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The development and application of a simulation
approach to advanced manufacturing systems planning

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SUMMARY

In the competitive field of metalworking industry, the planning of manufacturing systems so as to maximise their performance is crucial. The relatively new field of Flexible Manufacturing Systems presents a new set of planning challenges to the production engineer. This is due to the integrated nature of these systems and the resultant effects upon their performance. This thesis presents a structured approach to the planning of materials flow within these systems and develops it by the analysis of several proposed manufacturing systems. The approach is based upon the use of mathematical and discrete event simulation techniques.

The thesis gives the background to the need for a structured approach, investigates the parallel development of simulation languages and related techniques as applied to manufacturing facilities planning; and of the Flexible Manufacturing Systems themselves. The approach is then detailed and some specific types of planning tool are identified as suitable for use at each project stage. The effects upon the system of the integration of separate units, especially in low work in progress environments, are discussed in some detail.

The methodology developed is then used in the context of three projects, specifically developing the theme of automated tool handling and the requirements that it places upon other aspects of a manufacturing system. The projects cover the analysis of pooling strategies, a key factor in determining tool magazine sizes and handling capacity/frequency demands; an academic analysis of a system with both component and tool handling systems; and an advanced Flexible Manufacturing System, also with both automated component and tool handling, which is currently being installed.

Conclusions are presented at each stage, and these are drawn together to form a foundation for the planning of materials flow within Flexible Manufacturing Systems in general. Finally, suggestions are made for future work to develop the analysis.

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1.0 INTRODUCTION

1.1 GENERAL INTRODUCTION

A common perception of industry within the United Kingdom is that of decline. This view is even more strongly held when manufacturing industry is considered. These opinions have been formed, at least in part, by the reduction in employment caused by the fundamental restructuring that has affected all of industry, especially manufacturing and, most of all, engineering manufacturing.

For the purposes of this thesis, engineering manufacturing industry will be defined as Division 3 of the Standard Industrial Classification (SIC). The Division is defined as "Metal Goods, Engineering and Vehicles Industries", and covers almost all the metalworking manufacturing activities. An analysis of the different sections of this Division provides qualitative support for the generally accepted, if statistically uncertain, assumption that between 70% and 75% of engineering manufacture occurs in the medium-volume, medium-variety, batch process sector.

Despite the prophets of doom, research work on Advanced Manufacturing Technology [National Environment Development Office (NEDO), 1985] showed that almost 40% of the visible exports from the United Kingdom could be attributed to engineering manufacturing industry, as could over 10% of employment. SIC Division 3 had a total turnover in excess of £200,000 million during 1986 [Weaver, 1987]. The NEDO report also highlighted the sectors that had recently shown growth. These were aerospace, marine, transport equipment and electrical and instrument engineering. These industries are even more typically batch based, rather than the continuous or large batch industries, such as motor vehicles and metal goods, which have been at the forefront of decline.

The NEDO report identifies the main trends in engineering manufacture, and is supported by previous work [Advisory Council for Applied Research and Development (ACARD), 1983]. These trends are principally:

- A reduced number of smaller and more productive factories;
- A reduced labour force, with higher levels of education and training, giving higher productivity;
- A shift from direct to indirect labour;
- A change from dedicated to flexible production equipment;
- A greater use of Advanced Manufacturing Technology.

These latter two points offer the context, with certain reservations, for the remainder of this thesis.

1.2 ADVANCED MANUFACTURING TECHNOLOGY

Using the definitions of Advanced Manufacturing Technology (AMT) highlighted [NEDO, 1985], eight principle technologies are apparent:

1. Computerised Inventory Control.
2. Computerised Production Control.
3. Computer Numerically Controlled machining (CNC).
4. Computer Aided Design and draughting (CAD).
5. Computer Aided Manufacture (CAM).
6. Improved assembly and test.
7. Flexible Machining Systems (FMS).
8. Automated stores and parts issue.

Obviously, these technologies are not independent and this thesis concentrates on the seventh of these technologies - flexible manufacturing systems (FMS). The full definition is worth repeating:

"Two or more machines, linked by an integrated parts handling system and operating under the control of a computer. The control system can route parts between machines, so as to achieve, for example, maximum spindle utilisation or minimum lead time." *"a time of travel"*

Three points arise from this definition. First, the choice of "machining" as distinct from "manufacturing", which constraints the systems classified. Currently this is a realistic approach, as almost all FMS are machining systems, but the analysis of operational factors is independent of the process being carried out. Accordingly the term manufacturing will be used.

Secondly, the use of materials handling need not be confined to parts and it can be used to convey tooling, assembly fixtures, magazine loads of small components, etc. Accordingly, all types of consumable items should be conveyed as well as the parts themselves.

Third, the performance measures indicated in the definition are simple and constant. For any real manufacturing system, the more general objective is to optimise a set of performance measures.

Accordingly, the following definition of flexible manufacturing systems will be used:

"Two or more processing units linked by one or more automated transport systems, the whole operating under the control of a computer system. The control system is capable of routing parts and/or tooling between processing units with the objective of optimising a set of performance measures."

1.3 SCOPE OF THE WORK

Now that a broad definition of flexible manufacturing systems has been drawn, the area studied will be constrained. These constraints will be drawn to include only those systems which are relatively large, in terms of the number of units, and produce components at relatively high rates. See Figure 1.1 [Haas, 1976].

A large system will require a genuine materials handling system, so excluding single cells. Systems built up from cells where each cell may consist of two or three machine tools served by a robot would be included, but each cell would merely be a "processing unit".

High volume production, by the terms of the flexible class of manufacturing systems, is assumed. This highlights the central role of materials handling, whose importance tends to be marginal for low volume systems, as movement quantities are low. The question of what constitutes high volume will be discussed later.

Having already mentioned the concept of a processing unit, it ought to be defined. A "processing unit" is a machine tool, an assembly machine or any other station which performs one or more operations upon one or more components. The actual operation(s) need not be considered in detail, merely that they may need some form of tooling, as well as the component to perform it on. Processing units may be, and usually are, subject to some form of failure or breakdown. Processing units are the simplest form of operation performing device for the purposes of this study.

This set of parameters will be recognised as describing those systems of most interest to the motor vehicle industry, although not confined to that industry. The traditional view of near continuous production as applied to the motor vehicle industry is now only true for very large multi-national companies and then only to their major product lines. Within the definitions above, the thrust of this work can be said to be directed at large volume flexible manufacturing systems.

2.0 PROJECT METHODOLOGY

2.1 INTRODUCTION

The potential scope of investigation in the field of advanced manufacturing systems is almost endless. This chapter explains the scope of this research, and the methodology used to perform it.

The main objective of this work was to provide, for a certain class of manufacturing systems, a framework for their systems design. The approach is structured around materials handling and material flow as the centre of analysis, as the materials handling sub-system, both hardware and software, is crucial to the functioning of a complete system.

This work does not provide a rigid set of rules, even within the limits of the class of systems considered. The precise set of configuration and operational parameters used are, and will remain, uniquely system dependent. Accordingly, this work can be considered as an "envelope", providing constraints to the complex set of problems faced by the designers of Flexible Manufacturing facilities.

2.2 OBJECTIVES

The overall objective of the research project can be formally stated as the provision of a framework upon which to base the planning of a certain tightly defined class of manufacturing systems within that larger class known as "Flexible Manufacturing Systems". Certain common design issues are investigated with respect to some pre-defined systems. From this work, more general conclusions upon these issues have been drawn.

The planning and design of elements within such manufacturing systems - such as machine tools or conveyors - has been well documented as well as proven by many years of experience. These factors are not covered at all within this project. The integration of these diverse and separate elements into systems is a relatively new requirement. Some work has been done on this class of systems [Lenz, 1986] and definite "integration" effects have been highlighted. The net effect of these factors is to reduce the effectiveness of the system without the cause being directly attributable to any single part of it.

This project covers the area in four broad sections; first to review the background of flexible manufacturing; second, to detail the analysis and modelling tools usually used to cover these systems; third, to describe a methodology of using these tools to maximise their cumulative benefit; and finally to exploit this methodology to explore certain features of these systems. Although not any part of this project, the development of a better structured methodology for any problem solving procedure is a step towards the application of mechanistic methods, such as those based upon Artificial Intelligence.

2.3 PROJECT STRATEGY

The underlying theme of this project is systems analysis. As will be dealt with in more detail in Chapter 6, many factors have affected manufacturing system design so that traditional piecemeal analysis is now recognised as inadequate.

As a result of this theme, the major criteria for assessing performance will embrace the total system rather than measures based upon individual processing units. Attention will thus be directed at system output rates, lead times, and the level of resources such as pallets and tooling needed to sustain them, rather than traditional measures such as processing unit utilisation.

There are two main methods of systems analysis applied to manufacturing systems. They arise from separate sources and are based upon different philosophies.

One method, which may be attributed mainly to mathematicians, simplifies the system by making assumptions until the point is reached where the system can be solved by mathematical methods. Examples of this approach include the use of queuing network theory as well as normal workload analysis.

The second method argues that the complex, dynamic interactions that occur within advanced manufacturing systems are crucial and that they cannot be assumed out without loss of critical factors. This approach has led to the use of rules and concepts based upon experience and general systems theory.

This work will attempt to reconcile these two approaches by showing where each can be used to best effect, having careful regard to the assumptions made in relation to the objectives of each step.

The overall strategy adopted will be analysis by example, i.e. specific systems will be used. There are several reasons for this, of which the most important is the need for large quantities of realistic, consistent data in order to produce simulation models for the latter phases of analysis. This quantity of data can really only be obtained from studies of real or projected systems. Due to the privileged position of the author within, first, an automotive manufacturer, and secondly an international manufacturing consultancy, data upon real systems was readily available. This data has been used extensively throughout this work.

It is generally accepted that every advanced manufacturing system is unique [Kay, 1982A]. This might change, as cells based upon modern machines are now becoming available off the shelf, and this tendency may eventually extend to larger systems. This means that the use of general conclusions following analysis of a particular system needs great care. However, this is the route that will be adopted and it is valid, providing that the conclusions made are assessed in that light.

It needs to be stressed that none of the above affects the need for expertise from FMS designers, but this is a scarce resource, and any assistance to enhance their performance and productivity is valuable.

2.4 MANUFACTURING SYSTEMS - THE DESIGN PROCESS

The design process for manufacturing systems can be split into three distinct sections:

1. Equipment selection, covering the type and number of processing units, their configuration, the type of materials handling system, whether or not to use automated tool handling.
2. Organisational design, covering the level of pooling to be used, the allocation of work content within the system, the level of resources such as fixtures, tooling and pallets needed to support the desired level of output.
3. Operational design, covering the movement of components within the system and the level of robustness incorporated.

Obviously all of these sections are interdependent, but they provide a general overview of the process to produce a complete plan for a system. What is essential is that all these sections of planning should be completed, at a moderate level of detail, before commitments are made to system hardware.

2.4.1 Equipment Selection

This is the most conventional of the three stages, as it is very similar to traditional systems planning. The type of processing units are dictated by the features of the components to be produced and their approximate numbers by simple capacity planning.

The choice of materials handling is slightly more complex, but is constrained by the size and weight of the components, the traffic density and the complexity of the routings required.

The use of some form of automated tool handling systems is a separate decision unless it is to use common hardware with the component handling system. Its additional initial cost and complexity need to be balanced against the anticipated benefits. This probably accounts for automated tool handling often being a later phase of a staged implementation.

2.4.2 Organisational Design

This stage of systems planning involves a set of problems that do not usually arise with more conventional systems. This is caused by the options offered by the use of more flexible production units. The extent to which these options are used, both as a policy and under the dynamic control of the system control, needs to be addressed at this stage. In common with most decisions there is an ideal functionality requirements against cost balance to be considered.

The major factors to be considered at this stage are the level of pooling of processing units, the way of allocating work content, the level of manual/automatic operation of processing stations, the quantity of variable resources such as pallets and tooling to be provided, and the allocation of inter-process storage capability.

Pooling of processing units is the grouping of similar processing units and providing them with identical functional capability by providing them with the appropriate tooling etc. Any operation on any component can then be performed by any member of the pool.

Work content can be split into small sections or aggregated together. The former method allows the use of less complex processing units of lower capability, but the latter method reduces the demand on the materials handling system, usually improves the utilisation of processing units and can have quality benefits. The choice of manual or automatic operation is again governed by cost - both initial capital and ongoing running costs.

The provision of auxiliary equipment such as pallets and tooling is a very complex question. Against the benefits of duplication to allow for maximum use of processing units, there is the extra control complexity needed to handle an increased number of elements as well as the greater cost.

Inter-process storage can mitigate integration effects (see Chapter 6) that can reduce the overall effectiveness of a manufacturing system. However, it adds cost, increases work in progress levels and extends lead times. Hence it should be minimised to the extent possible without unduly impairing system performance.

2.4.3 Operational Design

Traditionally manufacturing systems have been grouped broadly into two classes - the low volume, high flexibility job shop and the high volume, low flexibility transfer line [Haas, 1976]. Flexible manufacturing systems, as already noted, cover the intermediate ground. Due to these historical reasons, little is known of the unique operational control problems of these flexible systems.

The operational design needs to address three distinct problems - which can be defined as the scheduling, assignment and control of component processing.

Scheduling is the overall strategy of what type of component needs to be produced, in what quantities, and when, relative to other components being produced by that system. Scheduling is at least a system level function. It could justifiably be argued that an even wider view is needed due to the impact of flexible manufacturing on most businesses. However, the characteristics of this level are the same - no internal optimisation is sought, the demands are driven by external needs such as customer orders. Naturally, an upper limit of capacity needs to be considered.

Assignment is the optimising logic. This level attempts to route the components through the system to meet a pre-defined set of objectives - as well as the overriding objective to meet the output required. These lower level objectives may include minimizing lead times, balancing out utilisation of processing units or minimizing work in progress levels. The overall objective is frequently assumed simply by the way in which components are loaded onto the system. Assignment rules decide which processing unit will process a component at any given time. Assignment rules form the bulk of the original software written for each flexible manufacturing facility.

