduction of new part types to the system.

In the FMS environment it is necessary to prove-out all part programs before they are used within the system. Although the company uses some computer assisted techniques to check the accuracy of part programs, the complex nature of part types does not allow the complete elimination of on-line proving out. Thus the first few workpieces of a new part type may take longer processing times due to manual interventions. The user suggests following 'factors' to estimate processing time for first few workpieces.

Adjusted processing time= (Factor)x(Processing time estimated from the part program)

Workpiece	1st	2nd	3rd
Factor	5	3	2

Thus introducing of new part types disturbs the current production plan and the timing of the introduction should minimize the effects.

d. Machine breakdowns

If a workstation is not available for a considerable length of time it may be necessary to re-allocate operations previously assigned to it. This is essential in the case of single machine groups. Thus it is important to evaluate the effects of these diturbances.

e. Bottleneck workstation and dynamic shift patterns

The specail machine has become the bottleneck of the system due to specific nature of operations assigned to it. To relieve this situation, an extra shift on this workstation is run from time to time. Thus the usual shift pattern is as follows.

	Day shift	Back Shift	Night Shift
Hrs. worked	9	5	10
Workstation	whole system	special m/c only	whole system

In addition, weekend shifts may be required to accomplish production targets. Therefore it is necessary to estimate number of addtional shift required and their time spans.

There are also conventional production planning problems, such as machine grouping and tool allocation. At present a static machine grouping strategy is used. However it is believed that the performance of the system could be improved by adopting a more dynamic approach.

4.0 THE IMPORTANCE OF REAL TIME DATA

This system is a classic example of a high variety, low volume FMS with long processing times. Therefore it is reckoned that the system may not reach the steady state. Thus it is necessary to capture real time data when operational strategies are constructed. Most of the data resides in the executive computer hence the development of on-line simulator.

5.0 SIMULATION AS A PERFECT MODELLING TOOL FOR FMS

Simulation is the only modelling tool capable of capturing all essential complexities of FMS. In particular fixture constraints and empty pallet handling should be modelled in this system.

Previous researchers had developed a simulation model based on ECSL [Carrie, et el,1984]. Although modelling is easy with ECSL it have several limitations for real-time applications, such as long execution time and restricted file handling. FORTRAN-based the GASP package was was selected as an alternative. Although much programming effort is required, GASP provides high flexibility to the modeller. This also simplified integration with the executive system since it was also written in FORTRAN. The program segments corresponding to continous simulation were eliminated and required routines were re-coded in FORTRAN 77.

6.0 DESIGN AND IMPLEMENTATION OF THE SIMULATOR

The first stage of the project involved the simulation of part flow. Although GASP is an event-based simulation package by using a special structure some features of activity-based simulation were incoporated. As far as the part flow is concerned, there are three major 'slave' entities (Crane, AGV and Workstation) which serve the part ('master'). Once the activity cycle diagram is constructed, activities can be grouped under slave entities. When a slave entity become idle, activities under this entity are scanned in a particular order which guarantees a predefined

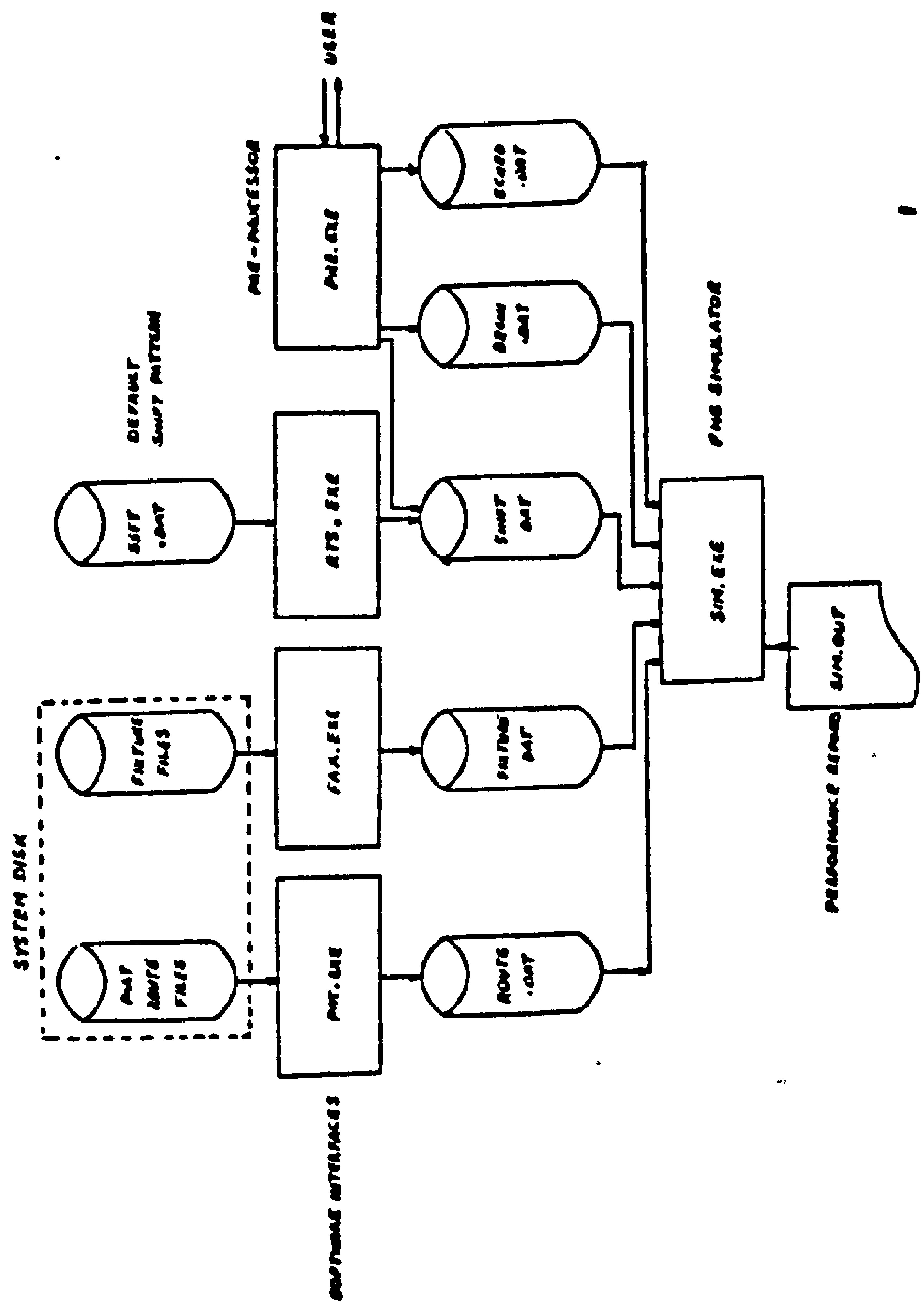

FIG. 1 FMS SIMULATOR AND ASSOCIATED SOFTWARE MODULES

activity priority, as in activity-based simulations. If an activity can be started, then the 'end event ' corresponding to the activity is scheduled. When the 'end event' is reached, the slave entity is released, and the activity scanning will proceed.

6.1 CAPTURING SYSTEM AND REAL TIME DATA

It is necessary to extract system data such as Part Route information and Fixture-operation relationships. A suite of software interfaces were constructed for this purpose (Fig. 1) . However a major difficulty was encountered in capturing the current status of the system. Access to some of this data was restricted by the supplier. The best alternative was to construct an user-friendly front end for the simulator. This is capable of capturing the current status of the system within a very short period of time. Additional facilities were also provided in the same module to change shift patterns and to input production programs. Another module sets default shift patterns.

7.0 APPLICATION OF THE SIMULATOR AND FURTHER ENHANCEMENTS

The management decision problems discussed above are assisted by the simulator. It provides more accurate information to the management, since real time data are used to drive the simulator.

Further program modules have been constructed to simulate tool flow within the system. However these cannot be implemented due to limited capacity of the computer sytem. It is anticipated this addtional feature will assist the management to improve tool scheduling. A graphical post-processor has also been written which can be integrated to the simulator.

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Simulation of Tool Flow within a Flexible Manufacturing System

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SIMULATION OF TOOL FLOW WITHIN A FLEXIBLE MANUFACTURING SYSTEM

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ABSTRACT

The Design and development of a tool flow simulator for a flexible manufacturing system is presented. The large volume of data involved is indicated and the need for an efficient and effective data handling environment is stressed. The advantage of linking the simulator to a relational database management system to provide a more powerful simulation system is pointed out. The basic modules including the tool configuration setup programs, are explained. Finally, the application of the simulator is demonstrated using data extracted from a real FMS.

INTRODUCTION

In the development of the first generation of the flexible manufacturing systems, except in few cases, tool management aspects were largely ignored. This negligence has generated various operational problems and many FMS users now recognize that tool flow control is a major obstacle in achieving the expected performance. Particularly, in the high tool variety environment, most of the production planning and control problems are constrained by tooling.

As part of this failure to perceive the importance of tool management aspects, most simulation studies are confined to part flow simulation. However in the design and implementation of a tool management system, the availability of a simulation package capable of handling tool flow within the system is a prime pre-requisite.

The design and development of a such a simulator is presented and its application areas are described. Data extracted from a real FMS are used to demonstrate specific applications of the simulator.

HIGH TOOL VARIETY ENVIROMENT AND ASSOCIATED OPERATIONAL PROBLEMS

Perera and Carrie [2] suggested three basic operational policies which depend upon the tool variety index. Particularly in the high tool variety environment (i.e. when the tool variety index is high) the parts may require many tools and the aggregate tool requirements may exceed the tool magazine capacity. Thus most of the planning and control problems are severely constrained by tooling. The following are some of them:

a. The Part Selection for Immediate Processing.

In the high tool variety environment, batching of parts is inevitable. However the traditional batching approach (one batch after another) may not be suitable when batch sizes are low and operation times are long. Thus a sequential part selection approach will be more appropriate for minimizing subsequent tool changes due to product variety.

b. The Part Releasing Strategy.

Having selected parts for immediate processing, they must be released to the system in a logical manner to reduce excessive tool changes. In the high tool variety environment, it cannot be guaranteed that all tools required for a given part type can be made available at all desired workstations, prior to the release of the part.

c. The Part Routing Strategy

Although groups of workstations can be formed to perform similar operations, due to excessive tooling reuquirements, individual workstations of a given machine group may have different tool configurations. Hence tooling must be taken into account when alternative workstations are evaluated.

d. Operation Assignment.

The way operations are assigned to workstations is also influenced by tool magazine capacity and tool requirements for a defined part mix.

Moreover, users and vendors of FMSs would decide the certain features at the design stage, for example:

a. The capacity of the tool magazine.
b. The distribution pattern of tool stores.
c. The type of tool handling system and the system layout.
d. The tool inspection, resetting facilities, etc.

When FMS are designed and/or operational strategies are developed, a 'model' of the system under investigation is invaluable. Among various modelling techniques, computer simulation has established as the most effective approach.

THE COMPUTER SIMULATION OF TOOL FLOW

Although there are various modelling techniques, such as queueing networks, only simulation can capture the essential complexitites of FMS. Even when the part flow is concerned, on many occasions, other approaches fail to produce satisfactory results. Undoubtedly the incoporation of the tool flow would increase the complexity of the modelling process and as a result simulation will become more important in this area.

As far as the computer simulation of manufacturing systems is concerned, three major scenarios exist:

a. Simulation Languages

There are a large number of simulation languages,including some oriented to simulation of manufacturing systems eg. SIMAN [5]. Although these provide special features to facilitate part flow simulation, none support efficient data handling techniques which are essential in the tool flow simulation. By contrast, many simulation languages restrict efficient data file handling.

b. Simulation Packages

These packages eg. GASP [6] provide the modeller with a library of basic routines. Routines associated with the operational aspects of the system are coded by the user. As these packages have been written in high level general purpose languages, usually they provide good flexibility in data handling aspects, but at the expense of greater programming effort.

c. Simulators

These data driven programs are limited to part flow simulation. However, it may possible to link user written routines to the simulator to mimic tool flow. But this requires good knowledge about the internal working of the base simulator.

It is clear that none of these established approaches is entirely satisfactory. Therefore it is anticipated that better simulation system can be developed by integrating a database management system with a simulation language/package.

DATA HANDLING REQUIREMENTS IN TOOL FLOW SIMULATION

The number of cutting tools in a medium size FMS can easily run into thousands [3]. Each of these tools may have a large number of attributes which define its status. They include static data (tool type, tool class etc.) and real time data (tool offsets, cutting life etc.). Even a simple FMS may have a massive tool database. Consequently, simulation models of them may also require and generate large amount of data.