Control is the actual movement of the components through the system, recording their location and the actions required by the materials handling system. The majority of the functional actions are handled by the controller of the appropriate unit, such as a processing station or materials handling device. Control functions are assumed throughout this work and no more attention will be paid to them.

These functions can frequently be seen in terms of the computer systems used. The control level is undertaken by NC controllers, Programmable Logic Controllers and other simpler devices. Assignment is performed by a system controller whilst scheduling should be a function of business level computers.

2.5 FLEXIBILITY CONSIDERATIONS

The term "flexibility" as applied to manufacturing systems is used to describe a wide variety of such systems with an equally wide variety of objectives. Six types of flexibility have been identified [Browne, 1984], which are:

1. Mix flexibility; to allow the proportion of production of a set of components to be changed.
2. Parts flexibility; to allow the actual components produced to be changed.
3. Routing flexibility; the dynamic changing of process routes depending upon system status.
4. Design change flexibility; the implementation of fast design changes to reduce product lead times.
5. Volume flexibility; to allow variations in total component demand to be handled.
6. Customising flexibility; processing components on more than one FMS within a company.

Those types of interest are mix, routing and volume. Parts and design change flexibility are mainly governed by the processing unit design, whilst customising deals with multiple systems.

A consideration of these constraints allows flexibility to be redefined for the purposes of this work. Flexibility is thus defined as the production of a limited variety of similar types of product, using equipment readily adaptable to altering proportions and/or modifications to that set of products. This may be said to describe manufacturing systems with flexibility rather than flexible manufacturing systems. It may be thought to describe an economic compromise type of system.

2.6 SCOPE OF WORK

The scope of work to be described needs to be addressed with regard to two parameters - the scope of systems and the scope within a system. An alternative method of differentiation is to consider which type(s) of system are to be considered as opposed to the level of detail to which systems are investigated.

First, to consider which systems are to be investigated. If the usual volume/flexibility graph is examined, then flexible manufacturing is seen to lie between the transfer line or high volume/low flexibility approach, and the job shop or high flexibility/low volume approach. See Figure 1.1 [Haas, 1976].

This work will consider the higher volume type of flexible manufacturing, those which can be regarded as competing with less well utilised transfer lines. This subclass is naturally of interest to automotive manufacturers, as lower volume passenger cars or higher volume specialist vehicles tend to fall within these volume constraints. Appropriately this application of manufacturing technology is thought to allow smaller automotive manufacturers to compete effectively in world markets or to allow lower volume products to be commercially viable.

Overall, this sector is the medium volume, medium variety area when the whole of manufacturing is considered. Having reviewed the conceptual constraints, physical constraints need to be considered. These are the type of manufacturing process and the nature of the components. This work will be restricted mainly to machining, as this process is generally at the front of applications technology in flexible manufacturing. The use of extremely small or extremely large components is also excluded in line with the subject area being centred on the automotive industry. However, it is worth restating the independence of much systems planning theory from the detail of the type of manufacturing processes to be used.

Second, the level of detail to which any given system is to be analysed. Since it is intended to centre upon materials handling, the first major set of assumptions relates to processing units, which are usually to be regarded as "black boxes". Only the parameters needed to describe the processing operations, together with any tooling requirements, need to be considered. No attempt will be made to model any of the actual manufacturing processes.

The above restriction of scope leads to two further dependent assumptions - a restriction of flexibility considerations and a restriction of system size. Of the types of flexibility discussed above, only three are relevant:

- a) Flexibility of volume, in that total output can be varied without modifying the manufacturing system.

- b) Flexibility of routing options, in that operations can be exchanged between processing units as needed.
- c) Flexibility of mix, in that the ratio of component types produced can be changed without affecting overall system performance substantially.

The other types of flexibility are "frozen" and need not be considered within this report. Maximum system size is limited by the characteristics of the systems - their very high productivity and high output rates, coupled with control complexity increasing almost exponentially with increased system size - naturally leads to a limitation on system size. This means that a maximum system size of around 20 processing units can be assumed to cover the overwhelming majority of such systems.

To summarise, the scope of this work is limited to certain classes of flexible manufacturing systems of particular interest to the automotive industry. The level of detail will be held at the level of systems analysis and no attempt made to model or investigate the processes themselves. These systems have high complexity, but with high levels of automation, a good level of predictability will occur. Hence, providing correct tools are used, an opportunity exists for extremely thorough planning to take place at early stages of any project.

2.7 PROJECT APPROACH

The conventional approach to planning manufacturing facilities is based upon previous experience and empirical rules derived mainly from that experience, although with some theoretical input. It is now evident that neither previous experience nor, more fundamentally, dedicated equipment based techniques, offer satisfactory solutions to current and future demands. One of the major reasons is that the minimal degree of flexibility provided by conventional automated equipment is now inadequate. Accordingly, a new generation of flexible equipment has placed radically changed demands upon planning methods, with emphasis upon minimum equipment levels, fast response and low inventories [Dempsey, 1985].

The advent of inexpensive, and apparently ever reducing in cost, computing power as provided by the latest generations of mini- and micro-computers, offers potential for a more rigorous analysis of manufacturing systems during the planning phase [Warnecke, 1984].

Materials handling is central to the operation of advanced manufacturing systems, especially that class described above as flexible manufacturing systems. The analysis of these materials handling sub-systems is thus crucial to the planning of the complete systems. The demands upon materials handling systems are complex, as the processing units need to be supplied with both components and tooling, as well as to have the completed, exhausted or worn items removed. This needs to be achieved without the need for large buffer stocks.

These complicated demands on the materials handling system mean that it must be functionally very flexible. Increased flexibility is double edged as it requires greater control and so even better planning. The use of more advanced planning tools is thus required as part of any extended use of more modern materials handling hardware. One of these planning tools is simulation, and in particular discrete event simulation, which will be meant by the term "simulation" in the remainder of this thesis.

Simulation methods provide an efficient, cost effective method of systems design before commitments are made to hardware. The degree of confidence in the adequate performance of the proposed system is increased. Simulation, unlike any other planning technique, is a dynamic systems analysis tool. Accordingly, planning need not be restricted to small units each of which is assumed to be isolated by large buffer stocks.

Since it has been established that materials handling is central to the performance of FMS, and that simulation is an appropriate technique to use, the analysis of materials handling hardware needs consideration. A study of materials handling systems was carried out for BL Technology [Bulmer, 1981]. From an analysis of the different units described, and other sources in the same area [Browne, 1983], four categories of materials handling system can be identified:

1. Simple, non-addressable conveyors, which merely move units from one point to another at a fixed rate of movement [Lenz, 1977]. This type of system is used within transfer lines.
2. Addressable conveyor systems, which can move units to a number of locations. These are also known as "intelligent" conveyors [Houston, 1982].
3. Free ranging wire guided or rail based independent units, such as AGV's and rail carts. These are the most flexible type of system, and are increasingly used [Warnecke, 1983].
4. Robotic handling devices, usually used within cells [Braganca, 1983].

Naturally, complete systems can be built up of combinations of these materials handling units, SCAMP being an excellent example [Cook, 1987].

Having established that the approach centred upon materials handling is feasible and that simulation methods provide a suitable tool, the remainder of this thesis will develop this approach.

3.0 THE EVOLUTION OF FLEXIBLE MANUFACTURING SYSTEMS

3.1 INTRODUCTION

The development of complex flexible manufacturing concepts as an integral part of complete production systems has occurred due to a change in the manufacturing strategies adopted in the developed world. All metalworking industries have felt the effects of intensified competition, which has caused a demand for reduced product life cycles, greater choice of product, and the need for more rapid introduction of new and redesigned products.

This scenario has been experienced severely in the automotive industry, and especially in the lower volume, higher added value areas such as diesel power units, and the higher cost assemblies which are traditionally "bought out finished" by the major vehicle assembly companies.

In order to maintain a competitive position, the major automotive companies and their suppliers have been forced away from the traditional sequential line method of production. So far this has been mainly apparent in the machining sector, but other sectors, such as body assembly, follow conceptually similar techniques and these will need to adopt new principles.

The disadvantages of the sequential line manufacturing system are seen most obviously in the transfer lines used for machining. These transfer lines are product specific; have a high initial cost, needing to be written off against many thousands of components; and the lead time necessary to produce one can be measured in years. These characteristics are becoming less suited to the current manufacturing scene. Accordingly, the use of flexible manufacturing concepts is becoming more and more common. This has happened gradually, initial steps being to provide some flexibility within basically traditional systems. The use of robots for spot-welding of body shells and the provision of some component flexibility on transfer lines are good examples of these early steps.

This development has resulted in higher initial system and unit production costs, which is countered by the ability to adjust more quickly to meet precise market requirements. Also, these systems can have their costs amortized over a higher total number of components, but of a number of component types rather than just one. Due to these inherent advantages, the use of these concepts is bound to increase.

Due to the diverse and dynamically varying nature of the materials handling requirements of these systems, 'new' transport techniques including Automatic Guided Vehicles (AGVs) and intelligent conveyors, become an integral part of any complete system.

There have been many excellent reviews of FMS worldwide, [e.g. Sim, 1982; Hundy, 1983] and this chapter does not attempt to replicate them. It is intended to provide the background to the importance of materials handling with FMS, and to put these requirements into perspective.

3.2 THE NEED FOR FLEXIBLE MANUFACTURING

A Flexible Manufacturing System (FMS) has been defined [Hutchinson, 1973] as a production system where:

- a) A relatively large number of Direct Numerical Control (DNC) machines are employed.
- b) Some form of automated materials handling system is used to move the parts into, within, and out, of the system.
- c) On-line computer control is used to manage the entire system, including the DNC for each machine and the dynamics of the handling equipment, under conditions of varying parts production mixes and priorities.

Obviously this definition of FMS is both narrower than the definition used in this thesis, and heavily biased towards machining systems, but if the terms are generalised, it covers systems using almost any type of processing units.

FMS benefits can be considered as extending the advantages of stand alone Numerical Control (NC) in terms of flexibility, especially design and product changes, to medium and higher volume production. This cost/production relationship can be expressed graphically as in Figure 3.1 [Anon, 1968]. FMS bridges the gap between the low volume, high variety job shop with its low capital investment and high unit production cost, and the high volume, zero variety dedicated transfer line with its enormous capital investment and low unit costs.

This medium variety sector is of crucial importance to manufacturing in all the developed countries, typically accounting for between 70% and 80% by value of manufactured metal goods [Solberg, 1978]. The type of products manufactured includes all defence equipment and other politically sensitive areas such as aerospace and ship production.

Traditional methods of production in this medium volume sector have consisted of a mixture of techniques, resulting in systems that suffer from one or more of the following disadvantages:

- a) Poor machine utilisation
- b) Low flexibility
- c) Extended lead times
- d) High capital cost
- e) High reliance upon skilled personnel

The net effect of these factors is that unit costs in this sector are out of proportion when compared with either small batch or high volume production. Flexible manufacturing concepts are thus mainly applicable to this medium volume sector. Additionally, use of these techniques will expand this sector as countries such as the UK can no longer sustain the larger volumes needed for continuing mass production. The automotive industry is the classic example of this, being faced by the opposing pressures of consumer demand for greater choice, and reduced unit costs from overseas competitors.

So far flexible manufacturing has mainly been applied to machining processes. However, its principles can be applied to the majority of production processes. These include assembly, which is the major area for potential application, as it currently accounts for the largest proportion of industrial direct manpower.

In order to avoid restricting the applicability of the methods described in this thesis, the term "processing units" will generally be used instead of "machines" although the subset of machines will be the usual processing units referred to.

3.3 THE ADVANTAGES OF FLEXIBLE MANUFACTURING

The only valid reason for adopting new methods of manufacturing is to improve, or at least maintain, the profitability of the company concerned. This means that the new method has to provide advantages in unit costs or other contract terms such as lead times or quality levels.

As happened with NC, when one or more companies in an industrial sector adopts new techniques, then other companies in that sector must follow or be forced into decline [Haas, 1976]. This philosophy has been summarized: "If we make things the cheapest way, then we will not have a recession. The world will be queuing up to buy our goods and industry will have to expand to supply" [Sims, 1982A].

FMS are one way of reducing unit costs and so maintaining competitiveness. It has been estimated that possible order of magnitude reductions in direct unit costs are possible by the use of FMS [Wynne, 1974]. Generally, unit costs are not the main reason for adopting FMS, these are [Collins, 1980B]:

- a) Reduction in manufacturing lead times.
- b) Reduction in stock and work in progress levels.
- c) Greater flexibility of the production schedule.
- d) Consistent product quality.
- e) Maximum effective use of capital equipment.
- f) Optimum use of skilled personnel.

These factors all affect financial performance, although they are not usually interpreted in this fashion. This leads to a major point, obviously these advantages are valuable to a company, yet how can the systems be justified?

3.4 THE JUSTIFICATION OF FLEXIBLE MANUFACTURING

"A major problem in justifying NC machine tools is the legacy of conventional machine tool justification..... This legacy says that all I may consider is what my accounting department allows me to consider." This quote [Haas, 1976] describes the problem of justifying any form of flexible manufacturing. Although the advantages can be expressed, they are not easy to quantify to suit conventional accounting methods.

There can be no doubt that accounting practice has failed to keep up with the development of advanced manufacturing technology. This problem has been extensively discussed, such as suggesting that the effects on the whole business must be considered [Collins, 1980B]. The Automated Small Batch Production (ASP) committee also commissioned research in this area, which has suggested that FMS are most likely to develop from installations of Computer Numerical Control (CNC) machines [Stokes, 1982].

There can be no doubt that the justification rules laid down by accounting departments have retarded the use of manufacturing technology. Fortunately, and contrary to what would be expected, the larger financial implications of FMS seem to have caused greater involvement of higher management, thereby avoiding these restrictive rules. Despite this, many FMS in the UK have only been agreed due to the considerable support provided under various Government schemes [Anon, 1985].

In order to overcome this hurdle, two factors will be crucial. There are historical results from the pioneering users of this technology, and the better analysis of proposed systems made possible by more powerful modern techniques, especially in the fields of simulation and financial modelling [Shale, 1984A].

3.5 THE DEVELOPMENT OF FLEXIBLE MANUFACTURING SYSTEMS

3.5.1 Numerical Control of Machine Tools

Numerical control (NC) originated in the USA soon after the Second World War. Started by civilians, the concept was developed under the auspices of the US Air Force (USAF) due to the complex machining requirements of contemporary military aircraft components. Massachusetts Institute of Technology produced a 3-axis milling machine and its controller, despite the handicaps of then current computer technology.

The increasing requirements of parts for supersonic aircraft saw USAF expand the use of NC until, by 1960, over 100 machines were in use. Three points had been proved [Thorton, 1982]:

- a) That NC was a viable technology.
- b) That the computer could survive on the shop floor.
- c) That production engineers could comprehend and use NC.

Over the subsequent 25 years, NC has spread to almost every metal cutting company in the industrial world. Reductions in the relative cost of control systems through the advanced in microelectronics have accelerated this growth. Today the cost of a controller is only a small percentage of the cost of a machine tool.

NC was also extended, first to other metal cutting processes such as turning, next to other metalworking processes such as sheet metal nibbling and recently, via industrial robots, these concepts have been applied to other processes such as assembly. NC is central to flexible manufacturing, but deals with individual processing units. FMS extends the techniques to complete manufacturing systems.

3.5.2 Molins System 24

In 1966 the Molins company, who had been working on new concepts of manufacture, were awarded a pre-production order for a multipurpose NC machine by the Ministry of Technology. The result was System 24 - a totally new manufacturing concept [Williamson, 1967A, 1967B].

Although the Molins system has been discussed widely [Rathmill, 1981] until recently, the extent of the concepts used has been neglected. These covered almost all the principles of modern FMS, as has been recognised by the US Patents Office when it awarded major FMS Patent rights to Molins [Wildish, 1983].

- a) Work palletisation. The machine tools were designed for all work to be fixed onto common pallets.

- b) Work and tooling transportation. Units to provide materials handling and buffer storage for batch component pallets and tool magazines were available.
- c) Control systems. NC was used throughout, initially from magnetic tapes, but later DNC was used. Adaptive control and spindle torque monitoring were used.
- d) Magazined tooling. This was standard, together with automatic tool changing.
- e) Total System Control. A complete System 24 was controlled by an on-line central computer.
- f) Provision for unmanned operation. The system was designed for minimally manned night shift operation.
- g) Reduced requirement for skilled personnel. Pallet loading was to be performed by unskilled labour. As an aside, the original intention was to use female labour for this job, giving an even greater saving in the days before the Equal Pay Act. Additionally, no actual machine operators were required.

Obviously the system was technically very advanced, but it was not successful, very few machines being sold. This commercial failure has been attributed to four factors [Holland, 1971]:

- a) Very high initial system costs.
- b) High system complexity, and consequent unreliability.
- c) The inability to cut ferrous materials.
- d) Low efficiency due to the Pelton turbine drive system.

System 24 has been discussed at some length as it illustrates the major features of modern FMS, as well as showing that the relatively high unit costs of batch manufacture were appreciated. However, the application of system flexibility by the use of high technology must not be compromised by poor reliability.

System 24 has, with the benefit of hindsight, acted as a catalyst for FMS, and it is interesting to speculate what would have happened if System 24 had been a commercial success. In reality much of the subsequent FMS development took place outside the UK.

3.5.3 The First Complete Systems

The first complete FMS, exclusively flexible machining systems, were built in the USA during the middle and late 1960's. They were characterised by:

- a) A very high degree of systems complexity.
- b) Intended as an alternative to transfer lines, where these would have been under utilised.
- c) Bought as completely new turnkey facilities.
- d) Used for high added value, relatively large components.

They also showed another less attractive feature, that of lengthy commissioning times, coupled with an inability to completely meet initial specification [Collins, 1980A]. These features were generally attributed to their extensive use of unproven technology, combined with their size making fault finding difficult. Undoubtedly the lack of adequately sophisticated planning and analysis tools was a contributing factor, especially in the light of the inadequacy of conventional tools when used for the planning of flexible facilities.

One of these early systems was supplied by Kearney and Trecker to Allis-Chalmers, and was designed to machine a wide range of castings for the power train of a new range of tractors. The system, with 10 machine tools, used two computers, one for the handling operations and one for the remaining operations [Kearney and Trecker, 1981].

The transport system was tow-line carts which reduced the overall flexibility of the system. However, the benefits of the flexibility that was built into the system were shown after the system was completed. The product demand profile was different to that anticipated, but with some slight alterations the system was able to adapt to match the new conditions.

Allis-Chalmers reported that they were pleased with this system, although it did not possess as much flexibility as they would have liked. They also noted that highly skilled maintenance personnel were required to keep it operating.

At least one of this type of system was planned for the UK, as part of a variable part machining system for Borg-Warner. One of the components intended for the system was transmission cases for the automatic version of the BMC A series power unit [Anon, 1968]. The system was never built, and the UK had to wait 13 years for its first FMS.

3.5.4 European Developments

The concept of complex systems, as in the USA did not impress the other industrial countries. The vast capital costs and lengthy commissioning times precluded their implementation on a large scale, and more gradual steps were taken.

The use of production processes other than machining has been more common outside the USA. The Europeans, in particular, have also tailored their systems to include the use of existing equipment rather than completely new facilities.

An excellent example of this pragmatic approach is the system built and used by BT Handling Systems in Sweden. Two rows of NC machine tools are separated by two rows of pallet storage in between which operates a standard automatic warehouse Stacker crane. Some of the machine tools are machining centres which are fed by the Stacker crane throughout a 24 hour day. The remaining manual NC machines operate on a two shift basis, being fed by the Stacker crane as required [Anon, 1981A].

Alternative transport methods were considered before the system was constructed, but these were rejected on a cost/performance comparison. The system used compared extremely favourably when compared to platen changers for the machining centres.

Another example of the broad European approach is the Fiat "Robogate" car body assembly system, and the smaller "Robocarrier" system for power unit assembly. The Robogate is an example of a FMS on a large scale, up to three different body shells with up to eight variations can be produced simultaneously [Hartley, 1978].

The Robocarrier employs the same philosophy for power unit assembly, the main difference being the far higher level of manual involvement. In both systems, the part completed unit only visits those stations where operations are to be performed on it. This avoids the redundant time problem that occurs when conventional lines are used, and have to be laid out and timed to suit the most complex variant being produced [Anon, 1981B].

As well as flexibility, Fiat also claim social benefits, as each man can work at his own pace. However, the cost is high, these systems carry an investment premium of at least 30% when compared with conventional alternatives [Mullins, 1978].

Coincident with the research described in this thesis, new flexible manufacturing facilities have been commissioned at an ever increasing rate. Worthy of particular note are those systems produced by major automotive companies such as Citroen, and by their suppliers such as ZF Gears. Both these companies have unveiled advanced systems that are totally different both in concept and realisation.

Citroen's system at their Muedon plant is intended to produce a wide variety of prototype automotive components in very small batch quantities [Anon, 1983B]. This system represents one end of the spectrum - very high component flexibility - and can be contrasted with the higher total volume and larger batch sizes that the ZF Gears one is intended for. This system at Friedrichshafen in West Germany is designed for the production of 40,000 gears per month. A cellular approach is used to give good system resistance against machine failures. Almost any gear, within certain size constraints, can be produced, but re-tooling of machines is needed between batches, hence large batches of 50 to 500 components, are the normal operating philosophy [Hoerl, 1981].

These systems illustrate the variety of systems that are suited to the automotive industry, and also show that industry's leading place in the development of advanced manufacturing.

3.5.5 The Japanese Approach

Japan is the world leader in FMS, possessing almost half the operating systems in the world [Collins, 1980A]. Their approach has been very different from that in the USA, the full FMS in Japan have mainly grown from experience with linked DNC lines. The first DNC system, with no automatic materials handling, was installed in 1968. Since then the level and complexity of the technology used has increased to include the use of robots and sophisticated work scheduling.

One major advantage of this staged approach is that the majority of the technology used at any stage has been previously proven. This reduces the level of risk that is incurred. Some systems have already advanced to running almost unmanned on two out of three shifts and production processes other than machining are starting to be used [Yamashina, 1986].

A good example of the trend of developments in Japan is the much publicised Fujitsu Fanuc factory for the manufacture of a variety of advanced manufacturing equipment, including industrial robots. In this system a number of machining cells are linked by unmanned trollies and pallet changers. When combined with automatic warehousing, a flexible and automated facility is available. This factory is fully manned on only one shift, with only one man required on each of the other two shifts [Inaba, 1982].

Fanuc cite an investment premium of approximately 30% when compared with conventional alternatives. Interestingly, this figure is similar to that quoted by Fiat. Fanuc also say that the benefits from not employing a nightshift are financial, not just social.

Japan is undoubtedly the world leader, especially as regards systems integration, in FMS. The interest lies not merely in the pragmatic and cost effective development strategy, but in the stress laid on the financial viability of systems. This is notable in the light of Japanese labour rates being historically low when compared to the USA, a situation which traditionally makes advanced manufacturing systems more difficult to justify.

3.5.6 Progress in the United Kingdom

In 1976 the National Engineering Laboratory (NEL) obtained funding from the Department of Industry (DoI) for a study into small batch production. This study developed into the Automated Small batch Production (ASP) committee, who commissioned and coordinated research and development for all aspects of small batch production. This work effectively became a FMS development programme, although much of the work had other uses.

The topics investigated include two of particular relevance to this thesis, namely simulation and workpiece transport systems [MacPherson, 1980]. The work in these two areas has provided much of the foundation for the research to be described.

In addition to research, practical work at the NEL included the setting up of an example cell based around a general purpose machining centre and using a modular and intelligent conveyor system for workpiece handling [Hill, 1982]. As an adjunct to the ASP work, the DoI has part funded several FMS projects, each project being intended to advance the level of FMS technology employed in the UK.

Most notable of these are the flexible machining cells at Normalair-Garrett and the SCAMP system. The system installed by Normalair-Garrett at Crewkerne, and widely heralded as Britain's first FMS, is based on two machining centres and cost about £1.5 million.

The Six hundred group Computer Aided Manufacturing Project (SCAMP) project is more significant, both in the scale and sophistication of its realisation and in its research and planning effort. The work in the fields of system planning, alternatives assessment, and operating philosophy development using simulation formed the background to the systems planning hierarchy described in Chapter 5 [Houshmand, 1982; Rathmill, 1983].

The actual SCAMP system uses nine machine tools, formed into eight cells, each cell being served by an industrial robot. Workpiece transport is provided by a conveyor system. The system cost £3 million, and although delayed by teething troubles, represented a considerable advance on the Normalair-Garrett cell [Anon, 1983A].

The research work to support the increasing number of FMS in the UK is now the responsibility of the Application of Computers in Manufacturing Engineering Directorate of the Science and Engineering Research Council (ACME). This work is now less specific and takes a longer and less immediately industrially relevant view than that supported by ASP.

A variety of manufacturing systems with flexibility are now in use in the UK, such as at Anderson-Strathclyde, for coal cutting machinery components; Gardeners for diesel engine crankcases and Rolls-Royce for the grinding of aircraft engine turbine blades. All of these, as well as many other schemes, have benefitted from grants under the Government's FMS support programme [Sims, 1982B].

The restricted nature of component flexibility in most UK systems will have been noted. This restricted component flexibility is characteristic of "demand driven" systems - which are built to suit the current needs of industry. "Technology pushed" systems, such as SCAMP, are the result of heavy Governmental funding to provide the background for the more flexible systems that will be needed in the future.

Overall, the rate of the growth of flexible manufacturing technology in the UK is promising, although still comparing poorly with European competitors such as West Germany and Sweden [ACARD, 1983]. By 1984, some 35 projects were at the installation stage [Kochan, 1984]. The reduction in Government support may have resulted in a temporary decline in the rate of increase of this technology.

Some of the 35 systems noted above have now been commissioned and conclusions can be drawn about them. They are typically machining system with enormous productivity compared to stand alone machines. A good example is the seven machine tool system at Hattersley Newman Hender which incorporates some manual assembly capacity [Tiernam, 1986]. Another common feature is manual tool pre-setting as used within the 5 machine system at Leyland Bus [Kochan, 1987]. Tool pre-setting is notable as a pre-requisite for automated tool handling.

The integration of the computer system control on Advanced Manufacturing facility into wider systems is as yet rare. A leading example is based on the 2 machine FMS at Victor Products, where the system control computer is linked to those concerned with the commercial and financial aspects of the business. Although a DNC link is currently in use for existing programs, an extension of this integration to include a CAD facility for direct linking of design to manufacture is planned [Baxter, 1986].

The rate of increase of the use of FMS is now more difficult to define, as companies do not now need to publicise their system - a condition of Government support for earlier schemes. Their growth appears to be steady and the use of non-machining processes is becoming more common.

3.6 CONCLUSIONS

Worldwide development of FMS, especially outside the USA, has followed and is following a general pattern although different countries are at different stages.

This pattern starts with small machining cells, for processing a variety of components, then links these cells together with automated handling systems, and finally completely integrated systems are commissioned. These will include automated work and possible tool handling; computer assisted assignment and scheduling; and a greater level of flexibility - however this is defined.

The objectives of future developments are also fairly clear. These are, approximately in order of likely realisation:

- a) Minimally manned operation on one or two shifts, giving greater use of equipment coupled with improved social factors.
- b) More rapid response to changing market requirements, assisted by reduced work in progress levels.
- c) Integration of the design process, to give a complete chain of CAD through CAM to DNC. This eliminates paperwork and gives complete control of manufacture from design to finished component.

Further development towards the completely "unmanned" factory will be constrained by financial rather than technical limitations. Each additional level of automation increases the investment premium required, and currently provides a diminishing level of benefits.