This vast amount of data must be accurately and efficiently managed. Database management systems (DBMS) can make a valuable contribution and they provide a mechanism that can be used to control, manage, store and retrieve associated data.

The DBMS are generally categorized as hierachial, network and relational [4]. Among them the relational approach provide a simple but powerful way of building the conceptual model. They use two dimensional tables as the basis for data representation. In early DBMS, although the conceptual model was created based on the relational approach, actual implementation used either the hierachial or network approaches. However there are now several relational DBMS packages (eg. ORACLE). A relational DBMS coupled to a 4th generation language and a simulation language/package which can access the database would provide an effective and efficient approach to tool flow simulation.

MINIMAL DATA REQUIREMENTS FOR TOOL FLOW SIMULATION

There are several variations in the tooling systems used in FMS. In this paper, the proposed model is limited to a tooling for machining centres. [Fig.1]. Various elements of the tool system such as holders, adaptors, etc. can be assembled to create a unique tool type.

Each element in the system requires the following attributes to be defined:

a. geometrical attributes
b. stock and inventory control attributes.

In addtion, for cutting elements further attributes such as tool life etc. can be defined. These attributes can be represented as 'tables' in the relational model. As an example,

ADAPTOR[Adaptor ID, Stock ID, Length, ...]
TOOL[Tool ID, Stock ID, Length, ...]

Having defined the entities, then their relationships can also be expressed in tabular form. As an example only certain tools can be used with a given adaptor type [Fig 1].

ADAPTOR_TOOL[Adaptor ID, Tool ID]

Similarly all other entities and entity relationships can established. However as far as the simulation of tool flow is concerned,not all of this data may be required. The the minimal set of data required to support tool flow simulation is as follows:

a. Part Routes and Tooling Requirements.
   PART_ROUTE[Part ID,Base Operation No.,Operation Sequence No., Station No., Processing Time]
   TOOLS_REQUIRED[Part ID, Operation Sequence No., Tool Type, Wear Increment]
   FIXTURES_REQUIRED[Part ID, Base Operation No., Fixture ID]

b. Tools and Their Related Attributes.
   TOOL_TYPE[Tool Type ID, Tool Class, Tool Life]
   PRESET_TOOL[Tool ID, Tool Type ID, Remaining Tool Life]
   LOCATION[Station No., Matrix No., Tool ID]
   CAPACITY[Station No., No. of Matrix Positions]

With the exception of 'Tool Class', these attributes should be self-explanatory.

When considering tool magacine capacity, generally tool requirements are expressed in terms of the number of tools. However, due to varying size of tools, the number of tools pockets required to accommodate a given set of tools may be higher than the number of tools in the set. Basically tools can be classified as follows:

a. Asymmetrical Tools
   The outer envelop of the tool is not symmetrical about the central axis of the holder.
b. Symmetrical Tools
   The outer envelop of the tool is symmetrical about the central axis of the holder.

These symmetrical tools can be further categorized upon the relative size of tools. The following notation is used with conjuction of Figure 2.

D_c = centre distance between adjacent pockets.
D_H = the largest diameter of the tool holder
d = the tool diameter

Classes of Symmetrical Tools

Class I $d < D_c$
These tools do not interfere tools in adjacent pockets.

Class II $D_c \leqslant d < 2D_c - D_H$
Although these do not cover neighbouring pockets, tools of Class II cannot be placed in adjacent pockets.

Class III $d \geqslant 2D_c - D_H$
Adjacent tool pockets are covered, hence no tools can be placed in neighbouring pockets.

According to the above classification Class II tools impose neighbourhood constraints while Class III tools demand multiple pocket requirements.

VARIATIONS IN TOOL MANAGEMENT SYSTEMS

Any tool management system basically consists of a set of tool stores (including tool magazines), tool handling system and other ancillary subsystems such as tool presetting, tool inspection etc. Although the nature of tool flow is governed by various factors, two factors have a major influence on the way simulatiom model is designed.

a. The Distribution of Tool Stores.
In addtion to the main tool store (tool crib) there may be many other secondary tool stores within the system. Tools are handled in between these stores. In some systems tools are delivered directly to the tool magazine from the tool crib, whereas in other systems, tools are first moved into a backup store and a local handling device exchange tools between the tool magazine and the backup store.

b. The Tool Handling Systems
In most systems tool handling between the tool crib and the secondary tool stores is done manually. Some modern FMSs have automated tool handling systems. In addition different systems employ different types of tool carrier. Wide variations in constraints imposed on tool handling system can be observed.

An ideal tool flow simulator should include facilities to accommodate all these variations. However at this stage of development not all of these variations have been incoporated into the model.

In a typical FMS, the flow of tools can be depicted as in Figure 3. On receiving the instructions from the central computer, preset tools are placed on pallets. Then they are delivered to the workstation and new tools are exchanged with used tools. These used tools are sent to the inspection area and subsequently they are preset and stored in the crib.

MODULES OF THE SIMULATION PROGRAM

Prior to any simulation excercise, the tooling configuration need to be setup. This includes setting up the tool magazines and the tool crib.

Module 1: Tool Assignment Program
This module generates lists of tools required at each workstation, for

a given product mix. The part route information and associated tool requirement data are used. [Fig.4]

Module 2: Tool Loading Program
As stated above, in the high tool variety environment, aggregrate tool requirements may exceed the tool magazine capacity. Furthermore different classes of tools are involved. Thus it is necessary to load these tools in a logical manner to minimize number of idle pockets. This intial setup also decides the subsequent number of tool changes due to product variety. The following is one of the simplest of tool loading strategies.

i. first load all Class III tools
ii. then load Class II and Class I tools alternatively, until the tool magazine capacity is exhausted.

Module 3: Tool Flow Simulator
Having setup the tooling configuration of the system, then the tool flow simulation can be initiated. Various decision rules have been incorporated into the model to handle tool flow within the system. Some major aspects are explained below.

a. Redundant Tools
As the processing of parts progresses, some of the tools may become redundant (a particular part type has been completely processed). In the high tool variety environment, it may be necessary to remove any redundant tool as soon as possible, in order to accommodate an other tool. This is achieved by maintaining a dynamic tool-operation module list. When a part type is taken for processing, its part program is broken into operation modules and number of times this operation module to be performed is established. Then these modules are linked to the associate tools. As the machining progresses the completion of operation modules are monitored, and when all linked operation modules are finished, the tools become redundant.

b. Triggering Other Tool Changes
In FMS two major scenarios exist, as far as tool changes are concerned.

i. Tool Dominant System
In this type of system, a fairly static tool configuration govern the part flow. Routing flexibility is limited and reactions to random disturbances may be difficult to manage. However tool management is comparatively easy.

ii. Part Dominant System
Most of the tools move in and out of the magazines as parts flow through the system and some common tools may be held in the magazine for long periods. Routing flexibility is high but this requires a comprehensive tool management system.

The part dominant system has been incorporated into the simulator. As soon as a workstation is assigned for the current operation, the tool magazine of the associated workstation is searched for tool availability, and a list of addtional tools required at the workstation is generated. This list is eventually used to exchange tools.

c. Loading Tools at Intermediate Stages.
When tools are exchanged due to tool wear and breakage, the new tool can be placed in the same pocket. However complex logic may be required to place tools due to product variety. As an example, if a Class III tool is brougt into the magazine, then the three adjacent empty pockets are required to hold this tool. If this combination is not available, some

of the existing tools have to be removed to accept this Class III tool. Hence various logical routines were built into the simulator to handle such cases.

Some major routines of the simulator are shown in the Figure 5.

APPLICATIONS OF THE TOOL FLOW SIMULATOR

The tool flow simulator may have numerous applications.

a. Tool Requirement Planning
The tools required to meet a given production schedule can be output by the program. This includes list of tools required at each station at the beginning of the shift.

```
Week No: 10  Day: 2  Shift: Day
 Workstation: 5  No. of Tools: 5
   [Tool ID]     [Tool Type]
    I145           T31
    I546           T22
     ..            ..
```

b. Tool Requistion and Inventory Control
Once the tool inventory policy is decided, tool requisitions can be generated. The effectiveness of various tool inventory control policies can also be tested.

c. Tool Usage Analysis
The performance of each tool and usage counts of tools are also output.

d. Solving the part selection problem (for immediate processing)
The part selection problem in the high tool variety environment is solved with assistance of the tool flow simulator. An algorithm based on a mathematical model is used conjuction with the simulator [2]. This sequential part selection algorithm communicates with the simulator to obtain possible future tool changes. Application of the algorithm is demonstrated using data extracted from a real FMS [1].

Work requirements for a period of 4 weeks are estimated in response to customer and other inter departmental requirements. The following is an example which is randomly generated based on typical work requirements.

	PART TYPE											
WEEK NOS.	1	2	3	4	5	6	7	8	9	10	11	12
1 - 4	4	4	3	6	7	7	-	-	4	7	-	2
5 - 8	6	-	6	8	-	5	5	8	-	6	-	4
9 - 12	7	3	6	4	-	2	4	5	2	-	7	2

When orders are selected for immediate processing the following strategies can be implemented.

Strategy I - All orders are taken for simultaneous processing and they are launched to the system as soon as the required fixtures, pallets, etc. become available.

Strategy II-Orders are selected in a sequential manner based on the heuristic procedure.

These two approaches are compared in a simulated setting. It is assumed that raw parts are available whenever required to meet production targets.

STRATEGY I
(Earliest possible release)

Week No.	Output (units/ week)	Average machine utilization	Tool changes due to wear	Tool changes due to product variety
1	3	0.532	79	351
2	14	0.705	165	459
3	12	0.583	163	280
4	10	0.655	176	296
5	13	0.691	226	264
6	13	0.681	192	301
7	11	0.605	170	304
8	12	0.708	197	315

STRATEGY II
(Release according to Heuristic Algorithm)

Week No.	Output (units/ week)	Average machine utilization	Tool changes due to wear	Tool changes due to product variety
1	5	0.546	93	33
2	8	0.507	152	1
3	11	0.622	190	41
4	15	0.699	218	246
5	10	0.576	165	101
6	10	0.520	168	131
7	13	0.689	246	235
8	14	0.648	187	286

Average values were computed (with data coresponding to the first two weeks were omitted to eliminate transient effects). Due data achievements are measured in mean tardiness (mean tardiness = total tardiness /number of completed orders). Significiant improvement in number of tool changes due to product variety and mean tardiness were observed:

	Strategy I	Strategy II	Precent Improvement
Output(Units/week)	11.8	12.6	+ 6.77 %
Machine Utilisation	0.653	0.625	- 4.28 %
Tool Changes due to product variety	293	173	-40.95 %
Mean tardiness(mins.)	876	464	-47.03 %

FUTURE DEVELOPMENTS

At the beginning of this research program relational DBMS were not widely available and consequently, special data structures were used to implement the model. At present linking the model to a relational DBMS is underway. Once implemented it can also be used as an extensive tool requirement planning package.

The simulation model will be extended to include variations in tool management systems this will include the distribution of tool stores and tool handling devices and tool systems.