4.0 THE SIMULATION MODELLING OF MANUFACTURING SYSTEMS

4.1 INTRODUCTION

Simulation, and especially computer simulation, are widely used terms to describe a large class of mathematical modelling techniques. The main parameter linking these techniques is that they model time dependent systems using dynamic models which are not self optimising.

For the purpose of modelling manufacturing systems, as distinct from manufacturing processes within such systems, the simulation technique usually used is discrete event simulation using a digital computer. ↑ This approach models systems by a process of changing between discrete states at definite time points. The approach is shown diagrammatically in Figure 4.1. Unless otherwise noted, the term 'simulation' will be used in the remained of this work to mean digital discrete event simulation.

This chapter describes the development of simulation as applied to manufacturing systems, reviews two major groups of simulation languages, and the major stages of constructing simulation models. Finally, the application and use of simulation in this research work is described, and the use of the approach justified.

4.2 MATHEMATICAL MODELLING AND SIMULATION

4.2.1 Overview

All forms of mathematical modelling, of which simulation is one type, follow the classic 'scientific method' of Hypothesis - Experiment - Analysis - Deduction. This method is based upon the building of a 'system model', which is used as the basis for the carrying out of experiments. Simulation is the only current effective method for analysis of stochastic problems, where random effects present within the system prevent single, simple, analytical solutions being derived.

The use of simulation modelling methods for other classes of problems is possible. In the case of queuing networks, analytical methods are now being applied to problems where simulation was the only practical method previously able to give results.

Simulation can be distinguished from almost all mathematical models, in that it does not provide optimum results, although it is frequently assumed that it can. Accordingly, the best result that can be obtained is the best one that is considered. However, simulation does allow the rapid and unbiased comparison of many alternatives, allowing decisions to be made on the basis of the best available information.

Although the precise definition of simulation is unclear, Models which are Abstract, not physical; Dynamic, not static, Numerical not analytical, Explicit, not implicit and Stochastic, not deterministic, are Simulations. This definition can be remembered by the, perhaps unfortunate, acronym MADNESS [Clementson, 1982].

4.2.2 The Development of Simulation Languages

There are a wide variety of simulation languages available. These have mainly been developed in two groupings - the material based approach that is widely used in the USA and the machines approach used in the UK. This separation was clear by the mid-1960's as a review of contemporary languages showed [Tocher, 1965]. Their parallel development continues to cover the majority of simulation languages, although there are some exceptions, notably SIMULA [Dahl, 1970], which has recently been extended to DEMOS [Birtwistle, 1981].

The scope of this review will mainly be confined to the two larger families used in this work. These are the three phase languages based on the concepts developed at United Steel in the UK and the Q-GERT/GASP based languages developed in the USA.

4.2.3 Three Phase Based Languages

This is sometimes known as the 'British Approach', and is based upon the concepts developed by the Operational Research Group of the United Steel Company [Tocher, 1960]. The three phases are:

1. Time Advance ('A' phase) which advances the simulation clock to the next soonest future event.
2. Processing of the Bound events ('B' phase), which scans the activities in progress, and terminates those which can be ended.
3. Processing of the Conditional events ('C' phase), which tests conditions on all events, starting any which meet appropriate conditions.

Although various languages offer enhancements to adjust this progression, it has stood the test of time; languages using this concept now having been used for nearly three decades. The advantages of this approach are that models are relatively simple to code, and amendments are easily accomplished. Models are also fairly easy to understand, and pre- and post-processors can be added if required. The disadvantages of this approach are that programs tend to be large and that there is a certain amount of redundant processing which can affect run time efficiency, especially if smaller computers are being used.

The first language based on this approach was the General Simulation Program (GSP) as already noted, which was developed and used in the steel industry. Work followed in the petro-chemical industry, leading to the Control and Simulation Language (CSL) at ESSO. A third variation, SIMON, which formalised many of the three phase concepts, was produced in ALGOL initially [Hills, 1965] and later converted to be based on FORTRAN.

Improvements in computer hardware and software allowed languages to be both portable and quicker to process. This led to the wider availability of simulation languages, and greatly increased their academic use. More recently, the needs of advanced manufacturing technology have caused a large increase in the use of simulation within the engineering industry [Shale 1984].

There are currently at least five packages available based on the three phase simulation approach. All of them are available as micro-computer based installations with dynamic colour graphics. They are FORSSIGHT, the current development of GSP [British Steel Corporation, 1981]; SEE-WHY [Fiddy, 1982]; OPTIK [Insight International, 1984]; Extended Control and Simulation Language (ECSL), which was developed from CSL, and can be implemented on a wide range of equipment from micro-computers to mainframes [Clementson, 1982]; and the Hand Or Computer Simulation (HOCUS) package, allowing manual hand or computerised simulation to be used [Poole, 1977]. The progressive development of three phase languages is shown in Figure 4.2.

4.2.4 The GASP Based Languages

This family of packages developed in the USA uses a two phase approach. This technique advances the clock and then starts or finishes events in the order they are listed on an event calender. This implies that greater consideration of activity ordering and resolution of possible conflicts is necessary at the model design stage.

GASP is a discrete event simulation language based on the normal American process approach. It was developed at US Steel [Kiviat, 1969], and developed by Pritsker through GASP II to its final version GASP IV [Pritsker, 1973]. GASP IV is notable as it was the first combined framework simulation language allowing continuous, as well as discrete event simulation models to be handled. It also allowed the two approaches to be combined in one model, an extremely useful facility in certain situations.

Pritsker was also responsible for the queuing network modelling language, Queuing Graphical Evaluation and Review Technique (Q-GERT) [Pritsker, 1977]. Network modelling languages are popular in the USA, allowing flows of entities within a system to be modelled using a special set of symbols called nodes representing various functions. Their limitations are that complex relationships and control functions cannot be specified. Due to these limitations, queuing network languages can only be used to model manufacturing systems at a superficial level. Accordingly, it is now usual to allow high level language subroutines to be included in the model as does the later INS language [Roberts, 1983]. Q-GERT does not have this capability.

To meet these requirements the Simulation Language for Alternative Modelling (SLAM) was developed. Basically an extended combination of GASP IV and Q-GERT, SLAM allows models to be constructed in either network, discrete event, or continuous constructs, or any combination of them [Pritsker 1979]. SLAM is accordingly a very powerful language, although many of its more advanced features are of little interest to this study of manufacturing systems.

Two other developments have occurred, SLAM has been extended as the central point of The Extended Slam System (TESS) to provide support to a model builder in the areas of model and program construction, data management, analysis and presentation and options analysis [Standridge, 1983]. Although this provides a very powerful integrated tool, the disadvantage that at least mini-computers are required remains. Although SLAM, in a restricted form, is now available on a micro-computer, the introduction of the SIMulations ANalysis language (SIMAN) represented a great advance in this field.

SIMAN [Pegden, 1982] is a general purpose simulation language which is claimed to have the same facilities as SLAM, but is available for a range of micro-computers. SIMAN is also based upon graphics and interactive concepts for model building, data input and program execution. SIMAN follows the concepts of separating the model from its execution and data blocks, an approach which is becoming widely adopted due to the ease of experimentation that it permits [Oren, 1979]. The development of the GASP based family of languages is shown diagrammatically in Figure 4.3.

4.2.5 Other Simulation Languages

There are many other simulation languages which can be used for modelling manufacturing systems. Probably the best known is GPSS, which was originally developed by the IBM Corporation for use on their mainframe computers [Schriber, 1974]. GPSS now has several versions, of which the earlier ones are widely available.

SIMSCRIPT, developed to a certain extent out of GASP, is used extensively in the USA, especially for military purposes, and has been used for the modelling of manufacturing systems.

The statement that a 'best buy' simulation language does not exist, and that machine/language compatibility and availability are the most important factors remains true [Tocher, 1965]. Obviously any comparison of simulation languages will be to some extent subjective. A useful diagrammatic evaluation of inherent capability against ease of use for several of the major simulation languages has been produced [Browne, 1983]. An enhanced and refined version of this is given as Figure 4.4. It would be anticipated that capability would vary inversely with ease of use, and that language development would tend to enhance both features. These trends can both be distinguished in Figure 4.4. Comparisons of this sort are useful, even if they are to some extent flawed, as they serve to encourage prospective users to consider their requirements against the relative strengths and weaknesses of the various languages.

No recent review of simulation languages overall is known to this author, however a good contextual review of the major US process based languages has been published, unfortunately it was written before the availability of SIMAN [Menon, 1982].

4.3 SIMULATION MODELLING SUPPORT PACKAGES

4.3.1 Code Generators

Due to the highly structured nature of three phase simulation languages, the use of a code generating pre-processor to give a more 'user friendly' approach was an obvious development. The disadvantages of such code generators are that the full features of the host language cannot be incorporated. Accordingly, they are most useful for first models and where relatively simple models are required quickly [Carrie, 1985].

Code generators are now available for ECSL, called Computer Aided Programming of Simulations (CAPS); for FORSSIGHT, called FORGE; for SEE-WHY, called EXPRESS; and the program DRAFT, which can act as a code generator for several simulation languages, although it was originally developed with SIMON as its host language [Matthewson, 1984].

4.3.2 Output Facilities

The original and still the most common method of obtaining the results from a computerised mathematical model, including a simulation model, is numerical printouts. This method is more than adequate for the model builder, but has been justly criticised on the grounds that these figures are of very little use to anyone not connected with the model [Hurrion, 1978].

In view of the need not only to improve communication of the results of the model, but to show how it works, in order to allow decision makers to assess these results meaningfully, the use of dynamic graphical displays has become more common. These communication methods can be regarded as modern versions of the control and information displays that were used in the early stages of the industrial use of simulation [Hollocks, 1983]. However they are more flexible and less difficult to interface.

There are two techniques of transmitting information to output devices, usually a visual display unit. These are either to use the central processor to drive the graphics directly, usually via a memory mapped screen and a dumb terminal; or to use an intelligent terminal to post-process the information from the central processor. The latter is more efficient, but increases the complexity of both the hardware and software required.

Additionally, it is not unusual for some degree of interaction to be provided between the model and the user, as distinct from the model builder. This is a facility that can easily be misused, due to the low level of confidence that can be placed in short term results from most models, which are designed to show long term performance.

Overall the use of these powerful communication techniques is useful at all stages of modelling. The disadvantages of the extra coding required are small, but the main difficulty of tending to concentrate attention on the effects rather than the causes of a situation remains.

4.4 DEVELOPMENT TRENDS

The major trend, especially in the non academic use of simulation, is towards the selling of general purpose simulation packages with powerful user interfaces for both input and output. Although this allows the provision of powerful analytical tools, great stress is being placed on ease of use, rather than correct use of the technique. This is particularly true of statistical validation and analysis. Additionally, the development of realistic, and hence large, models on these micro-computers results in extended compiling and processing times.

4.5 THE CONSTRUCTION OF A SIMULATION MODEL

There are four main stages in the construction of a simulation model. The process involved has been explained in detail elsewhere [Martin, 1968; Law, 1982]. Accordingly, this review will be brief. The four stages are:

1. Problem definition and data collection.
This consists of the system analysis to determine the scope of the model, and to establish the assumptions to be made to allow the model to be as simple as possible yet fulfill its function. Once the framework has been established the data needed should be established and collected. This can be one of the areas causing major difficulties, especially where proposed systems are concerned. For example, realistic reliability statistics for modern machine tools are extremely difficult to obtain [Stewart, 1976].
2. The construction and refinement of the model.
This is probably the easiest and most rapid part of the process, as it has been the subject of much effort by the authors of simulation languages. Major problems at this stage are almost always caused by inadequate attention to Stage 1.
3. Verification and validation of the model.
Verification is the process of checking to see that the model functionally meets its specification. Validation is the process of ensuring that the model does what is intended. This is usually done by the comparison of the results of several runs of the model with each other and with real data, where this is available. It is at this stage that any unconsidered assumptions reveal themselves. Overall the objective of this stage is to instill confidence in the model and to assess its level of meeting reality [Mihram, 1975].
4. Model experimentation and results analysis.
This section is often treated in a summary fashion. It needs to be carried out with an understanding of the effects of random number generation and duplicate runs should always be made to avoid any statistical bias. Variance reduction techniques can be employed to isolate the effects of various parameters economically [Law, 1982].

More detailed information on certain procedures followed will be given in the chapters where these factors become of more than usual importance.

4.6 SIMULATION IN THE CONTEXT OF THIS THESIS

As has already been mentioned, conventional planning techniques are not adequate for the planning of advanced manufacturing facilities. Accordingly, it was necessary to use other methods. Other types of models have been successfully used for the study of certain elements within advanced manufacturing facilities; [Nof, 1980]. However, for complete systems, the use of simulation methods has now become the accepted technique. Such systems have been formally proven to be NP-complete, and hence fundamentally unsolvable by analytical methods [Stecke, 1981].

Simulation has successfully been used by several major research efforts into flexible manufacturing systems such as the 'Optimal Planning of Computerised Manufacturing Systems' project at Purdue University [Solberg, 1978], work supported by the ASP programme [Chan, 1978], as well as now gaining increasing acceptance for industrial planning [Shale, 1984B].

Previous work at Cranfield had established the utility of the technique and provided an experience base, from which this author was able to extend [Houshmand, 1981; Walmsley, 1982].

As will be obvious, simulation was to be a tool for the work. However, the development of adequate models for experimentation was a crucial part of the project. As a matter of definite policy, a wide range of simulation techniques and languages were used. This had the advantages of using the most suitable method for a set of requirements, as well as reducing the dependence on any one. These techniques are described in the appropriate sections.

5.0 THE APPLICATION OF SIMULATION TO MANUFACTURING SYSTEMS PROJECTS

5.1 INTRODUCTION

This chapter details a strategy for the use of simulation modelling methods for the planning of advanced manufacturing systems. This basic approach has been developed from ideas originated by several authors and has been proven, not only for academic purposes, but also in the feasibility and planning stages of several real projects.