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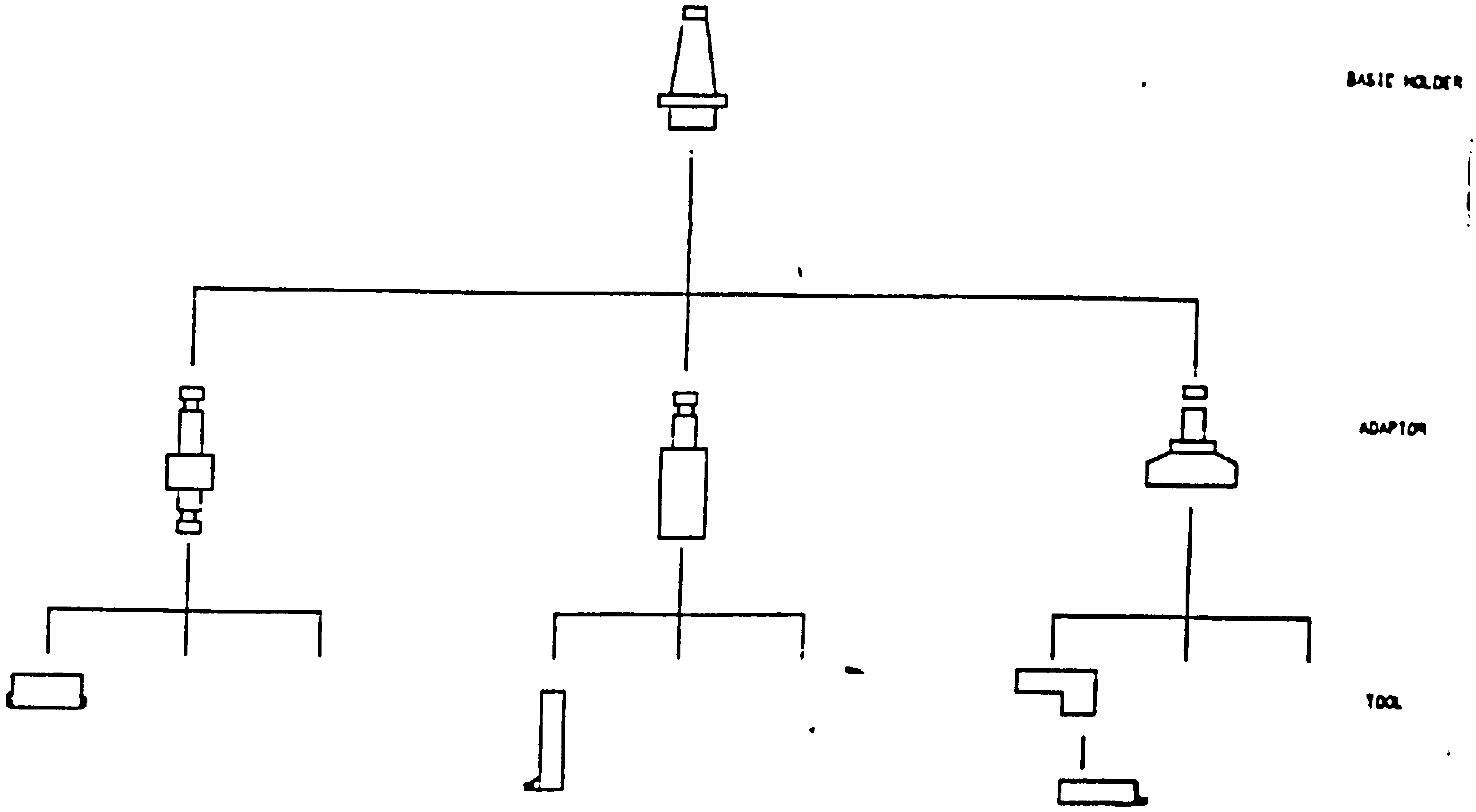

FIGURE: 1 A TOOL SYSTEM FOR NC MACHINING CENTRES

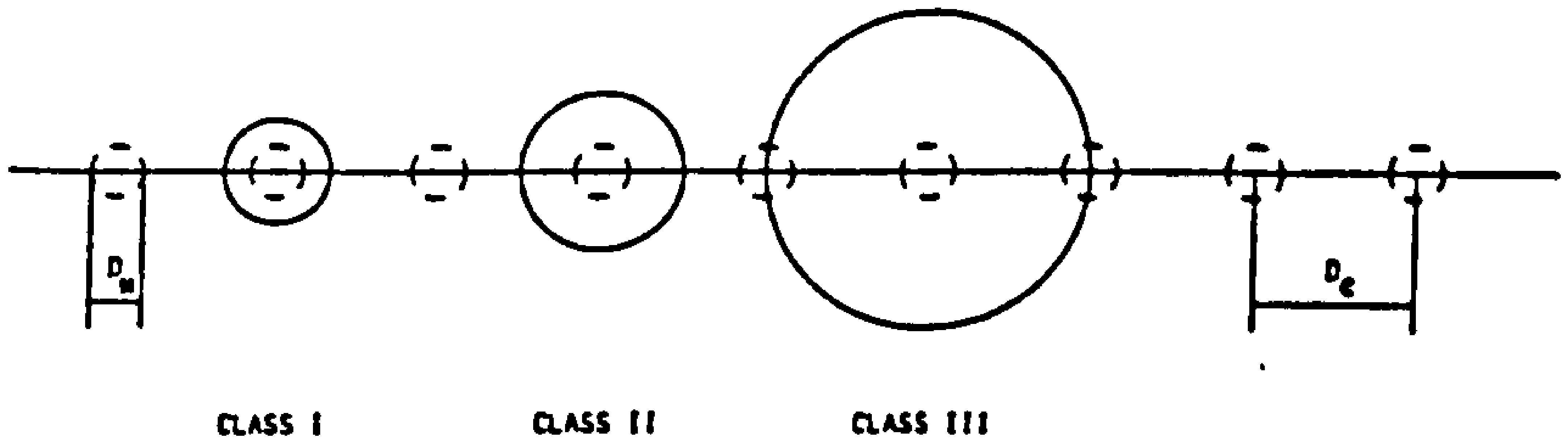

FIGURE: 2 DIFFERENT SIZES OF TOOLS

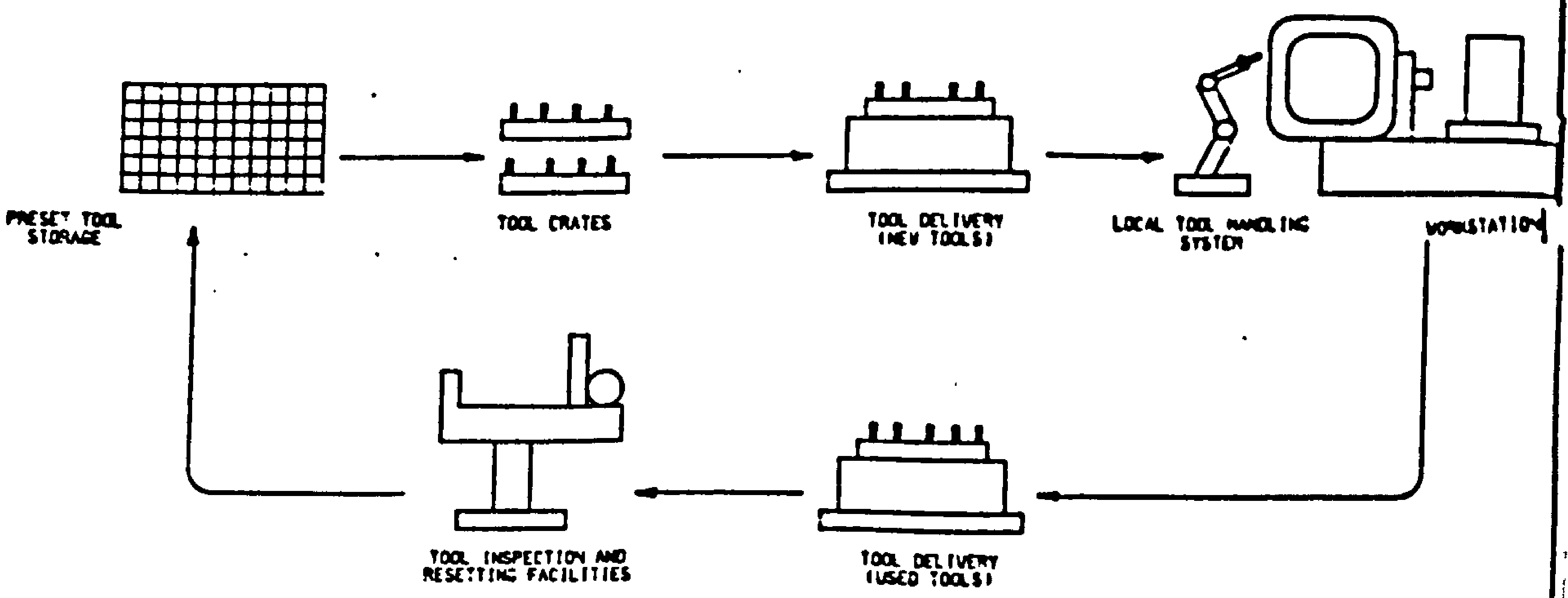

FIGURE: 3 A TYPICAL TOOL HANDLING SYSTEM

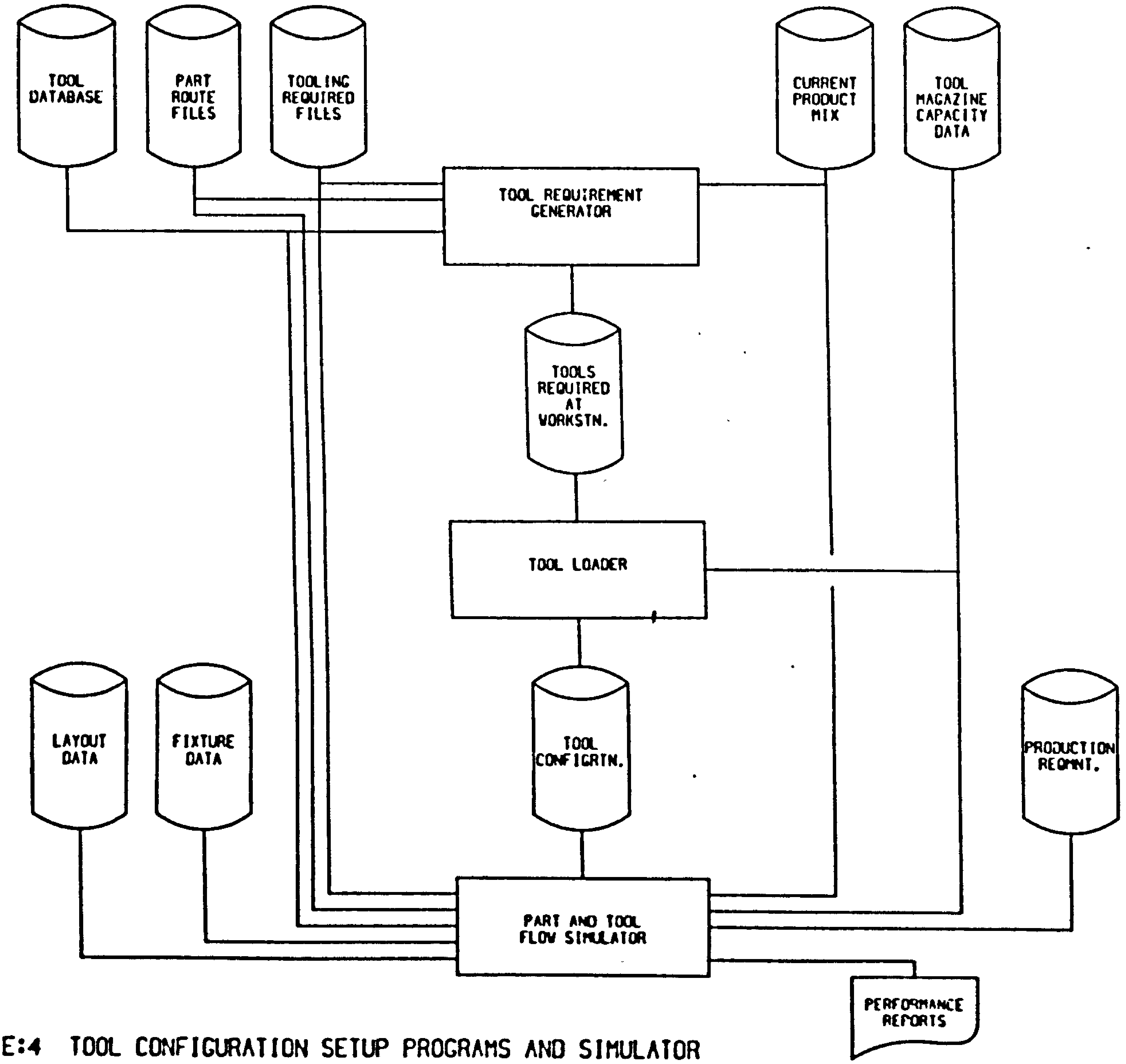

FIGURE:4 TOOL CONFIGURATION SETUP PROGRAMS AND SIMULATOR

Tool Availability Strategies for Flexible Manufacturing Systems

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TOOL AVAILABILITY STRATEGIES FOR FLEXIBLE MANUFACTURING SYSTEMS

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1.0 INTRODUCTION

As flexible manufacturing systems (FMS) have evolved through several generations, technologies associated with these systems have been constantly enhanced to solve the various operational problems generated by these systems. Sadly, not all of these technologies have received adequate attention from the system designers, users and researchers. One of the lagging area is that of tool management. Failure to perceive the importance of tooling aspects of the system has led to poor performance in many systems.

In this paper, several UK based FMS are reviewed to highlight the varying nature of the tool management problems. In particular, operational problems in a high tool variety environment are discussed. The development of a tool flow simulator is presented and the way it is used to develop tool availability strategies for a real FMS is explained.