The overall objective of the strategy is to provide a cost effective approach with the level of effort and detail of modelling at each stage being geared to the needs at that stage of planning. This contrasts with a more traditional approach where a project is 'firmed up' using conventional planning methods and a very detailed simulation model is constructed to highlight any potential problems. This latter method tends to avoid the great potential benefits of using simulation when more fundamental system parameters are still to be decided.

The strategy, as described, can be thought of as a 'heirarchy of analysis' and requires a number of modelling tools to be used. The main emphasis is geared towards the analysis of the flow of material within the system, rather than being built around capacity planning. This route is used due to the need to ensure that materials handling is efficient and so maintain high processing unit utilisation without the need for high work in progress levels. This contrasts with the alternative method of maintaining high utilisation of processing units by decoupling them with large buffering between processes. This low work in progress thinking is in accord with current views on production systems in Europe, North America and Japan.

5.2 DEVELOPMENT OF THE APPROACH

A study of the classic production function curve, as shown in Figure 5.1 shows the relationship between production and the work in progress in the system. This curve originates from queuing theory and it assumes a constant set of facilities. This curve may be thought of as increasing work in progress causing less dependence between processing units, and thus allowing production to curve asymptotically towards a limit imposed by 100% utilisation of the bottleneck production unit.

A brief consideration of the preceding paragraph will suggest that a similar result to increasing the work in progress can be obtained by:

- a) Improving the control of the materials handling to provide an improved level of service to the bottleneck processing unit(s).
- b) Concentrating the available engineering effort on reducing the average cycle times at that bottleneck unit.

Both of these alternatives are dependent upon the correct identification of the bottleneck processing unit, and continued knowledge of that bottleneck as steps are taken to reduce its adverse effects. This is the background to the need to study like flow within the system. The use of the analysis of flow as the basis for the control and scheduling of manufacturing systems is the foundation of the OPT approach developed in Israel [Haylett, 1986].

The exponentially declining additional benefits from the increasing levels of modelling complexity have long been realised [Rathmill, 1979]. An understanding of this led to the use of a structured analysis approach for the simulation work for the SCAMP project [Houshmand, 1982]. This work was the first reported formal use of a multi-level modelling technique. This technique forms the foundation for the more detailed concepts discussed here.

Another notable point from the SCAMP project was the understanding of the value of simple, low cost models, provided that their limitations are realised. These classes of model will be discussed first, as part of the general order coincident with their order of use during a typical project.

5.3 STATIC CAPACITY PLANNING

Static capacity planning is the technique of establishing the number of processing units required by simple arithmetic based upon operation times and volume throughput required. Additional allowances are usually incorporated for breakdowns, setting-up, and so on.

Static capacity planning does not take into account any reduction in processing unit utilisation caused by congestion in the materials handling system. It is thus best suited to traditional systems where processing units are effectively decoupled by work in progress.

Static capacity planning models can be computerised, typically using a spreadsheet package. This permits sensitivity analysis to be undertaken, allowing rapid adjustments to the data, with fast re-calculation of results.

Overall, this level of modelling gives the minimum number of processing units, by type, and gives some measure of the workload in the system. Sensitivity analysis can be performed, but no account is taken of congestion in the materials handling system.

5.4 QUEUEING THEORY BASED MODELS

Mathematical methods are a preferred method of approaching any problem, as opposed to simulation modelling, as they are deterministic and predictable. These factors are mitigated by the level of assumptions needed in order to fit a real situation into the framework of the model. Although complete solutions have been developed for simple cells with limited numbers of processing and handling units [Elsayed, 1978], the modelling of larger systems requires the use of queueing theory methods.

Queueing theory based models analyse the materials (or tooling) flow within a system. This analysis is undertaken by using queueing theory to build up networks and so provide a quasi-dynamic view of flow statistics. These models are characterised by broad assumptions to fit queueing theory, and their input data is limited.

Specific queueing models could be developed for any system, but usually a standard program is used [Chow, 1984]. The original program of this type was Computerised Analysis of Networks of Queues (CAN/Q), developed at Purdue University specifically for use in manufacturing systems planning [Solberg, 1980A]. One of the disadvantages often cited for CAN/Q, and similar programs, is the lack of a theoretical basis for the application of queueing theory to these constrained, complex interacting systems. However, considerable validation work for the CAN/Q model has been carried out against real systems and their performance [Solberg, 1980B]. This pragmatic validation has shown CAN/Q to give extremely good results.

To summarise the advantages of these queueing theory based models, they are relatively flexible and accurate within the constraints imposed by limited input data. ✕ Their high speed of application is useful allowing many alternative systems to be quickly evaluated. ✕

5.5 GENERALISED SIMULATORS

5.5.1 Concept

Generalised simulation models consist of a validated model of a particular system framework, which the user tailors to his requirements by the input data used. More advanced users can also incorporate patches of code into the model to allow special features to be handled. This latter option considerably extends the capabilities of the simulator, but needs to be done with extreme care combined with a thorough understanding of the model and its underlying assumptions.

For a manufacturing systems simulator, a typical model will be based on a varying number of processing units served by one or more types of materials handling system(s). The model data file, written by the user, will need to specify:

- a) The number and functional grouping of the processing units.
- b) The operational sequence and processing times for all the component types.
- c) The type(s) of material handling used, the number of units, and the travel times between points.

The above represent the minimum data requirements. More advanced simulators require extra information such as breakdown details, decision rules to be used, etc.

Usually a generalised simulator is written in a general purpose simulation language such as SLAM or ECSL. The simulator is at a higher level than its host language and so can present a more 'user friendly' environment. Some of the flexibility and features of the original language are not available. This is the trade-off required to give the simulator ease of use and quick execution times.

5.5.2 Development

The main thrust of development of this class of model has been in the United States, where a wide range are now commercially available [Bevans, 1982]. Probably the first generalised simulator to become generally available, although others had been produced by machine tool and system suppliers, was the General Computerised Manufacturing systems Simulator (GCMS), written at Purdue University in 1977 [Lenz, 1977]. Although initially a research project, this program has since been refined, and at least two versions are commercially available [Dunn, 1985]. A more detailed survey of these and other generalised simulators has been written [Mills, 1985].

5.5.3 Usage

Generalised simulators can be used without expert simulation experience and this can be of significant value. Within the constraint that no optimum solution is produced, their most useful aspect is the ability to compare, and so iteratively improve, basic system configuration and control parameters. A useful comparison of the results obtained from several modelling methods has shown the utility of generalised simulators for performance assessment of proposed systems [Talavage, 1980].

5.5.4 Limitations

The limitations of generalised simulators are:

- a) Those imposed by the specific modelling framework used by any given simulator.
- b) Those imposed by the overall concept of generalised simulators, so limiting the degree of detail modelled.

The limitations imposed by the model used must be thoroughly understood to avoid using it to try and deal with a system falling outside its domain. The second type of limitation is shown when additional detail is required in the model. At this stage the need for this detail should be re-examined, and if it is genuinely required then a more detailed level of modelling will be needed.

5.5.5 Future Development

Two areas that are currently of interest in the whole of the wide field of computer aided design area are sophisticated dynamic graphics and expert systems. Many general purpose simulation languages now include dynamic graphics and they are now being applied to generalised simulators [Lenz, 1983].

The linking of a generalised simulation model with an expert system would provide a manufacturing systems design tool of unprecedented capability and utility. This has been suggested as a useful route [Crookall, 1986] and research work in this area is now in progress in several countries.

5.6 NETWORK SIMULATION MODELS

Network simulation models are built up from special sets of nodes provided by network simulation languages. The flow of material, or movement of materials handling devices within the system can then be modelled. Such models are thus extensions of queuing network models, but they are true simulation models, not based upon averages, so giving more and additional detail at the expense of extra modelling complexity.

The type of network that can be built up is shown in Figure 5.2. A sample output is shown in Figure 5.3 [Roberts, 1983], and shows the detail usually provided on the throughput and utilisation of each node of the network.

In many cases a network simulation model will provide more than adequate detail for complete system analysis. This is frequently true when the materials handling is the principle concern, and even more so when the language used allows the use of high level language subroutines to control decision making. PATHSIM, as described in Chapter 8 gives a good example of a complete simulation program written using a network approach.

To summarise, the use of network simulation models gives a great deal of additional detail on movement within the system and its configuration, but processing unit detail is not enhanced significantly.

5.7 GENERAL PURPOSE SIMULATION LANGUAGE MODELS

5.7.1 Modular Methods

When it is necessary to proceed to the use of a general purpose simulation language and the unique model that this implies, a modelling strategy should be adapted. For most applications, where similar work has been done previously, a collection of modules of code will be available. Maximum use should be made of these to reduce the quantity of new code required.

At this stage, a general purpose simulation language will be used, thus allowing the model to be developed into as great a degree of detail as required. Initially, a modular approach is usually adopted; with modules covering the executive of the model, input and output, monitoring and statistical blocks being provided by the language used. This approach is the technique suggested by the configuration of several simulation languages [Oren, 1979; Pegden, 1985]. Chapter 7 describes work on pooling strategies using a model built up from a standard language using modular techniques.

5.7.2 Model Development

As the development and concept refinement of the real system takes place, the simulation model develops in parallel. The model builder needs to take great care to avoid unplanned growth of the model as this inevitably makes further changes much more difficult. The model builder needs a detailed and thorough understanding of the real system in order to assess the implications of assumptions. This requirement has severe ramifications for the skills and experience of the personnel required.

It is at this level of modelling that the use of dynamic graphical displays becomes common. As already noted, this facility provides a superb communications tool, but it adds very little to the actual model and the amount of effort given to graphics should be rationed. As the model continually highlights the areas of the system that require more detailed evaluation, it will change and develop towards an emulation model. This route is the most common method of attaining this level of detail, although some emulation models are still built directly.

5.7.3 Emulation Models

This class of model are the ultimate development of the simulation concept as currently applied to manufacturing systems. They are almost inevitably written in a general purpose simulation language and are usually developed from simpler models. They require an enormous input - a model for an average FMS of 8 to 10 processing units can take several man years up to write, contain many thousand statements of code and require access to mainframe computing facilities.

In return for this large investment, these models provide a detailed insight into a complete manufacturing system. This type of model can obviously only be justified when the progress of a project is at an advanced stage, and they can then be used for fine tuning of the system and for the comparison of alternative strategies for dealing with breakdowns, product mix changes, etc.

A properly constructed emulation model will inevitably become very closely involved with the control, scheduling and assignment software logic to be used by the system. An appropriate design of emulation model will allow the executive (or controlling) level of system software to be included within the model [Crookall, 1986]. This model can then be used as a proving ground for this logic. This procedure allows easier location of faults in the control logic and so reduces overall system commissioning times.

Once a system, for which an emulation model has been written is commissioned, then that model should be maintained. This will allow proposed changes to the real system, either in hardware or software, to be evaluated before implementation. The running of an emulation model in parallel with a real system also gives a facility for the trial of the policies to be used in response to a 'crisis' situation as well as providing a training tool for system management personnel.

5.8 POST PLANNING APPLICATIONS

The uses of simulation once a system has been installed are either for assessment of development or an on-line decision support aid. The techniques for the use of simulation when changes are planned are similar to those used when complete systems are being investigated.

The application of simulation as on-line decision support aid is superficially very attractive. The facility to be able to input a changed factor, e.g. a machine breakdown, to a model and see the effects on system performance over a following time would be beneficial. In this way, at least in theory, an optimum response to the changed sets of conditions could be obtained.

Research work has been reported [Chen, 1982] on trials with a decision support system using a simulation model for predictive analysis. This work is based upon an interactive procedure, and field trials have been limited. Initial benefits are that more complex, dynamic scheduling, assignment and control rules can be used effectively. This form of decision support program is an ideal case for the application of 'expert systems' technology, but their present state of development is not adequate for general application.

The most successful assignment programs in current use are based either upon:

- a) Pure human logic and experience.
- b) Rigid application of standard rules.
- c) Computerised Gantt type charts, frequently with an interactive facility [Grant, 1985].

The last is the nearest to the use of simulation concepts, but is still a deterministic model, and so optimistic with respect to breakdown effects etc.

Overall the area of post implementation decision support aids is relatively undeveloped. the requirements, both computer hardware - for quick response; and software - to permit complex situations to be adequately analysed, are in excess of the current levels of that which is commercially viable.

5.9 THE USEFULNESS OF SIMULATION

Simulation provides a powerful method for the analysis of complex systems. However, it is expensive and time consuming so it is crucial that it is used to best effect. There are alternative approaches to the design of advanced manufacturing systems which do not involve the use of any form of simulation model. In a few cases very able engineers have produced successful systems with these conventional planning methods. More typically though this has resulted in systems, like the early ones in the USA, that failed to meet their specifications as a result of inadequate planning [Ingersoll Engineers, 1982].

Once it has been established that simulation is required for a successful project the hierarchical approach described needs to be considered along with the requirements of a model at that stage. There are two main areas of direct use for these models:

- a) Technical analysis of the system.
- b) Communication of the details obtained.

Technical analysis of the system will be discussed later, but the communication aspect should not be neglected. For a manufacturing system to be successful, many people need to be convinced that it provides a workable solution to a set of problems. These usually include - management, who authorise the system; designers, who design the components to be manufactured; and the operators and maintenance personnel who will run it.

Simulation models, especially with the use of dynamic colour graphics, provides an unrivalled facility to explain the operation of the proposed system and allow the instillation of confidence in its correctness. In this regard, simulation provides a uniquely effective communications tool [Elmaraghy, 1982], as well as providing an insurance policy against the system being inadequate, either in facilities, control or for industrial relations reasons. *

5.10 SUMMARY

This chapter has presented a detailed framework for applying simulation, and related planning methods, during the stages of an advanced manufacturing systems project. This 'heirarchy' has been designed to provide a cost effective approach, as well as providing as much useful data as practical at each stage.

The structure of each level and the degree of detail required for it has also been discussed. Finally the use of the models generated has been explained in terms of their use during and after a project, and for dealing with technical problems as well as communicating information.

6.0 SYSTEMS INTEGRATION EFFECTS

6.1 INTRODUCTION

The trends in new manufacturing facilities have forced their planners to consider them as complete, closely coupled systems, rather than as loosely knit collections of individual units. Traditionally, a manufacturing facility would be required to produce a given number of components or assemblies in a given period. The appropriate process planning would be done and the necessary number of processing units of each type calculated by simple arithmetic. This 'system' would then be assumed to meet the functional needs, and no account would be taken of any imbalance due to different set-up times, production batch size differences and other such irregularities. The, usually unstated, assumption was that work in progress would effectively isolate each unit and allow the system to be considered as uncoupled.

The benefits of low work in progress have been often cited [Illingworth, 1985] and will not be repeated here. However, the implications are that there is now a need to assess systems effects resulting from this integration of processing units. In fact the entire focus of Advanced Manufacturing Technology has been driven by low work in progress philosophies, even if this has not been readily apparent. The financial implications of conventional manufacturing systems being modernised would have been impractical. Consider the vast quantities of sophisticated pallets, storage systems, et al that would have been required to hold the levels of work in progress normal in 1960's style machining facilities. Clearly this would not have been allowed, so costs were reduced by fewer pallets, no storage systems, and a consequent need for lower work in progress levels.

This chapter will examine the major types of manufacturing systems, review some of the scheduling and control philosophies used, examine the need for system analysis and outline some of its implications.

6.2 PRODUCTION SYSTEM TYPES

6.2.1 Overview

The often quoted view of manufacturing systems categorises them by variety against quantity, as shown in Figure 1.1 [Haas, 1976]. The range is from the highly automated, high volume, low (or no) variety transfer line to the manual intensive, low volume, high variety job shop shown at opposite corners of the volume/variety spectrum. This type of graph was often used in the early days of FMS to show how they filled the gap between these two extremes.

These three types of production system will be examined in some detail and some of the implications that arise for systems effects will be briefly considered.

6.2.2 Transfer Lines

The transfer line is the basic technology of low unit cost, high quality machined components, providing that the volume is high enough to justify the large capital investment required. It can be compared with the automotive style assembly track, but with one important difference - the transfer line indexes, placing each component in an accurately defined location suitable for processing by automated equipment; the assembly line is a continuously moving track with large tolerances and requiring the adaptive abilities of human operators to process adequately [Driscoll, 1982].

Returning to our original concept of transfer lines as suitable for high volume, low variety production, leads to a definition of low flexibility, however flexibility may be defined. The development of flexible machining systems caused a spurt of developments by the manufacturers of transfer lines incorporating electronic control systems. The main objective of these developments was to improve their flexibility to product development and component engineering changes [Wilson, 1976].

Another disadvantage of transfer lines is their lack of robustness to any form of failure. The breakdown of any one unit means that the complete line has to be shut down. Also the speed of output of the line is governed by the cycle time for the longest operation. Use has been made of sophisticated monitoring techniques to raise transfer line output by locating problems quickly, but efficiency can still be as low as 10% [Yeoh, 1982].

Finally, the lead times for ordering transfer lines are lengthy and their large capital cost is almost independent of the volume required. Despite all of these disadvantages, transfer lines remain popular, especially in the automotive industry, because of the low unit cost of components machined, providing that the volume required is high enough.

6.2.3 Job Shop Manufacturing Facilities

The conventional job shop can most easily be described as the opposite of a transfer line in almost every respect. The most dramatic difference is the variety of routes through the system rather than the single route of a transfer line. This need for high routing flexibility is probably the most significant factor in preventing the automation of this class of system.

However, the disadvantages of transfer lines are reflected in job shops robustness to failure, an incremental cost structure, and an ability to produce a wide variety of different components concurrently. This flexibility is based on the high manual involvement which gives the resultant difficulty of control of such job shop systems.

6.2.4 Flexible Manufacturing Systems

The classic volume against variety graph places flexible manufacturing systems between transfer lines and job shops. As has already been noted, the main characteristic of these systems is their automated handling system allowing far tighter control than more conventional systems at this variety/volume level. A consideration of the other system features shows that flexible manufacturing systems can be thought of as more akin to transfer lines in almost all respects, except flexibility.

The principle characteristic of automated handling is its cost, and so the resultant need to minimise the total component holding. This leads to the reduced work in progress notable of these systems. From this lower work in progress, the imbalance of systems effects develops as the isolating feature of intermediate buffers is removed. Another important feature is the need to minimise the sensitivity of the automated handling system to failure of one section. The use of AGVs is a good example of this, as once the control hardware and guide lines have been proven they are extremely reliable, the vulnerable part of the system, the actual AGVs, can fail individually with minimal impact on the complete system.

Overall, as closely coupled systems, flexible manufacturing systems are subject to the same basic problems as their automated companions, transfer lines. However, the system designer has scope to offset some of these problems by the use of improved system design and control methods [Edghill, 1985].

6.3 SYSTEMS CONTROL PHILOSOPHIES

6.3.1 Overview

As there are several types of manufacturing system, so many methods of controlling these systems have been developed. This section will attempt to outline some of these methods at a high level. The emphasis will be put on the objectives of each philosophy and its effects, rather than attempting to address details of their application. The structure will be by means of the three categories of manufacturing system as identified earlier.

6.3.2 Transfer Lines

To restrict the number of alternatives to be considered, the definition of transfer lines will be expanded, for this section only, to include the closely linked machining lines as used extensively by the automotive industry. These systems share many features with transfer lines, not least of which is that the control strategy is defined at the hardware level and so is inflexible. Processing units are used with certain capabilities and so any alterations are achieved by modification, addition or removal of units.

The obvious method of control is to balance the workload between processing units so that they all have the same cycle time and the system behaves like a true transfer line, perhaps with some limited, and constant, buffers. A modification to this is to reduce the cycle times slightly from start to end of the system. This is an adjustment developed to reduce work in progress by allowing components to flow out of the system faster than they are input. Accordingly, following a breakdown or other failure at a station, the buffer built up somewhere in front of it would progressively be reduced.

Ingersoll Milling Machine Company use a balancing technique known as "The Hour Glass Theory" and originally applied to true transfer lines only. This is based upon consideration of the technology of the processes involved at various stages of metal component production. Broadly, the theory states that the central stages of a manufacturing sequence e.g. drill and tap, should have a longer cycle time than initial stages, e.g. rough machine, or final stages, e.g. finish machine. This is justified by the central stages requiring less maintenance and producing less scrap. Accordingly, the output of good components from the system will be maximised [Droy, 1977]. The methods are compared graphically in Figure 6.1.

Research based upon queuing network theory, and discussed in more detail in Chapter 7, suggested that work content should be based upon the number of processing units dedicated to that task (pool size). The larger pools should be relatively more highly loaded than smaller ones. This method is based upon the analysis of complete systems and so is an attempt to consider some "systems effects" [Stecke, 1984].

6.3.3 Job Shop Manufacturing Facilities

The systems used to control this class of facility are paperwork ones to direct the actions of manual operators. They can be very flexible when this is required, but suffer from the usual failings of manual systems. At least four main philosophies can be identified.

Queue manipulation methods are the conventional approach and rely on various techniques to choose the next component or batch of components from the queue in front of a processing unit. They rely on there always being a queue somewhere in the system from which control can be exercised [Blackstone, 1982]. This will be the case, except for a facility in perfect balance or with large excess capacity. Various enhancements to this class of technique include batch splitting options and preemption of a processing unit to process a more urgent batch.

Materials Requirements Planning (MRP) can be described as an advance planning system for the manufacturing facility. From a bill of materials for each completed product, it works backwards through sub-assemblies to individual components. It then calculates when the input raw materials or unmachined components need to be delivered by, allowing for various constraints such as those imposed by capacity limitations at particular processing stations. MRP represented a great step forward, but has implementation difficulties mainly due to the volume of precise data needed.

Just in Time (JIT) and KANBAN (meaning card in Japanese) are related philosophies developed in Japan for higher volume production systems. JIT especially is based upon common sense flow principles and has been claimed to have originated at many early production facilities, e.g. Ford Motor Company's River Rouge plant [Iacocca, 1985]. The essence of this approach is to control and limit unproductive work in progress.

Optimised Production Technology (OPT) is both a control philosophy and a computerised control package which aims to implement that philosophy. The philosophy is based upon determination of a bottleneck and the scheduling of work through it, whilst restricting the production of the other processing units to the levels that the bottleneck processing unit can handle [Goldratt, 1985]. Some excellent results have been reported where this technique has been used [Haylett, 1986].

The choice of philosophy depends upon the type of facility and the production requirements. Sophisticated computer based methods must be regarded in the light of the need for them to be implemented and used by manual controls and actions.

6.3.4 Flexible Manufacturing Systems

These systems again fit between job shops and transfer lines. They have control philosophies defined at the software level and so have the scope to be very flexible indeed. All of the techniques described under job shops have been applied to FMS along with many others [Buzacott, 1980]. The first FMS had complex control systems developed either by an iterative approach on the installed equipment, by a similar approach using a simulation model, or by a combination of these. Later systems built on experience and used more sophisticated simulation models to greatly reduce commissioning times.

Overall, although the usefulness of philosophies and experience should not be underestimated, the usual solution to FMS scheduling and control problems will be system specific. Some general conclusions can be drawn - these systems are usually operated on a low work in progress basis, with generally First In, First Out workflow through each processing unit. The aims are usually defined in total system terms, rather than by individual processing unit, and work allocation to the system are used to maintain its overall utilisation. The systems are also usually controlled on a dynamic basis with decisions such as which processing unit to allocate a component to, being deferred until the latest possible time. This relies upon the extensive use of computer based monitoring and control.

6.4 SYSTEMS THEORY AND INTEGRATION EFFECTS

The need for a system based approach to the study of manufacturing systems in general is now known. An excellent and detailed, if informal, treatment has been published and widely noted [Goldratt, 1985]. A simpler example, which highlights the major feature of systems effects, is given as Appendix A. As will be appreciated, the use of lower levels of work in progress has removed the isolation of each processing unit and so idle time can occur due to congestion and/or starvation effects.

An analysis of a FMS built by Renault at Boutheon in France [Arnaud, 1986] showed that the expected effect of increased output from increased batch sizes was not obtained, but that a definite optimum batch size existed, as shown in Figure 6.2. The same type of analysis applied to another flexible machining facility within Renault showed the different results obtained from the different analysis techniques, see Figure 6.3, a factor that will be discussed in more detail in Chapter 7.

The recognition of these types of effects has led to the investigation of manufacturing facilities by system control methods [Cresswell, 1987]. Some useful and interesting results have been obtained, as shown by Figure 6.4, where transient effects as occur within control systems are obtained. So far this work is at an early stage and no details of practical application are available.

The need to study the flow of components within manufacturing facilities has been apparent as the method to minimise systems effects [Nof, 1983]. Due to the complexity of Advanced Manufacturing Systems, simulation is currently the only planning tool to study these effects and so reduce their impact.

6.5 CONCLUSIONS

The perception of flexible manufacturing systems as the medium volume, medium variety solution to manufacturing needs is confirmed by analysis of the other main types of production systems - transfer lines and job shops. Analysis of the control philosophies adopted for these three types of manufacturing system has highlighted the combination of variety and automated system problems that a FMS provides.

This uniquely challenging feature of FMS planning is augmented by their integrated nature which gives rise to the system effects. This means that FMS must be dealt with as complete systems, and by tools of adequate capability. The errors that can result from misuse of certain tools have been mentioned and will be explored in greater detail in Chapter 7.

7.0 THE POOLING OF PROCESSING UNITS

7.1 INTRODUCTION

The work described in this chapter was chronologically the first to be undertaken and had two objectives. The first was to analyse the pooling concept and the second to compare and contrast the analysis tools used, so as to obtain information on their respective strengths and weaknesses for use when these tools were used for future sections of work.

This first objective addressed one of the fundamental system design parameters for manufacturing systems - that of the functional grouping or pooling of processing units. This is quite simply the grouping together of processing units performing the same set of operations on the same set of components, such that any processing unit in the pool may be selected equally as to any other. The technique has been extensively used for conventional automated systems, typically for gear production in the automotive industry.

When successive processing stages for a component are amalgamated or processing units are given additional capability, there will be a cost penalty. This can range from extra tooling or fixtures to the need for larger or more complex processing units. Accordingly there is a trade-off between the potential benefits to be gained from pooling and the additional costs involved.

The pooling concept was investigated by applying it to a specific, if not untypical, manufacturing system. This work was performed by the use and comparison of three modelling techniques - static workload analysis, a queuing network model, and a simulation model. The use of these different methods satisfied the second objective, that of their comparison.

7.2 DEFINITION OF THE POOLING PROBLEM

The concept of pooling is best explained using the example of machining centres. If several machining centres are provided with equivalent tooling then they can process the same set of operations on the same set of components. Other machining centres, of the same type, with a different set of tooling do not have the same capability. The first group of machines are defined as being pooled whilst the others are not.

The extensive use of machining centres and other flexible processing units within FMS has complicated the organisational aspects of pooling. This is due to two factors:

1. The ability to allocate the separate operations within a production route in more than one way, due to the capability of modern processing units to undertake work previously requiring two or more different types of machine.
2. The capability to move operations between processing units, not merely within a pool, but also between pools on either a temporary or permanent basis. The classic example of this capability is shown by machining centres which can produce any component for which they are provided with tools and fixtures. However, their capability can quickly be changed or extended by the addition or substitution of other tools and/or fixtures.

Intuitively, pooling appears to be beneficial and the larger the pooled groups the better. However, these organisational benefits are offset by certain technical and/or financial limitations which place an upper limit on pool sizes in any given situation. The advantages of pooling are that:

- a) Reduced variability in waiting time at multi-server stations as compared to single server ones [Stecke, 1981].
- b) The duplication of equipment reduces the effects of the failure of any one unit.
- c) When, as is usual, the number of stages in a process sequence is reduced by combining subsequent operations, then there is a reduced total load on the materials handling system.