2.0 VARYING COMPLEXITY OF THE TOOL MANAGEMENT PROBLEM

There are about 40-50 flexible manufacturing cells(FMC) and FMSs in UK. Although all FMSs encompass similar hardware sub-systems such as workstations, material handling systems etc. , they are operated in different ways. In particular, in the management and control of tool flow, a wide variety of operational strategies are adopted. In the following four examples, tooling aspects of systems are discussed to highlight the varying complexity of the tool management problem.

System-A

This is a relatively small FMS for the production of valve components. The system includes 4 identical machining centres each with a free standing tool magazine with space for 100 tools. One special feature of this system is that FMS is used in assembly related batch manufacture, so that the sets of parts for a valve assembly are produced in line with assembly programme. The tool types at a workstation are left in the magazine until the product mix changes at which point, some of the tools in the magazine are replaced by new tool types. This approach of bulk tool exchanges keeps the tool management problem relatively simple.

System-B

This company manufactures a range of diesel engines with powers upto 8700 kw. At present the system consists of two workstations and the company expects to add to more machines, in the next stage of implementation. Batch sizes vary between 1 and 150. The high tool requirements forced the company to install an automatic tool delivery system between the tool store (180 stations) and tool magazine. A rail guided truck with integral tool transfer device takes worn tools out the magazine (72 ports) and replaces them with new tools from the store. Although the system consists of two workstations, it has a quite complex tool management problem due to high tool variety. A set of 20-25 different types require 300 different tool types.

System-C
This is one of the most advanced FMS in UK. It consists of seven machining centres each with a 80 station tool magazine and auxiliary 24 tool carousel, a co-ordinate measuring machine and two washing stations. The system includes several AGVs which can deliver and remove 24-tool turret at each machining centre. The system has a capacity to machine 28 part types and their variants at a rate of 1400 parts per week. Worn out tools are removed from the turrets at a centralized tool maintenance and presetting facility. New tools are replaced in the turret ready for an AGV to deliver them back to the workstation concerned. A second tool changer at each workstation transfers tools between the turret and magazine. There is a computer link between the company and the tool supplier to ensure replenishment of all tools and tooling components within 24 hours. The integral tool handling system and the nature of production create a complex tool management problem.

System-D
This is the largest, most sophisticated and intricate flexible manufacturing facility in UK. This is capable of machining 1500 part types in steel, titanium and aluminium alloys in batches of 5-10.It consists of 2 FMSs with different_ hardware configurations and operational features. Notably, different methods of tool handling systems are adopted. In one system, crates of tools are delivered to workstations by AGVs. At a workstation, the AGV exchanges the new crate for the old crate which is then delivered to the central tool storage area. A tool crate can accommodate 63 tools, which may be sufficient for several different parts. The second system is dedicated parts manufactured from hard materials which consume cutting tools quickly necessitating more frequent replacements. An AGV delivers crates with new tools to the system and then they are transferred to a robot trolley which replaces the new tools with used tools in the magazine. Tool management is a major task. There are several thousands tool assemblies which have to be managed by the system.

It is clear from the above discussion, that different tool management policies need to be implemented in different systems. Specifically, in high tool variety environments, more attention must be focused on tool management as tools can impose additional constraints on production planning and control strategies.

3.0 HIGH TOOL VARIETY ENVIRONMENT

There are several system parameters (such as the number of tools, the number of tools required per operation and the tool exchange rates etc.) which influence the management and control of tool flow within the system. The nature of tool management problems are highly dependent on the ratio between aggregate tool requirements (at workstation) and the tool magazine capacity.

$$\text{Tool variety index(TVI)} = \frac{\text{aggregate tool requirement at workstation}}{\text{tool magazine capacity}}$$

As aggregate tool requirements depend on the product mix, this is a dynamic parameter. If TVI is less than one,during a particular planning period, then tools are exchanged due to wear and breakages only. However when TVI exceeds one (high tool variety environment), additional tool exchanges occur due to product variety (i.e. certain tool types may not be readily available at workstations). Worn or broken tools are replaced by their duplicates and new tools can take up the same location in the tool magazine. On the other hand, tool exchanges due to product variety force some other tool types out of the magazine. The selection of tools to be unloaded is a crucial factor. For example, if a tool used by many part types is taken out, the number of tool exchanges is unnecessarily increased. This could be further complicated if different sizes of tool exist. When the tool exchange rate is high due to product variety, two different strategies can be considered to improve the situation.

Increasing the Tool Magazine Capacity

Tool magazines which have modular architechture, may be extended to accommodate more tools. Although this is technically possible, it is quite difficult to implement in practice. This option must be considered when there is an upward trend in the number of tool exchanges. If excessive number of tool exchanges are observed only in certain planning periods, perhaps the operational policies can be enhanced to reduce the number of tool exchanges.

Changing Operational Policies

In this approach, the number of tool exchanges are reduced by controlling the product mix and/or adopting more effective tool availability strategies at workstations. Although it is desirable, to reduce the number of tool exchanges due to product variety to zero, it is not essential. What is important is that the number of exchanges is reduced to a manageable level. In the following sections, this approach is discussed in detail with reference to a real FMS.

4.0 A FLEXIBLE MANUFACTURING SYSTEM

This system produces components (gear box housing, motor housing etc) of heavy mining equipment [1]. The system consists of five identical machining centres (with a 100 station tool magazine) and a special workstation. These machinig centres together with two load/unload stations are served by a single automated guided vehicle. Identically tooled machine groups provide alternative routes for the parts which have very complex processing characteristics. Every part type requires two or more fixtures. Processing times can vary from few minutes to several hours.

In this system tools impose severe constraints on management decisions. The following system data highlights the complexity of the tooling problem.

System Data

At present 12 different part types and their variants are processed and require 372 different tool types. The growth of tool requirements at workstations is shown in Fig. 1.

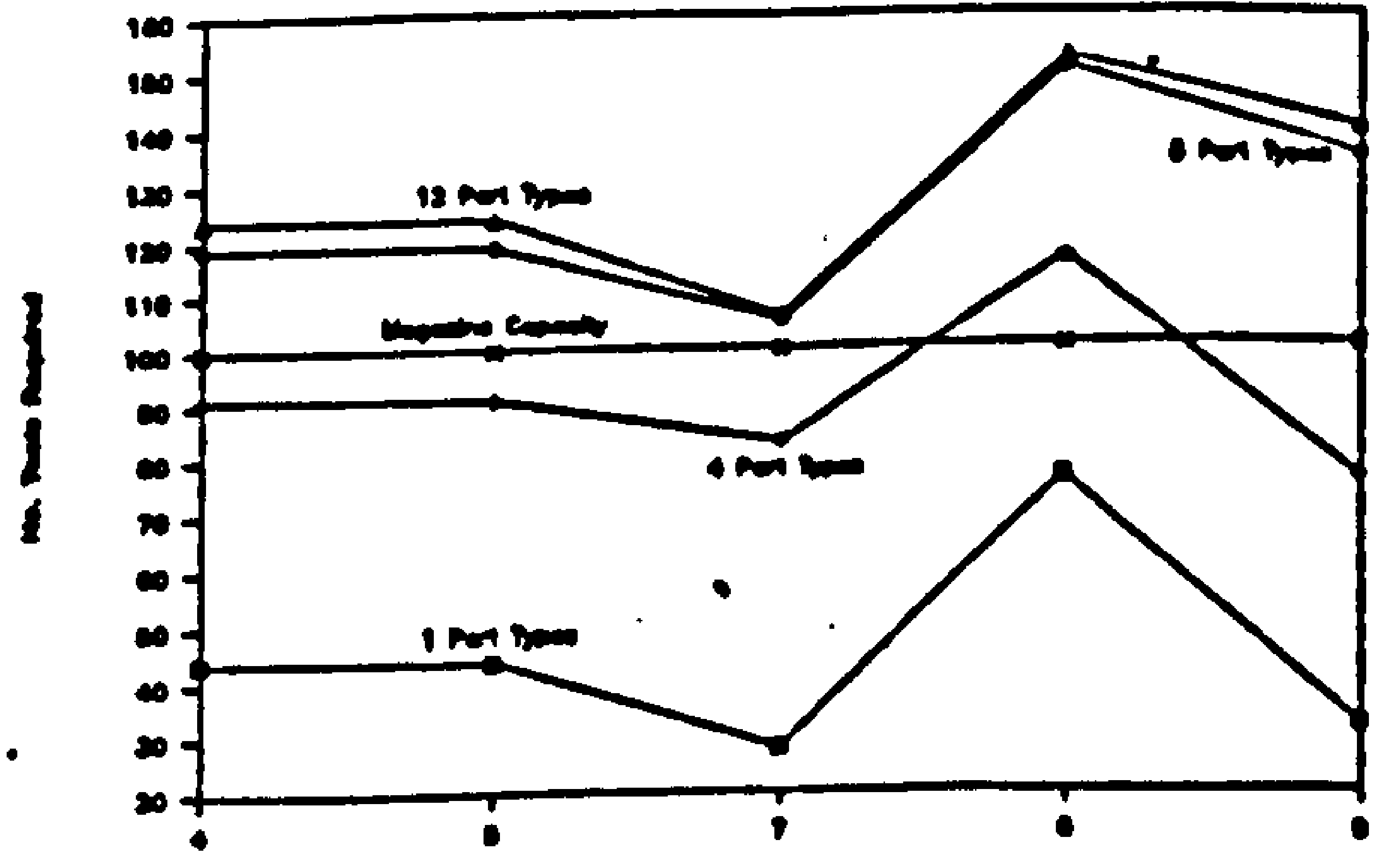

Fig.1 The growth of tool requirements

As Tool Variety Index exceeds one, tool exchanges due to product variety is unavoidable for certain product mixes. The situation is further complicated by the fact that tools vary in size. The following classes of tools are found in the system;

Class I tools which take only tool position.

Class II tools which take up only one position, but because of their size, prevent another class II tool being positioned in the pocket next to it.

Class III tools which take up three positions, the pocket in which the tool is placed and the positions on either side.

The distribution of tool classes in the system are as follows;

Class I	Class II	Class III
283	34	45

The average number of tools needed per operation is about 18 tools.

Operational Problems
As expected, for certain product mixes, the number of tool exchanges due product variety was very high. The traditional approach to this problem is to split production requirements into batches of parts with similar tool requirements. These batches are released to the system in a sequential manner with bulk tool exchanges between batches. However, in this system, production requirements cannot be grouped due to several reasons. The major factors are small batch sizes, long processing times and random processing of parts. Due to random processing and small batch sizes, the product mix changes rapidly and as processing times are long the system may not reach a steady state. Thus instead of bulk tool exchanges, tools are changed constantly to support the varying product mix.

In the case of bulk tool exchanges, the number of tools involved can be estimated by aggregating the tools required for each batch. In this case a simulation model is required to compute the number of tool exchanges.

5.0 TOOL FLOW SIMULATION

As a part of failure to percieve the importance of tool management aspects, most simulation studies are confined to part flow simulation. Although there are numerous simulation systems available for part flow simulation, there are no proven tools to study tool flow within manufacturing systems. Furthermore, many simulation systems do not provide essential features required for tool flow simulation. For example, extensive data handling capabilities is more important in tool flow simulation as even a simple FMS can claim a massive tool database.

A tool flow simulator was developed for this system to study the nature of tool exchanges in detail. It was done in two stages;

Tool Post-processor
The post-processor reads a file of work flow data and by refering to the part routing and tool requirement files, maintains a list of tools which would be present in each tool magazine. Hence the occurance of tool changes due to product variety can be deduced. By aggregating the

cutting time of each tool on each operation performed, the program computes the occurance of tool changes due to usage.

Tool Flow Simulator

Although the tool post-processor can output essential statistics about tool exchange rates, it has a major drawback i.e., it cannot be used to study interactions between part flow and tool flow. Thus program modules written for the tool post-processor were enhanced and linked to a part flow simulator. A separate user-interactive module was also constructed to set up the system tool configuration prior to simulation.

These tools were used to evaluate various tool availability strategies which are explained below.

6.0 TOOL AVAILABILITY STRATEGIES

As different sizes of tool are involved and aggregate tool requirements exceed the magazine capacity, tool loading must be done logically to minimize the number of intermediate tool exchanges due to product variety. Different strategies are described and evaluated below, using the data drawn from the FMS.

Strategy-I: Load all class III tools first

Class III tools are the most difficult ones to handle, as they need three consecutive empty pockets on the magazine. When tools are exchanged, it is easy to change a class III tool with another class III tool rather than a set of class I and class II tools. Therefore all class III tools are loaded first and remaining pockets are filled with class I and class II tools alternatively. (Note: Class II tool cannot be placed in neighbouring pockets.)

The system was simulated for a period of 6 weeks (the output data corresponding to first two weeks are omitted to eliminate transient effects). The results are shown in Fig. 2.

No. of tool exchanges (per week)	Week No.			
	3	4	5	6
Due to wear	128	114	131	140
Due to product variety	408	360	415	387

Fig. 2. The number of of tool exchanges.

The number of tool exchanges due to product variety is very high and some changes in tool availability strategies are required to reduce it to a manageable level.

Strategy-II: Strategy I with a set of permanent tools

It was thought the number of tool exchanges due to product variety can be reduced if a set of tools is held permanently in the magazine. The tools which are used by many part types can be given a higher priority. The distribution of the number of parts assigned to each tool type is shown in Fig. 3.

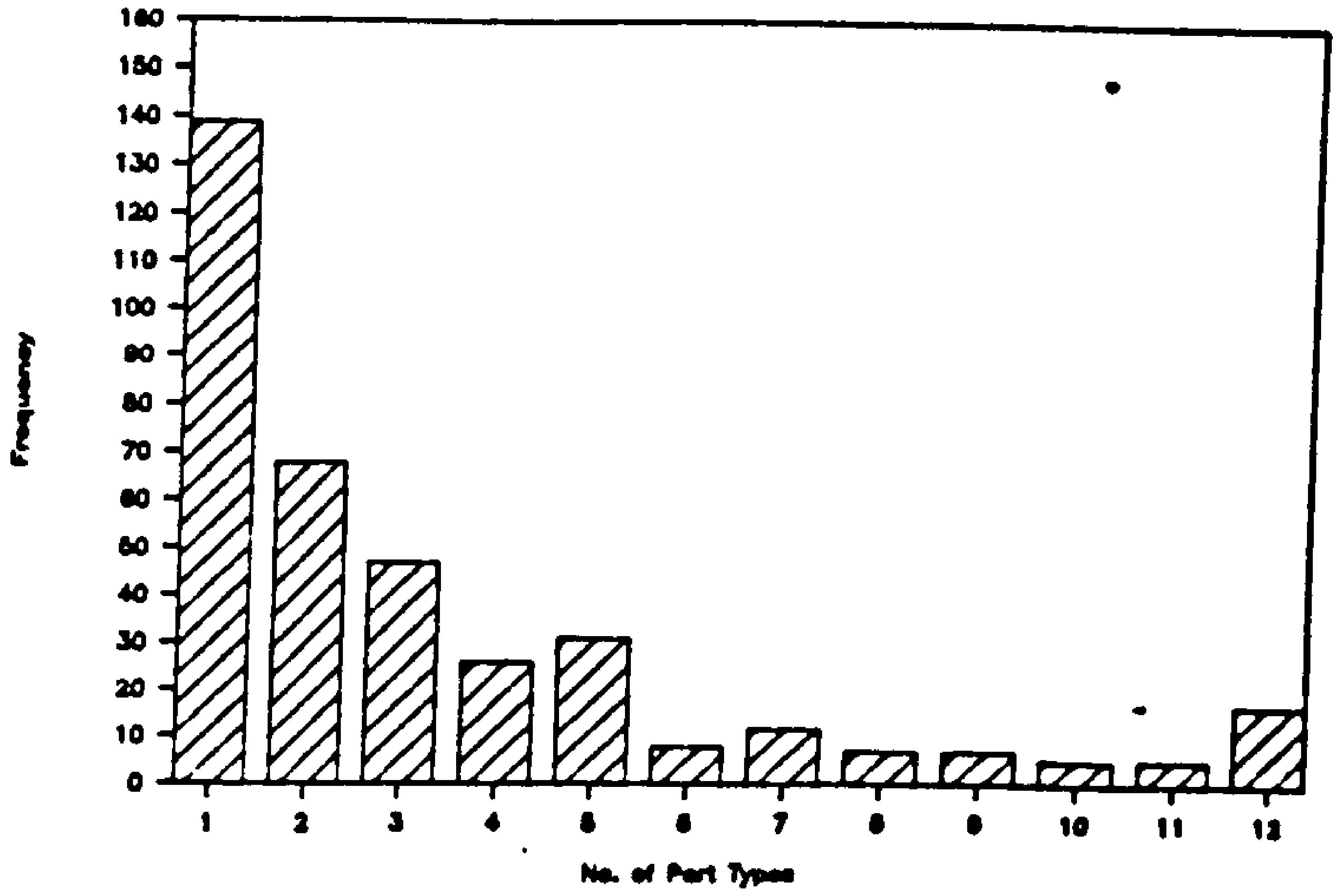

Fig. 3. The number of part types assigned to each tool type

It is evident that most of the tools are used only by one part type. There are also many tools consumed by many part types. The tools are ranked in the order of decreasing usage by part types and a set of tools taken from the top of the list is classified as permanent tools. The results are shown in Fig.4. Some improvement in the number of tool exchanges was noted, but it was not very significant.

	Week No.			
	3	4	5	6
Strategy-I	409	360	415	387
Strategy-II				
20 permanent tools	394(3.7%)	346(3.8%)	394(5.1%)	366(5.4%)
30 permanent tools	389(4.9%)	327(9.2%)	378(8.9%)	347(10.3%)
Strategy-III (No permanent tools) 10 class III tools	340(16.8%)	319(11.3%)	335(19.2%)	298(22.9%)
Strategy-IV (10 class III tools)				
20 permanent tools	324(20.7%)	298(17.2%)	313(24.5%)	279(27.9%)
30 permanent tools	323(21.0%)	301(16.4%)	311(25.0%)	275(28.9%)
Strategy-V	196(52.0%)	181(49.7%)	155(62.6%)	194(49.8%)

( ) precentage reduction.

Fig. 4. The number of tool exchanges due to product variety

Strategy III: A limited set of Class III tools
As class III tools take up three pockets in the magazine, there may be a quite number of pockets which cannot be used. Thus, if the number of class III tools held at the magazine is reduced more tools from other classes can be loaded.

In order to avoid a class III tool being changed with a set of class I and class II tools, a certain number of class III tools have to be maintained at the magazine. The tool requirements for operations are grouped under each class and the maximum number of tools used in each class at each workstation are shown in Fig. 5.

The Development of Operational Strategies for a FMS Using Graphical Animation

D T S Perera
The Fourth National Conference on Production Research
Sheffield, United Kingdom
September, 1988

The Development of Operational Strategies for an FMS Using Graphical Animation

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1.0 INTRODUCTION

The development of operational strategies for flexible manufacturing systems (FMS) is reckoned to be one of the most difficult task. In many systems, the operating policies have to be redefined from time to time, to overcome new operational problems created by the changes in the production environment.

The computer simulation is a powerful tool which can assist the system designer to identify the effects of changing production environment. In particular, the graphical animation may improve the system designer's intuition about the system behaviour.

In this paper, the design and development of a graphical post-processor is presented. The way it was used to modify operational policies of a real FMS are also discussed.

2.0 THE CHANGES IN PRODUCTION ENVIRONMENT

During the life cycle of an FMS, various changes in the production environment may be encountered by the system users. They can be broadly categorised as follows;

a. Changes in the system hardware configuration
   In a typical FMS, the hardware modules include workstations, material handling system and computer system etc. When necessary the capacity of the system may be increased by adding further hardware components to the system. This type of enhancement may require some changes in operating policies.

b. Changes in part characteristics
   In many systems, part characteristics such as the part route sequence, processing time and tooling requirements etc. ofte change due to design modifications. These changes may have som impact on the operating policy.

c. Changes in product mix.
   Generally, different product mixes are processed in differen planning periods. A more flexible, product mix dependant contro logic may well improve the system performance.

The system configuration is altered to overcome any existing problem but the last two types of changes may create new operational problem Therefore, whenever these changes occur, it is vital to simulate t System to identify any adverse effects of these changes.

3.0 COMPUTER SIMULATION AND GRAPHICAL ANIMATION

The computer simulation is a well established modelling technique for manufacturing systems. In recent years, there have been many significant developments in discrete event simulation. Among them graphical animation is an outstanding improvement. This uses computer graphics for animated displays of movements of entities, through the simulated system. Most simulation languages now support graphical animation capabilities which can be broadly classified as follows;

a. Graphical Post-processors
   In this case the graphical animation system is available as a separate module. The associated simulation program is first executed and the output is stored in a separate file. The graphical post-processor then reads this file and animates the entity flow. BEAM (for MAST) and CINEMA (for SIMAN) are graphical post-processors.

b. Concurrent Animation
   The current trend is to display the animation concurrently with simulation. In this mode of operation the user can stop the simulation while it is running, make changes and continue running it. The immediate effect of the changes on the simulated operations can be observed. SEE-WHY and HOCUS provide this concurrent animation facilities.

Although concurrent animation is more useful in some applications, graphical post-processors have a major advantage i.e. its operation is independent of the simulation system. Generally commercial graphical post-processors are dedicated to a particular simulation system, but it is possible to develop a generic graphical post-processor which can process output files from different simulation systems.

4.0 DESIGN CONSIDERATIONS

The main objective of the development of the graphical post-processor is to animate the dynamic nature of the system. However, moving entities alone cannot depict the behaviour of the system. For example, in a manufacturing system, stationary items such as workstations must be displayed in different ways to represent their different states (such as workstation idle, workstation down etc.). In addition more information such as waiting times and queue sizes can be appended to the display, to provide a more comprehensive picture of the system.

The graphical post-processor is driven by a data file which contains the history of the system behaviour. A text file containing these data can be easily generated by adding a few program statements to the base simulation system. The animation software processes this data and take appropriate actions (such as moving an entity, changing colour etc) to display the system state.

In order to simplify the software design process, system events can be grouped based on similar animation requirements. The program routines can be constructed for each group to visualize the graphical changes. Each event group can be given a code number and the code number can be used to fire the associated program routines.

A typical animation display consists of a large number of elements such as workstations, shuttles etc. They can also be grouped according to representative shapes. For example similar workstations can be represented by a specific element type. A number of basic elements are defined for this graphical post-processor (fig. 1). For each element in the display several attributes can be defined, such as location co-ordinates, element types etc. Fixed elements, such as workstations have static attributes (location, element type etc.) as well as dynamic attributes (colour). For moving elements, all attributes may be dynamic. The values of dynamic attributes are changed as events are fired.