To balance these advantages, pooling also requires:

- a) An increase in the capability of certain processing units. This may be confined to additional tooling, but may extend to additional fixtures, or even to a need for a different type of machine tool.
- b) Changes in the levels of work in progress buffering needed.
- c) Changes to the control and scheduling rules used by the materials handling system.

7.3 LOADING STRATEGIES

Conventional machining methods are based on the use of functionally dedicated processing units such as drilling machines, vertical and horizontal milling machines. At the most basic level process planning is dictated by the type of process required. The use of processing units with multi-process capabilities has added flexibility to this stage of planning in that operations can be moved between operational stages. This has further given a capability to control the level of loading of processing units in a system. In terms of pooling, this control allows pooling sizes to be adjusted at the design stage of a system without affecting the qualitative functional capability of that system.

Balance is the traditional loading strategy. The objective is to achieve, in the limit, maximum output with a uniform and high level of processing unit utilisation [Stecke, 1983]. Following the balance theory, process planning for flexible manufacturing systems uses this additional flexibility to balance out the target utilisation of all processing units. This level of utilisation is set high so as to minimise the number of processing units needed.

Two alternative types of loading strategy have been suggested to exploit the increased flexibility. These are:

- a) Organisationally directed approaches.
- b) Functionally directed approaches.

Organisationally directed approaches attempt to modify the relative loading of processing units to take advantage of system features. Usually the objective is to maximise output. The adjustment of loading in proportion to pool size, [Stecke, 1984] is an example of this approach.

With conventional systems using pooling, and thus implied large buffers, line balancing led to pool sizes being inversely proportional to processing times. Work using queuing network concepts has indicated that larger pools should be given a higher utilisation level than smaller pools.

In contrast, functionally directed approaches attempt to modify the relative loading according to the functional capability of the process involved. In other words, this method takes into account the expected level of breakdowns and other interruptions, and modifies the target utilisation to balance out these factors. This approach was initially applied to transfer lines [Droy, 1977].

Both of the types of approach detailed above may well have serious limitations, although these do not affect the basic validity of the concepts. These possible limitations arise from the techniques that have been used for analysis. Some details of these limitations are mentioned below.

7.4 THE TARGET MANUFACTURING SYSTEM

The manufacturing system used as the vehicle for this set of work was proposed as a solution to an expanding demand for certain types of prismatic component within part of the then BL group. The original layout is given as Figure 7.1 and, as can be seen, consists of a number of processing units served by a single uni-directional conveyor. There were 11 CNC machining centres, with manual load, unload and turnover stations. Each processing station was provided with a 4 station rotary table, which was intended to provide limited buffering to smooth out irregularities caused by the transport system, as well as by the breakdown of other processing units.

This type of arrangement is increasingly being used for FMS type systems where higher volume production is desired. Each processing unit can be considered as a 'cell' with its own limited buffering space and separate controller responding to higher level instructions from a central system computer.

The system was intended to machine three families of castings, which were required in approximately equal quantities. All components within each family required the same set of operations in the same order as others in that family. In practice, although the operational times within a family were anticipated to differ slightly, these variations were neglected. This assumption also simplified the model slightly.

Although the system was analysed without consideration of tooling constraints, these meant that pooling limited to machines 7 to 11 only would not require any increase in the capacity of the machine to tool magazines, but some increase in machine controller memory would be needed for a non DNC solution. To pool machines 1 to 4 would need an increase in tool magazine capacity, and total pooling of machines 1 to 6 would imply a large increase in this parameter. The cost and additional control complexity of these measures would have to be considered in the light of any extra output and flexibility obtained.

7.5 METHODS OF ANALYSIS

The techniques used were those usually used for the analysis of manufacturing systems. The same data was used throughout, although some tools only required a subset.

7.5.1 The Workload Model

This model is a conventional static analysis of the workload for each processing unit, based upon an even distribution of the required components. The model assumes that the utilisation of processing units within each pool is uniform. The only information needed for this model is the available hours for each processing unit and the component processing times.

The output calculated by this technique is the maximum possible, whilst the lead times are the minima. These calculations are based solely on the bottleneck pool of processing units and do not include any allowance for queuing or any other waiting times.

The workload model gives figures for comparison with those obtained from other models by providing definite 'best case' results. It is not a good model for the establishment of system performance measures due to the unrealistic assumptions made about component waiting times.

7.5.2 The Queuing Network Model

The second type of model used was a closed queuing network, using the package CAN/Q. This package models the workflow in the system as a network of queues.

This type of model is governed by the level of work in progress and so the system was modelled with several different levels for the maximum work in progress permitted. Materials handling is based upon discrete units and so a large number of these units was specified in order to model the high capacity of a conveyor system and so avoid any queuing for transport.

The results obtained from this model should compare well with the workload model for overall output and minimum lead times, but should provide more detail on lead time variation and on work in progress levels.

7.5.3 The Simulation Model

As this section of work was the first undertaken, it took place during the early and middle phases of the 'learning curve'. However, due to the basic techniques used, it provided a useful insight into the structure and facilities of the more sophisticated languages used later.

Previous work carried out for BL Technology [Hallstron, 1981] had established the potential for the use of micro-computers, despite their limited processing power, for the analysis of manufacturing systems using relatively simple simulation methods. Although limited memory and processing power were major disadvantages, especially with the most popular micro-computer being the CBM PET series, with only 32kB memory and based on the Motorola 6502 micro-processor, these problems were balanced by the advantages of the availability of this equipment, its powerful software environment and single user configuration.

The micro-computer used for this phase of the work was a CBM PET, with 32kB of RAM, and the usual peripherals of twin disc drives and printer. The model itself represented an attempt to code a simulation model in the BASIC general purpose computing language, rather than use an existing simulation language. This approach was taken to establish an understanding of the operation of the executive section of a simulation model. This section is usually provided by the simulation language. The time penalties imposed on the development of the model by this approach exceeded those anticipated.

The structure of the model was a rather unusual two phase one. The time advance is followed by a single processing phase, meaning that the ordering of activities is central to the correct operation of the model. This has the benefit of reducing the total amount of processing at each time beat. A description of the model can be found in Appendix B.

The use of a first generation micro-computer imposed constraints upon the complexity of the simulation model. An obvious alternative would have been to use a compiled language, or a machine code program rather than interpreted BASIC. These were both rejected due to the developmental nature of the model, and the consequent frequent alterations needed.

At later stages the model was transferred to Cranfield's Digital Equipment Corporation VAX computer using a compiled version of BASIC running under the VMS operating system. This transfer greatly speeded up the experimental section of using this model.

This model made certain broad assumptions, including neglecting breakdowns of processing units, conveyor congestion, and providing a fixed input schedule. The original model was thus completely deterministic, rather than a true simulation. This approach permitted easier comparison of alternative pooling configurations.

7.6 EXPERIMENTAL PROGRAMME

The experimental programme covered the analysis of six different pooling alternatives, ranging from the original proposal to a system with two pools only, one before and one following the manual turnover station. Briefly, the alternative layouts were:

- Level A - This was the system as originally proposed, using machines pooled into groups of 2 and 3. See Figure 7.1.
- Level B - The five machines following the turnover station were pooled together. See Figure 7.2.
- Level C - The first four machines only were pooled together. See Figure 7.3.
- Level D - This was a combination of the pooling arrangements as at Levels B and C, giving three groups of four, two and five machines respectively. See Figure 7.4.
- Level E - The first six machines, all those prior to the turnover station, were grouped together. See Figure 7.5.
- Level F - This is the final pooling, a combination of Levels B and E, giving two groups only, one on each side of the turnover station. See Figure 7.6.

As previously noted, Level B could be achieved with only limited extra tooling over Level A. Levels C and D would need both larger tool magazines and considerable numbers of additional tools. Levels E and F were considered to be almost impossible to achieve in practice, due to the sizes of the tool magazines that would have been required. Subsequently it has become apparent that automated tool handling would provide an ideal solution if this level of pooling was required.

Each pooling option that amalgamated consecutive operations together also reduced the total cycle time for the components affected. This was due to a reduced number of machine visits cutting the number of clampings and unclampings needed. This adjustment gave, at least theoretically, a further advantage in overall output to the Levels using larger pools.

For both static analysis and queuing network models, a unique solution is produced for each set of data. Both these classes of model are thus deterministic mathematical models, which simulation models are not. For this comparison, the simulation model used was deterministic and so also gave a unique set of results for each set of data. This allowed direct comparisons to be made between the three models.

7.7 RESULTS

7.7.1 The Workload Model

These results, as shown in Figure 7.7, were a step increase from 1190 components per week at Levels A and B, through 1210 components per week at Levels C and D, 1263 components per week at Level E and finally 1287 at Level F. This represents an increase of 8% from Level A to Level F.

As the level of pooling changed, the bottleneck station changed also; each change being caused by the bottleneck machine group being merged with another less heavily loaded one.

The lead times were marginally reduced as the level of pooling was increased. This was solely due to the reduction in the unproductive element of processing unit time. Typical lead times were in the order of 33 to 34 minutes, a not significant change of about 3% between the different levels of pooling.

It should be emphasised that the figures obtained from this model are the best that can be achieved under theoretically perfect conditions and serve only as a vehicle for comparison with the results obtained from other methods. However, they indicate that there are considerable benefits to be gained by the use of the higher levels of pooling.

7.7.2 The Queuing Network Model

The results from this model were typical of this type of model with both the output and lead time against work in progress level curves showing their characteristic profile. Each of the six levels of pooling yielded progressively increasing output as the work in progress was allowed to increase. Figure 7.8 shows the results for output and the corresponding lead times.

The initial work in progress was estimated at 21 using the empirical rule of "work in progress equals number of processing stations plus 50%". The queuing network model was studied for work in progress levels of 10, 21 and 42. As noted previously, the later stages of pooling had slightly reduced total cycle times as operations were combined. Figure 7.9 shows the theoretical maximum, to be obtained with infinite work in progress and compares this with the output actually obtained for each level of work in progress. As can be seen, the estimated level of work in progress gave approximately 80% of the maximum outputs. However, to fully support these theoretical maxima, work in progress levels of 100 to 120 were predicted. The output maxima predicted were similar to those from the workload model.

The predicted output rose significantly, at every level of work in progress, as pool sizes were increased. The final grouping of machines into two groups gave an increase in output of some 8% over the original configuration, with higher gains at lower levels of work in progress.

The lead times predicted rose as the work in progress level rose. A significant difference occurred between the different levels of pooling, times for Level A being up to 15% greater than those for Level F. At lower work in progress levels, lead times were less than the minima calculated by the workload model, a theoretically impossible set of results. See Figure 7.10.

Summarising the results from the queuing network model, the use of pools is beneficial and the larger the size of the pools the better. Significant increases in output are obtained together with additional benefits in reduced lead times. However, the level of work in progress required is an order of magnitude higher than expected. To what extent these findings are reasonable, and how they are affected by the underlying assumptions of queuing networks will be discussed later.

7.7.3 The Simulation Model

One of the main benefits of a simulation model is that a great quantity of information can be obtained allowing specific aspects of a system to be investigated in detail. This evaluation was confined to the basic performance measures in order to allow comparison with the other methods used.

The lowest level of pooling gave output steadily rising as the work in progress level was increased, until output stabilised at a work in progress level of 24. Any further increase in work in progress merely extended lead times, as shown in Figures 7.11 and 7.12.

The pooling of all the machines following the turnover station (Level B) did not improve output nor significantly affect lead times. The subsequent levels of pooling gave reduced output, even when almost unlimited levels of work in progress were allowed. Figure 7.13 shows these results, which show a trend that is the exact opposite of that predicted by both the workload and queuing network models.

7.8 DISCUSSION OF RESULTS

The detailed analysis of any single system such as the one described in this chapter has to be regarded with care during any attempt to generalise the results obtained. However the comparison between the various results should be more useful.

For the lowest levels of pooling, all three analysis techniques - static workload, queuing network and simulation - gave very similar results for output. However the simulation model indicated a much lower level of work in progress than suggested by the queuing network model. The lead time predictions from the queuing network model were not reflected in the results from the simulation model, which were much closer to the minima obtained from the workload model. These two factors, work in progress and lead times, are central to the justification and operation of Advanced Manufacturing Technology and so the variation in results is especially interesting.

At the higher levels of pooling, the differences between the queuing network and simulation models become more marked. The queuing network model gives the expected increase in output, at the expense of extended lead times, as the level of work in progress is increased. There are also significant benefits obtained from the higher levels of pooling. The simulation model shows no noticeable benefits of larger pools, indeed output is reduced and lead times remain largely static.

As the results trends obtained from the simulation model were the opposite of those both expected and predicted by the queuing network model, the operation of the simulation model was analysed to ascertain what was happening. It was found that the level of buffering was inadequate to balance out the control and scheduling problems. As a relatively simple set of control algorithms was used, it is likely that a more complex set would improve the performance of the system. This would change the balance of comparison towards favouring larger pools. It is also worth noting that the use of larger pools is often suggested as an aid to reducing the need for complex scheduling. The results from this model do not support that approach, and further suggest that for certain systems with low buffering levels, the usual assumptions about larger pools may not be valid.

The results from the simulation model have been used as the base for comparison of the other techniques. This is because this type of model can be verified by studying its behaviour at discrete time slices and comparing this with the actions and outputs with those anticipated for a real system.

The use of deterministic workload analysis is based upon the crucial assumption that workpiece transport can be neglected, or at least merely given a single finite capacity. Short term fluctuations in workload, both on the transport system and on processing units are neglected. These steps lead to the consequential assumption that (effectively) limitless buffering capacity is available to balance out these irregularities. Another feature is that lead times cannot be determined, even approximately, as waiting times are ignored. These well known limitations of static analysis were supported from the comparison of the results from the workload and the other models.