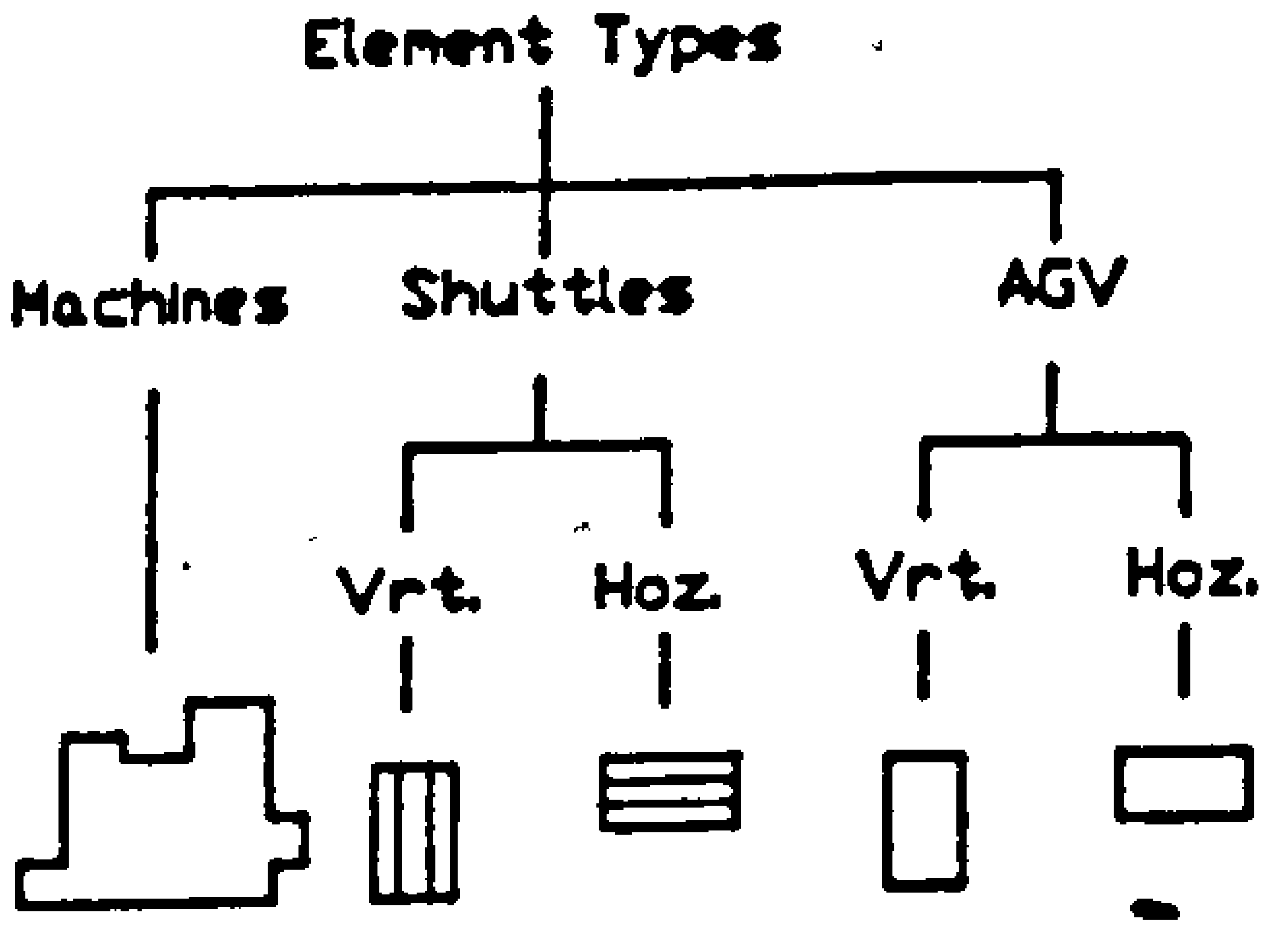


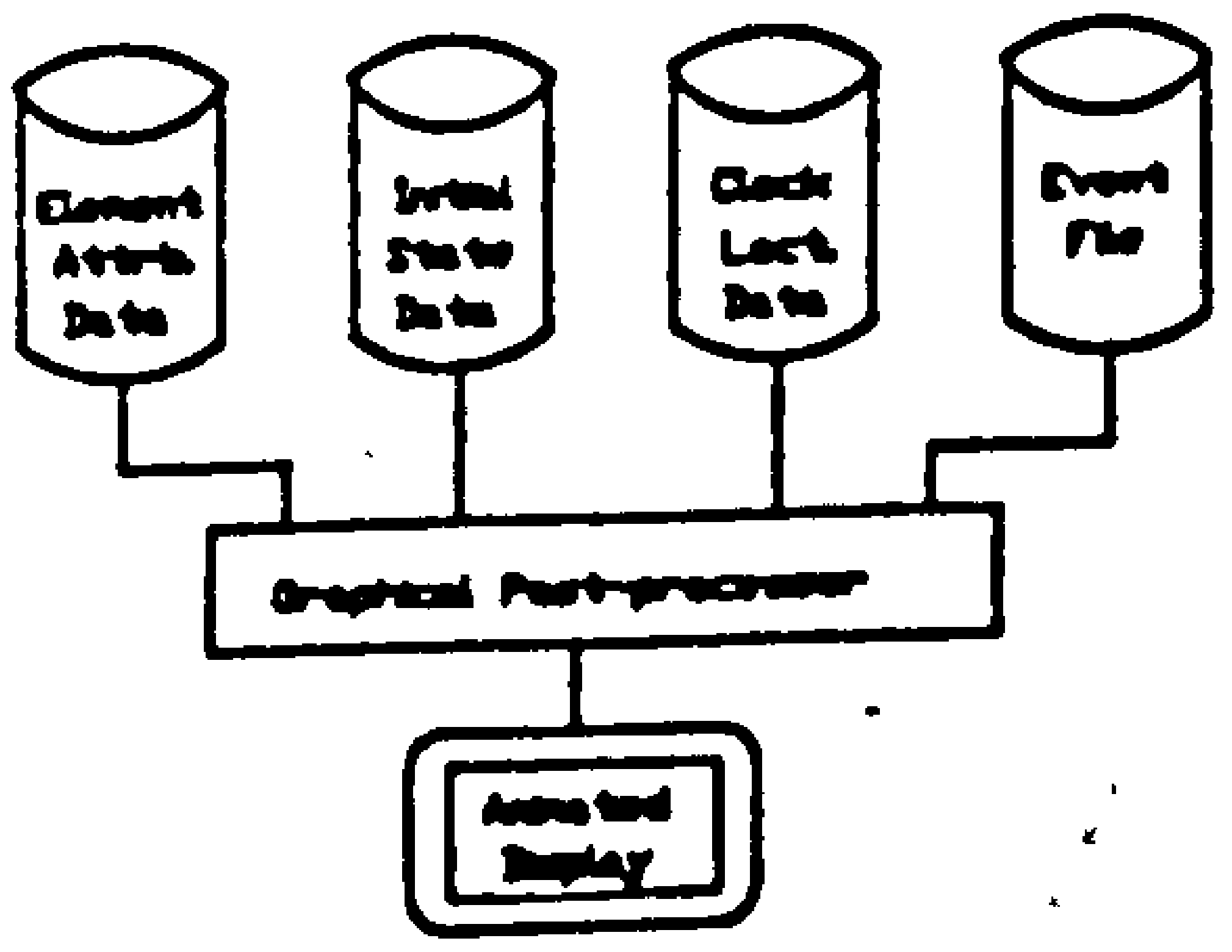
Fig. 1 Basic Element Types

5.0 IMPLEMENTATION

The graphical post-processor is a separate software module a therefore a general purpose language can be used. However, most o high level general programming languages such as FORTRAN do n include special language syntax for graphical applications. There a several graphical software systems which can be linked to high le languages. Among them Graphical Kernel System (GKS) is a gener software system which has become one of the international standards f computer graphics [2]. This system allows programs to support a wi variety of graphic devices and it is defined independent of th programming language.

Before it can be used from a particular language, a language binding [4] must be defined for that language. In this graphical post-processor, IBM Personal Computer GKS [3] is used with IBM FORTRAN (V2.0). A number of functionary independent program routines were constructed. The overall program structure is shown in Fig. 2.

Fig. 2 The Grpahical Post-processor



6.0 APPLICATIONS OF THE GRAPHICAL POST-PROCESSOR

The graphical post-processor was used to identify some operational problems in a real FMS. More information about this system can be found in [1]

6.1 THE PROBLEM OF EMPTY PALLET MOVEMENTS

When a pallet becomes idle at a load/unload station (i.e. a part is unloaded) it may not be possible to load it immediately. Either fixtured parts may not be available and/or all target stations for fixtured parts are busy. When this occurs, in this system, the empty pallet is circulated within the system. Its movements should be carefully controlled to minimize possible interference with the part flow. The following system states may trigger empty pallet movements.

State 1: The current operation at a workstaion is near completion or has been completed, but the off-shuttle of the workstation is occupied by an empty pallet.

State 2: A part is waiting at the off-shuttle of the workstation or at a load/unload station, but in-shuttle of the target workstaion is occupied by an empty pallet.

State 3: A part is waiting at the off-shuttle, for a load/unload station which is occupied by an empty pallet.

State 4: A fixtured part is available for loading, but no empty pallet is available at the load/unload station.

In order to estimate the average number of empty pallet movements per period (e.g. week), AGV assignments were individually monitored. It was found that the number of busy pallet movements is approximately equal to the number of empty pallet movements. But in some periods an excessive number of empty pallet movements were observed [Fig 3]. At this stage the graphical post-processor was called to identify the cause of the excessive empty pallet movements. It was discovered that the AGV moves empty pallets in a circular manner, due to pre-condition of the state 2 (see above). In this state empty pallet on an in-shuttle is moved away when one of the following pre-conditions prevails;

a. Workstation as a target station
   The workstation has become the target station for a part at another workstation or load/unload station.

b. Look ahead feature
   The fixtured parts waiting for loading are scanned and their first target workstaion is identified. If the in-shuttle of the target workstation is occupied by an empty pallet, then it is moved away pending the loading of the part.

Since the State 2 caused this problem, the empty pallet movements due to the above two components were individually monitored. It was observed that the number of empty pallet movements due to the look ahead feature was very high.

The reason for this circular movement of pallets was also identified. Although the look-ahead feature moves an empty pallet away from the target in-shuttle for an unloaded but fixtured part, it cannot be loaded immediately due to subsequent changes in the system state. Unnecessary empty pallet movements are trigerred, whenever this activity is scanned.

The look-ahead feature of this logical module was removed and the model was re-run with the same product mixes. The results are shown in Fig. 3.

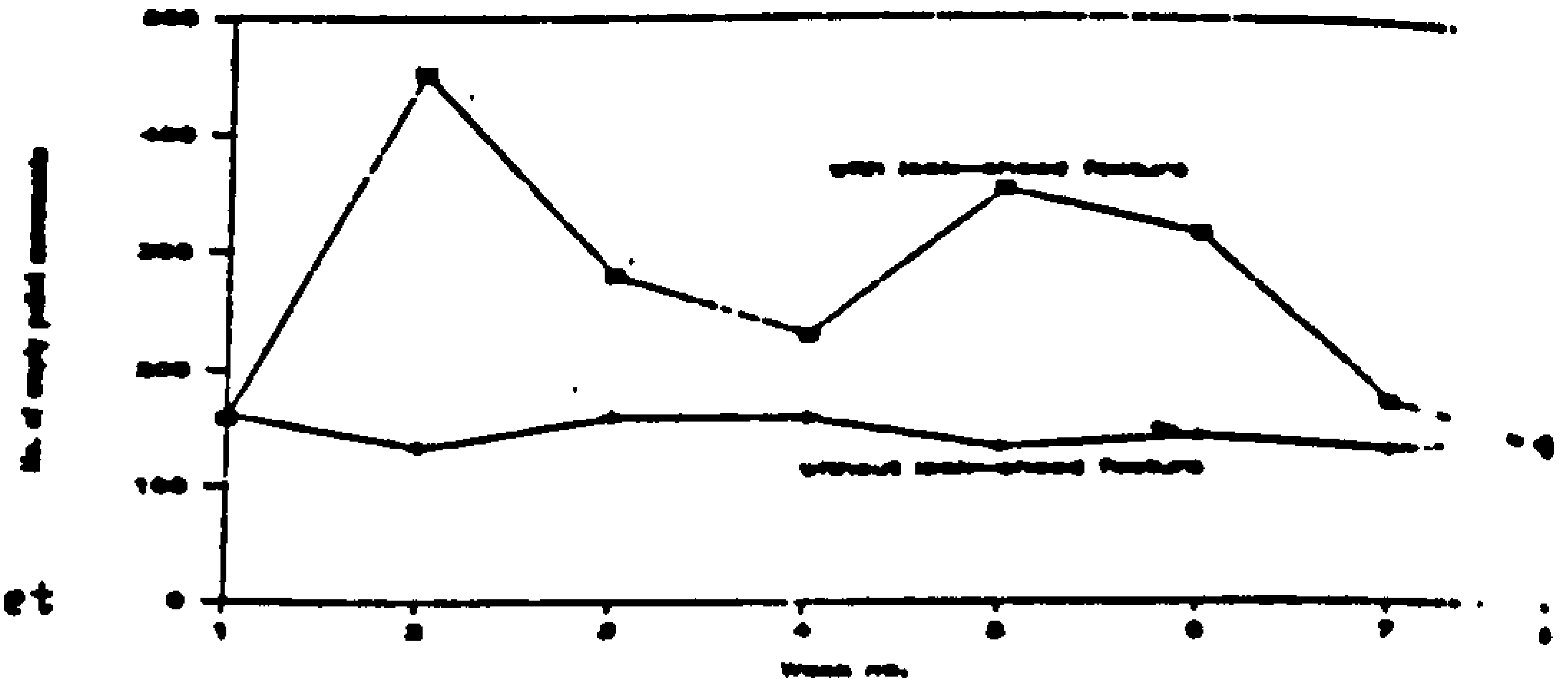
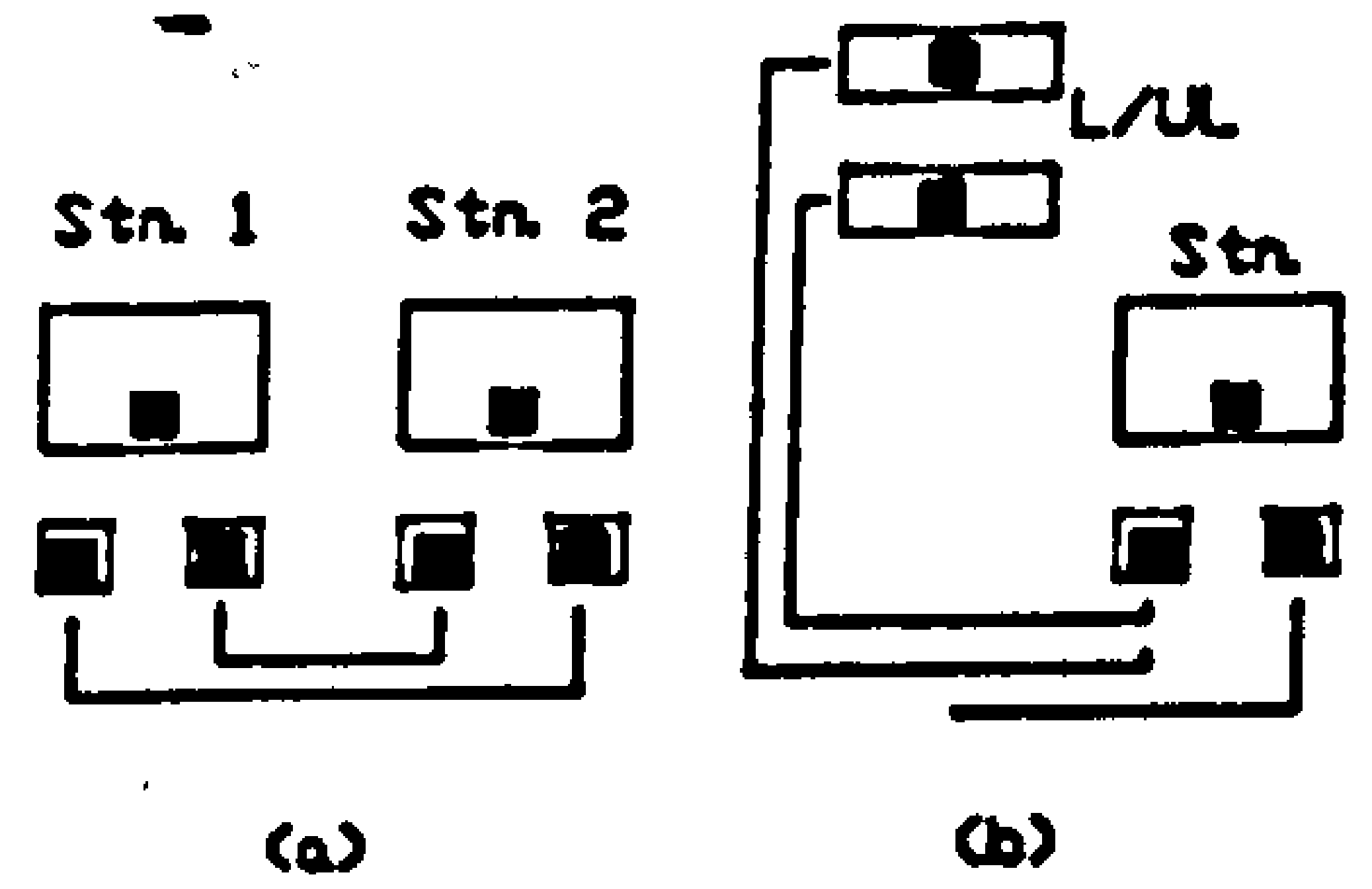


Fig.3
The Empty Pallet Movements

6.2 THE PROBLEM OF SYSTEM BLOCKAGES

The problem of deadlock in material flow has been investigated by various researchers and a comprehensive review on this aspect of manufacturing systems can be found in [6]. A typical deadlock in material flow is show n in Fig. 4.a. This type of deadlock is known as deadly embrace or circular waiting in the computer operating system literature [5].

Fig. 4 Different Types of Blockages



The system logic includes a module to relieve blockages between any two workstations. When deadlock in material flow occurs a pallet is taken out of the circular wait and place to alleviate the blockage. Despite this, some abrupt termination of simulation experiments were observed.

Again, the assistance of the graphical-post-processor was sought and a new type of deadlock was discovered which involved load/unload stations. This can occur when the following conditions exist [Fig. 4.b];

a. Two loaded pallet are waiting at load/unload station for the same workstation (target station).

b. All pallet positions of the target station are busy.

c. The pallet on the off-shuttle of the workstation is waiting for a load/unload station.

However this discovery raised another problem.

'Why were these types of blockages not encountered in previous studies despite enormous number of simulation experiments carried out ?'

Obviously, the formation of system blockages is unpredictable. Action can be taken to avoid blockages, but it is difficult to identify factors which contribute to the formation of blockages. However in this case, changes in part route data were suspected as the prime cause for these deadlocks. Due to a variety of reasons, the part routes are constantly changed. Therefore one of the major differences between early experiments and this work is new part route files. Thus the progress of each part within the simulated setting was traced and the stage at which the system became stagnant was noted. Surprisingly, the part types_involved and the stage of the part route were the same for all blockages. The old and new part routes are shown in Fig. 5. The main cause was that parts returned from a certain workstation were waiting for the same workstation after re-orientation of fixtures, at load/unload stations.

Operation	Station
Load	1,2
Op-11	4,5
Op-12	7
Op-13	8
Unload	1,2
Refix	
Load	1,2
Op-21	4,5
Op-22	7,8
Revert	1,2
Op-23	3
Unload	1,2

(old route)

Operation	Station
Load	1,2
Op-11	4,5
Op-12	7
Op-13	8
Unload	1,2
Refix	
Load	1,2
Op-21	4,5
Op-22	7,8
Op-23	3
Revert	1,2
Op-24	3
Op-25	7
Unload	1,2

(new route)

Fig. 5 The Changes in a Part Route

Thus a new logic was incoporated to handle this type of blockages. Basically it unloads a part involved in the blockage and the part is given a higher priority over others when parts are scanned for loading.

7.0 CONCLUSION

The changes in production environment may have a great impact on operating policies. Due to complex interactions between sub-systems, it is difficult to identify effects of these changes, without a detailed simulation study.

Although use of graphical animation in industry is quite controversial, undoubdtely, it is a powerful tool which can assist the system designers.

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Solving Production Planning Problems of FMS with Computer Simulation

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SOLVING PRODUCTION PLANNING PROBLEMS OF FMS WITH COMPUTER SIMULATION

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ABSTRACT

Certain limitations of modern simulation systems are highlighted by modelling a complex manufacturing system and its tool flow. The development of a comprehensive simulation system is presented. Finally, a solution procedure for the part selection problem in high tool variety environment of FMS is proposed.

INTRODUCTION

The production planning and control problems of FMSs are reckoned to be major operational problems. Although different FMSs have many common characteristics, their production mission and the constraint imposed on their operation may well be different. In the quest for solutions to these problems, a model of the system can play a major role.

In this paper, the characteristics and the production planning problems of a real FMS are presented. Some problems associated with a simulator and a simulation language are highlighted. The development of an alternative simulation system is discussed. Finally, a production planning problem is solved with the aid of the simulation model.

THE FLEXIBLE MANUFACTURING SYSTEM

This FMS consists of two load/unload stations, a special workstation and another five identical workstations which have tool magazines with 100 tool pockets. All these stations are served by a single AGV which travels on a bi-directional single track [1].

Although the system hardware configuration is quite simple, it has quite unique operational features due to the complexity of parts. This FMS produces components (such as gear box housing etc.) for large mining equipment. At present about 30 different part types go through the system. However some part types have very similar processing requirements.

All part types require two or more fixture types and a number of different operations are carried out on each fixture type. Furthermore certain part types require re-orientation within the same fixture, therefore these part types visit the load/unload stations at which the part is re-oriented and released to the system. A typical part type is involved in 10 or more different cutting operations which require on average 18 different tool types per operation.

At this stage it would be appropriate to introduce some of the specific characteristics of the system;

a. Empty pallet movements.

Unlike most other systems there is no dedicated storage area for empty pallets, therefore they have to be routed within the system with busy pallets. It is most important to control the movements of empty pallets to avoid any possible interference with busy pallets. This further complicates the pallet routing within the system.

b. Fixture assignments.

At the early stage of operation, a set of dedicated fixtures were used but now they are augmented by a flexible fixturing system which allowed the expansion of part spectrum. However this created another operational problem of assigning fixtures to competitive part types.

c. Tooling constraints.

As tooling requirements for most product mixes exceed the tool magazine capacity, almost all production planning and control problems are severely constrained by tools. Therefore tooling constraints must be taken into account when operational strategies are developed.

MODELLING THE FMS

Although there are numerous modelling techniques, it was recognized that only computer simulation can capture all essential complexities of this system. This has already been modelled using different simulation techniques. However, there is now a wider choice of powerful simulation tools and more recent attempts were made to model the system with the latest simulation tools. Two simulation tools with different modelling techniques were selected;

SOLVING PRODUCTION PLANNING PROBLEMS

For the system described above, it appears that the rate of tool exchanges due to product variety can be very high for certain product mixes. When this occurs, two different strategies can be considered to improve the situation;

a. Increasing the tool magazine capacity.
   The tool magazines which have modular architecture can be extended to accomodate more tools. Although it is technically possible, it is quite difficult to implement especially when the system is fully operational.

b. Improving operational straegies.
   More effective operational strategies which take tooling into account can be developed [4]. These techniques may utilize the advantage of the real time data available in FMS.

The rate of tool exchanges depends mainly on the characteristics of the product mix being processed. The nature of the current product mix can be explicitly controlled when the parts are selected for immediate processing.

In this FMS the batching of parts is not viable as the tool variety is high and low volumes are produced. Therefore a sequential part selection method is more appropriate in this case. The parts are drawn from a pool of waiting orders in a sequential manner, when one or more of the following conditions prevail;

a. The work load assigned to the machine group with the highest utilization is less than a pre-determined work load level (a threshold value).

b. There are a considerable number of empty pockets available at workstations.

c. The urgent orders need to be processed.

These time instants are defined as stages. At each stage one or more orders can be selected. However, when multiple order selection is possible at a given stage, the selection procedure is repetitively used for each selection. The algortihm uses the real time data and it provides a better solution to the part selection problem by trading off the following parameters;

a. A balanced tool requirement distribution.

b. A balanced work load distribution.

c. Achieving due-dates.

In the experimental setup the simulator acts as the real system by providing the required real time data. When prescribed time instances are reached, the simulator pauses and allows the part selection module to access its database. If prevailing conditions permit, an order is selected for immediate processing. In order to handle special cases the analyst is allowed to override the decision of the part selection module.

As explained above , this procedure is invoked when workload assigned to the workstation with the highest utilization is less than a certain value. It is necessary to maintain a certain amount of work load in order to avoid possible work starvation. On the other hand excessive work load may result in a large number of tool exchanges. This threshold value can be established through simulation experiments by changing the work load level assigned to that workstation. The results are shown in workstation is assigned to more than one machine group) cannot be modelled at SPAR level. Therefore routing records have to be altered using a text editor. However, if the SPAR module is called again for the same model to redefine the MAST input data file, the SPAR will produce a new file and all changes done through the text editor are ignored.

e. Limited definition of tool types.
More recently a new program module has been incorporated to model tool flow within a manufacturing system. Although at the time of writing the module was not fully operational, its modelling features were studied. It appeared that certain types of tools cannot be modelled using this program module. For example, for the FMS described above, there is a class of tools which take only a single pocket but a tool from the same class cannot be placed in the adjacent pockets. It is also not very clear what would happen if the tool requirements for a given product mix exceeds the tool magazine capacity.

MODELLING DIFFICULTIES ASSOCIATED WITH SIMAN

The process orientation modelling concept allows the analyst to build simple simulation models quickly and excellent animation features can be incorporated. However, when complex manufacturing systems are modelled the following limitations may be encountered;

a. Diminishing use of block functions.
When complex manufacturing systems are modelled, the use of block functions diminishes and more event oriented components are used. This requires knowledge of FORTRAN (or C) and novices may take a comparatively long time to develop the model.

b. Modelling difficulties of activities which require multiple resources.
In some instances, when multiple resources are used within a single activity quite complex process sequences have to be developed.

c. Limited data handling facilities.
As in most other simulation systems, SIMAN does not provide special facilities to handle a large amount of information. If it is required to manage a large database within the model, the analyst will have to use FORTRAN based routines.

It is clear that when complex manufacturing systems are modelled, the easy to use modelling constructs cannot be used and the analyst is forced to use general purpose programming languages. Furthermore, data handling facilities in simulation systems are very primitive. Therefore when tool flow of complex manufacturing systems are modelled, none of the existing simulation systems can provide a total solution.

AN ALTERNATIVE SIMULATION MODEL

A comprehensive simulation model with tool flow modelling facilities was developed using GASP routines [3]. As a general purpose programming language (FORTRAN) is used, the GASP modelling methodology provides a higher flexibility to the modeller but at the expense of a comparatively long development time. The major features of the simulation systems are as follows [Fig. 1];

a. A hybrid modelling approach.
When the GASP routine library is used, the dynamics of the system is represented by event links. However, in complex manufacturing systems, it may be difficult to establish these event links therefore certain dynamic interactions were modelled using activity based modelling concepts which provides a mechanism to maintain a hierarchical priority order for certain activities. The facilities have also been provided to alter the priority order without any re-programming.

b. Special modelling features.

The analyst can define a single routine file for parts with multiple fixture requirements and fixture constraints are specifically modelled. The system components such as load/unload stations and workstations etc. are identified through the description of the initial state file. A number of logic modules have been incorporated to avoid possible deadlock in material flow.

c. Tool flow modelling.

The most interesting development is the tool flow modelling modules. This was developed at two stages. At the first stage, a tool post-processor was constructed and subsequently it was further enhanced and linked to the part flow simulator. The execution of the tool flow simulation program is preceded by the following sequence of activities;

Definition of input data

A number of input data files are created by the user;

Tool database file :- The attributes such as tool type ID, tool life, tool size and the number of duplicates allowed etc. are defined for each tool type in the system.

Tool requirements file :- A tool requirement file is created for each individual cutting operation. This file contains the tool type used and the estimated tool usage.

Tool magazine capacity file :- The tool magazine capacity of each workstation is defined here.

Permanent tool lists file :- A set of tools (for each workstation) can be declared as permanent tools. These tools are not removed when tools are exchanged due to product variety.

Product mix (for tool configuration) file :- This product mix is used to set up the initial tool configuration.

Setting up the initial tool configuration.

Having defined the require tool data, the analyst can execute the tool configuration set up module which works in the following manner;

Tool crib configuration set up

The attributes defined in the tool database file are used to setup the tool crib configuration. Each tool is given a unique identification number and the dynamic attributes such as location, cumulative tool usage etc. are initialised.

Tool magazine configuration setup

Firstly, the product mix defined by the analyst is used to generate the lists of tools required at each workstation. Then the tool loading module picks up the required tools from the crib and places them on the tool magazine. At this stage the analyst can specify the maximum number of over-sized tools allowed on the magazine.

d. The graphical post-processor.

A low cost graphical post-processor has also been developed using GKS. The data generated from the simulation system is used to animate the flow of parts and the state of resources.

e. The utility program modules.

A suite of programming modules have been developed to obtain various statistics about the tooling system.

SOLVING PRODUCTION PLANNING PROBLEMS

For the system described above, it appears that the rate of tool exchanges due to product variety can be very high for certain product mixes. When this occurs, two different strategies can be considered to improve the situation;

a. Increasing the tool magazine capacity.
The tool magazines which have modular architecture can be extended to accomodate more tools. Although it is technically possible, it is quite difficult to implement especially when the system is fully operational.

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In this FMS the batching of parts is not viable as the tool variety is high and low volumes are produced. Therefore a sequential part selection method is more appropriate in this case. The parts are drawn from a pool of waiting orders in a sequential manner, when one or more of the following conditions prevail;

a. The work load assigned to the machine group with the highest utilization is less than a -determined work load level (a threshold value).

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These time instants are defined as stages. At each stage one or more orders can be selected. However, when multiple order selection is possible at a given stage, the selection procedure is repetitively used for each selection. The algortihm uses the real time data and it provides a better solution to the part selection problem by trading off the following parameters;

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As explained above , this procedure is invoked when workload assigned to the workstation with the highest utilization is less than a certain value. It is necessary to maintain a certain amount of work load in order to avoid possible work starvation. On the other hand excessive work load may result in a large number of tool exchanges. This threshold value can be established through simulation experiments by changing the work load level assigned to that workstation. The results are shown in Fig. 2. While the average machine idle time declines with the increase in workload the rate of tool workload must be maintained about a specific value to avoid the excessive tool exchanges and starvation at workstations. For this system the threshold value is found to be about 5000 mins. Having established the threshold value, the proposed solution procedure was used to select the parts for immediate processing. A significant reduction (about 40%) in the tool exchange rate due to product variety was noted.

CONCLUSION

When complex manufacturing systems and the tool flow of manufacturing systems are modelled, the existing simulation systems fail to provide a total solution. The lack of effective data handling facilities is a major drawback.

The proposed part selection procedure significantly improves the system performance by reducing the rate of tool exchange rate due to product variety.

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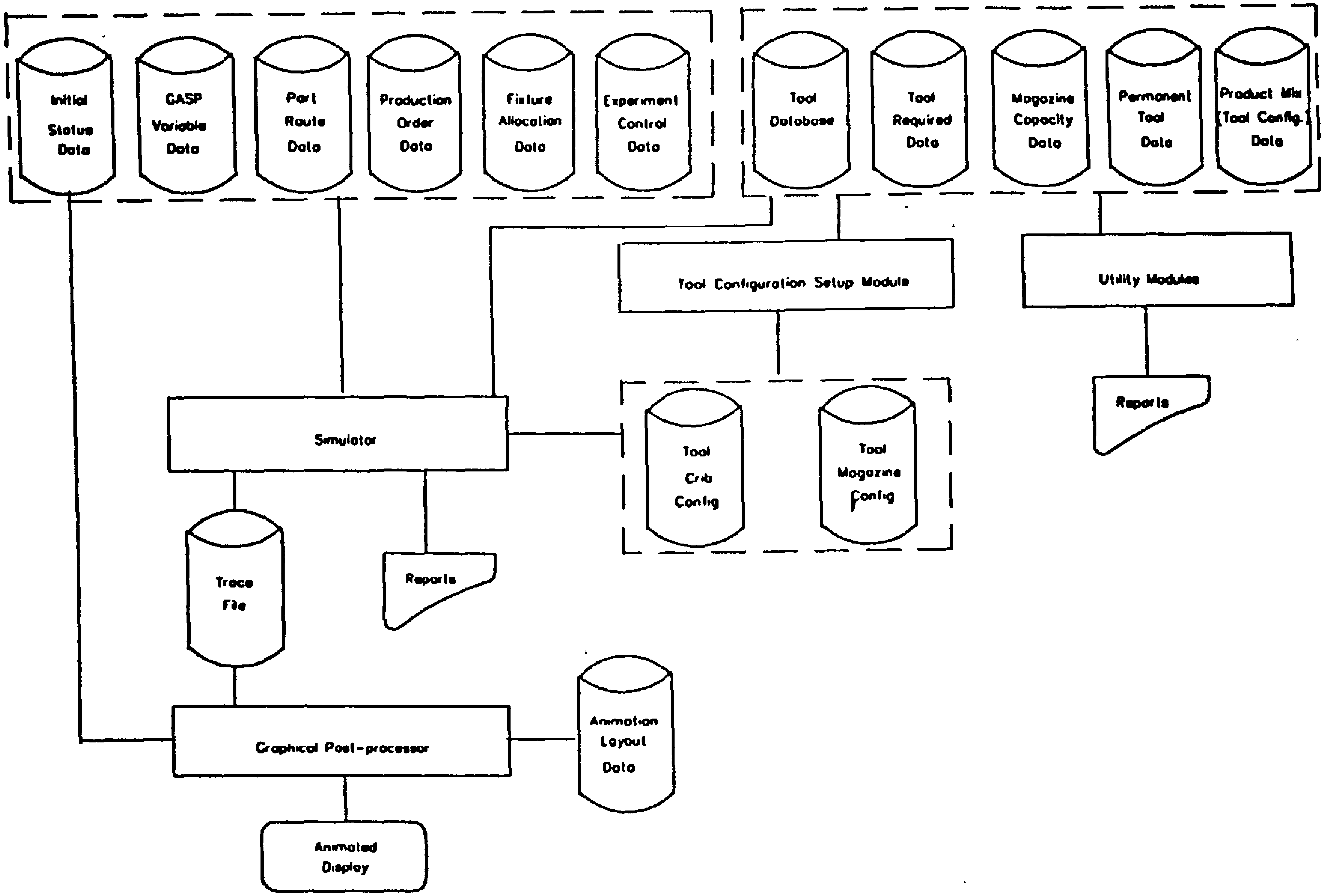

Fig 1 The Simulation System

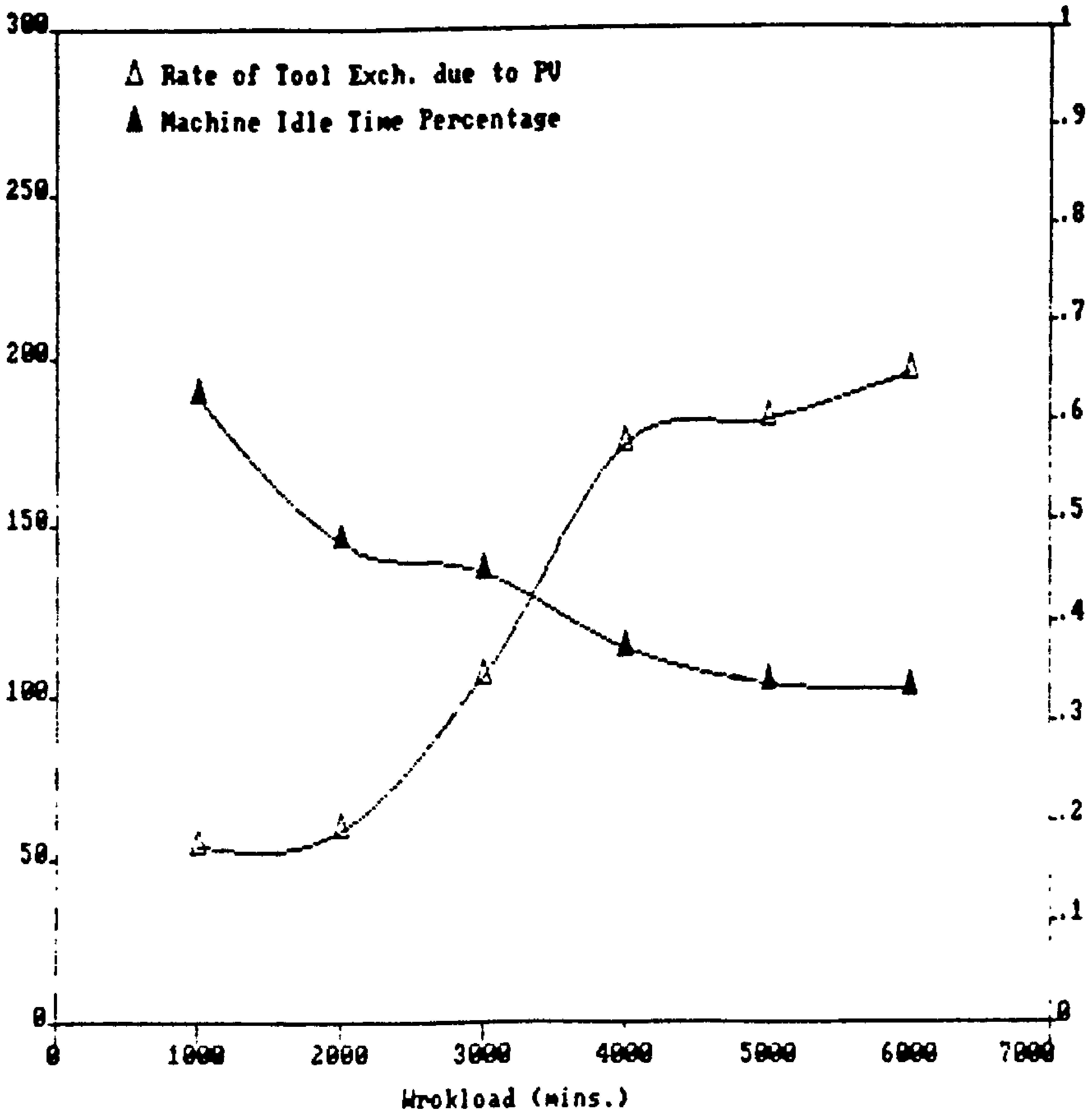

Fig. 2 The Effect of Workload Variations on the Rate of Tool Exchnages and Machine Idle Time