From the results obtained, the use of queuing network models applied to manufacturing systems with low work in progress can give misleading results. This is due to the exposure of the flawed assumptions made by these models. The most fundamental of these is the assumption that service times are exponentially distributed; clearly not the case for the majority of manufacturing systems. Specifically, the model CAN/Q, although geared to advanced manufacturing systems, uses these queuing network theory assumptions and so is most suitable for traditional production flow techniques. These considerations, as well as the results from the use of CAN/Q, lead to the conclusion that this type of model needs to be used very carefully when applied to advanced manufacturing systems. However, the advantages of this class of model means that they still have considerable utility in the earlier stages of planning.

7.9 COMMENTS AND CONCLUSIONS

Considering the twin objectives of this chapter, and taking the investigation of the pooling problem first, it has been shown that the results obtained are not independent of the analysis tool or technique used. This is as was expected and is central to the use of the hierarchy of the analysis that has been detailed in Chapter 5.

Traditional production engineering practice, backed up by some theoretical work supports pooling. Additionally, there is an intuitive basis towards larger and balanced pools, although this tendency is constrained by the additional costs involved. The work described in this chapter does not universally support these presumptions. The most general result is that every system needs to be examined individually at the latter stages of planning.

Much previous work on the organisational benefits of different pooling configurations has used queuing network models. The validity of these general results must be questioned in the light of the shortcomings of this class of model highlighted in this chapter. The crucial parameter appears to be work in progress levels, where these are high, the assumptions of queuing network theory are valid, low work in progress exposes the latent difficulties and resulting inaccuracies.

The second objective was to examine and evaluate the analysis tools. In this area the work in this chapter supports that described earlier - the simpler and quicker techniques of static analysis and queuing network models providing good indications of the results subsequently obtained from the more sophisticated simulation models. Over use of the simpler methods, such as the analysis before and after detail changes to system parameters, exposed their limitations. This highlighted the need to choose the correct tool for the level of detail required at each planning stage.

8.0 AUTOMATIC TOOL HANDLING AND ITS APPLICATION

8.1 PREAMBLE

This chapter describes work carried out during a period of research at Purdue University, West Lafayette, Indiana, United States of America. The research project was carried out jointly between Mr. G.D. Crite, a post graduate research worker at Purdue, and the author, under the supervision of Professor J.J. Talavage.

8.2 INTRODUCTION

Automated Tool Handling (ATH) will be defined as the use of a tool transport system, together with some form of tool magazine and exchanger at each processing unit. This allows the unmanned movement of tools around the system, including some form of tool warehouse and servicing area. The magazine at each processing unit serves as a buffer to even out the demand on the transport system.

The use of ATH has been considered as part of advanced machining systems since Molins System 24 [Williamson, 1967A, 1967B]. Since then technical improvements have changed the level of practicality until there are no technical difficulties in providing ATH for prismatic parts machining systems [Zelany, 1981]. The use of turning machines with automatic tool changers is becoming more common, thus allowing the use of ATH with these systems also.

Basic ATH concepts, as investigated in the work described here, can also be applied to non-machining systems which require the use of alternative 'tooling' units. These can include reusable magazines for assembly systems or even assembly jigs for multi-component assembly stations.

This investigation of ATH had two objectives - to establish the basic trade-offs between the benefits of ATH and the extra cost and complexity incurred, and to compare a selection of operational parameters for the ATH sub-system to establish their effect on total system performance. This work was performed by the construction and use of a generalised simulation model of this class of system.

8.3 THE BENEFITS OF AUTOMATIC TOOL HANDLING

As noted, ATH has been considered for many years. The requirement for this increased level of complexity of tool handling, whilst retaining effective tool control, has occurred due to the development of flexible machining concepts. As such systems are usually based on machining centres, they require tools to be changed periodically. However, unlike a transfer line where tool change times can be predicted, in a FMS environment, they are dependent upon so many factors that they are almost random. These factors include tool breakage and wear out (as in a conventional system), a change of part type, or a change of the NC program in use at a particular processing unit.

The benefits of ATH are a reduction of manual involvement and so reduced opportunity for variation in performance. This equates to fewer incorrect tool movements and a lower labour requirement [Aldred, 1982]. A reduction in the total tool inventory and a greater capacity for unattended operation are other significant benefits.

The major disadvantage, apart from the additional capital cost, is that total system performance could be impaired due to the automated system being unable to deliver tools as they are required. This would result in reduced utilization of the processing units.

8.4 DEVELOPMENT OF THE ANALYSIS

Published research work on the simulation of ATH systems is sparse. Work has been done at Cranfield on the operational strategies to be used for the movement of tools within layers of tool magazines [Kay, 1982]. This currently assumes a dedicated transport system for each link, and is intended for the analysis of situations where one or more magazines at the processing units are supplemented by a secondary level magazine. It does not consider the aspects of the interrelationships between the two handling systems.

Although the nature of any ATH system will be dependent upon the application, an initial framework for the analysis of these systems had been produced [Muller, 1983]. This had established the basic parameters for the use of simulation modelling methods in this context. The main features of this work were the advantages of the modular approach and a comprehensive analysis of the data requirements for each module. A case for the use of simulation as a vehicle for analysis was also given, based on the impracticality of either analytical techniques or full scale modelling for this purpose.

When real tool handling systems are considered, the most popular technique is the use of separate systems for tool and part handling. This approach provides a degree of decoupling between the two handling functions and so avoids the need for decisions between the relative priority of a tool movement and a component movement. The other method of automating tool movement is to use a common handling system. As well as being obviously more complex, this does not match the operational characteristics of the handling equipment to the differing demands of movements required by tools and components. For these reasons, the first approach of separate handling systems was used.

8.5 THE MODELLING APPROACH

8.5.1 Alternative Approaches

Three strategies were available to study the effects of tool movement, in order of reducing generality, these were:

- a) To develop a static analysis of the dynamic situation, using a queuing network model, e.g. are based upon CAN/Q [Solberg, 1980A].
- b) To develop a model adaptable to many system configurations, i.e. a generalised simulator akin to GCMS [Lenz, 1977].
- c) To study a specific system and add to it a tool movement sub-system. Obviously the development of more general conclusions upon this base would be subjective.

The third alternative was quickly rejected due to its lack of generality and its lack of significant advantages over the second approach.

The first alternative was investigated in considerable depth. CAN/Q has proved to be a very successful tool, both academically [Stecke, 1981] and industrially [e.g. Shale, 1986]. Despite the far reaching assumptions made by this model, in order to fit a simplistic queuing framework, it has the advantages of extremely fast response, coupled with a high degree of accuracy for the major performance measures. Additionally, its results are not clouded by the effects of random variants as are simulation model results.

Accordingly, a detailed specification for the use of two queuing networks, one for tools and one for components, was drawn up. These networks were to be mutually interacting and so provide a simple, robust analysis. The fatal flaw in this argument is the dynamic interaction between the two networks, an essential area if correct influences upon the processing units are to be obtained. In conclusion, the best that could be achieved was to use one network to obtain an average delay factor to weight to results from the other. This is clearly far too subjective an approach as it totally neglects interactions between items in each network.

The choice was therefore made upon the use of a generalised simulation model, to incorporate as high a degree of generality as possible within the constraints of program size and timescale. An adaptation of GCMS was considered, as this model already contains a basis for the addition of a tool movement system. This was rejected due to:

- a) Large size of GCMS coupled with a constraint on program size imposed by the use of the Purdue University CDC 6600 computer.
- b) The high degree of redundancy of facilities provided by GCMS and the corresponding adverse effects upon execution times and experimental design.
- c) The development of more advanced simulation concepts, especially network modelling constraints. GCMS is based upon GASP IV [Pritsker, 1974], which has been largely replaced by SLAM [Pritsker, 1977]. SLAM allows full use of network modelling, a feature not supported by GASP IV. This permits greatly simplified constructs to be specified, by using a set of symbols to represent network operations.

This process led to the route that was followed - the construction and use of a new generalised simulator largely written with the network modelling constructs provided by SLAM. This model was to use a modular approach and to allow these to be assembled to represent a variety of real world systems. Also, the use of different operating parameters could be included. The acronym used, PATHSIM, is derived from Part and Automatic Tool Handling SIMulation.

8.5.2 Modelling Assumptions

One of the major modelling assumptions has already been discussed, the use of a modular technique where the differences between processing units are restricted to those defined by a restricted set of data parameters. This greatly simplifies model construction, at some cost in processing efficiency, and with very little loss of generality.

A series of assumptions regarding tools, and their use for any given component(s), was made. The major one is that "tool kits" rather than individual tools are considered. A tool kit is the set of tools required to process one component type for one operation at one type of processing station.

The processing of a component cannot start until the required tool kit, as well as the component, are together at an appropriate station. The assumption that tools are moved in complete kits reduces the volume and complexity of the records that have to be maintained. It does not have any effect upon the number of cart movements required, as at least one tool, the tool 'controlling' that movement, would have to have been moved even if tools were being considered individually.

The use of tool kits also simplifies the consideration of regrinding. A tool kit will contain a variety of tools with varying regrinding complexity. It therefore follows, from the central limits theorem, that the variation of total regrinding time for a tool kit will be low. Accordingly, the model assumes a standard regrinding time per tool kit type.

The concept of two separate handling systems, one each for components and tools, is extended to their control and scheduling. These are totally independent, any tactical (short term) benefits of integration being assumed to be balanced out by strategic (long term) added complexity and confusion.

8.6 CONSTRUCTION OF THE MODEL

8.6.1 Description

The model developed during this section of the work consisted of a SLAM network, made up of four types of module, and controlling subroutines. The network as used for the experiments is shown in Figure 8.1, and the modules in Figures 8.2 - 8.5. The flexibility of the modular approach is shown by the alternative layout in Figure 8.6. To change between these layouts is purely by alterations to the data file. A functional description of the model to subroutine level is given as Appendix C and the structure of the data file in Appendix D.

Basic operation of the system is that components are introduced at the load station and are then moved to processing units by the component carts. At a processing unit components are processed if, and only if, the appropriate tool kit representing the tools required for that component is available. Once a component has been assigned to a processing unit it is not rescheduled even if its selected processing unit becomes unavailable.

After the component has completed all its processing operations, it is moved to the unload station where it is removed from the system. Tools remaining in the system are considered 'worn' after having processed a set number of components, and are moved to the tool warehouse where they are reground and stored for movement back to an appropriate processing unit.

8.6.2 Selection of System Characteristics

The system used as the vehicle for the experimentation was based on a moderate volume machining facility with a relatively high level of flexibility. This is the type of facility central to the work described in this thesis. The system was actually designed for the production of a series of small families of components, and is typical of systems being installed in the automotive and related industries.

The data used was obtained from a feasibility study for a system to produce large automotive components, and, as such, it is not merely arbitrary. Within this class of system the individual priorities of components are not important, only the priority of component types.

Accordingly, the heuristics used were to pool machines into the largest groups possible, constrained by tool magazine sizes; and to progressively reduce the work content of successive operations slightly, i.e. first operation groups have a slightly higher workload than second operation groups, and so on. Further discussion of these strategies and their application will be found in Chapter 6. More detailed information on algorithm choice for the PATHSIM model is given in Appendix E.

The introduction of the system was planned to be on a staged basis, and an automated tool handling system was to be part of the final stage. However, a change in product strategy altered the need for the components for which the system was intended. Accordingly it was never built.

8.6.3 Model Development

The model was developed on the Purdue University CDC 6600 computer facility, accessed in a batch mode through a DEC VAX 11/780. The VAX was used for editing and program setting up operations. The model was developed progressively, a two machine network being debugged initially and additional modules being added until the full network was operational. The final stage replaced the default subroutines provided by SLAM.

This approach proved to be extremely successful with both logical and coding errors being quickly detected. Only one significant logical change was made, dealing with the cart initiated scheduling rule.

8.6.4 System Parameters

For almost all purposes the factors affecting the performance of the modelled ATH system can be divided into two groups - those considered as experimental variables, and those that were kept constant so as to remove them as sources of variation. Taking this latter group first, the following were not considered by the model as variable parameters:

- a) Assignment of operations to machines. This is obtained from the system data. Any complex variations used to obtain better performance are unlikely to affect system operation, unless extremely unbalanced assignments are used with a corresponding unbalance of tool change requirements.
- b) Control and scheduling of the component materials handling. This will not affect ATH performance directly, but some indirect effects could be anticipated.
- c) Variation in tool regrinding time. As previously noted, these times are assumed to be sensibly constant.
- d) The use of tools for more than one component type. This is ignored, any reduction in total tool inventory would be balanced by additional handling complexity. The model could easily be adapted to assess these effects.
- e) Anticipatory type tool change algorithms. These algorithms hold considerable promise for improved tool control, and reduced processing unit idle times.
- f) Tool handling system control and scheduling algorithms. To assess the effect of alternative algorithms would require an extensive programme of work, as differences would be difficult to isolate.

Many of the above parameters are considered elsewhere in this thesis, although not in the specific context of ATH systems. The experimental variables considered were in line with the overall objective of considering the additional compromises caused by the use of ATH, and to initially assess some of the major operational parameters of ATH sub-systems. Accordingly, the following were varied:

- a) The number and speed of the tool carts.
- b) The number of tool kits of each type in the system.
- c) The tool kit regrinding time and the level of priority given to each tool kit type in the regrinding queue.

- d) Part input strategies, in terms of batch sizes, component type mix and frequency of arrival.
- e) The existence of component types with higher priority, and the extension of this priority to its associated tool types.

These factors are not independent and do not, by any means, represent all the variables that could be considered. However, they are the major factors considered to have fundamental effects on system performance.

8.7 USE OF THE MODEL

8.7.1 Assessment of System Performance

The assessment of the operational efficiency of any manufacturing system is by regard to performance measures. The measures that are selected can influence the assessment, and will depend upon the requirements for which the system has been designed.

The performance measures collected from the model were extensive, comprising:

Total system performance:

- Throughput times, overall and by component type.
- Production rate, overall and by component type.

Machine performance:

- Utilisation.
- Non productive time, split by breakdown, tool shortage, and component shortage.
- Machine buffer queue length.

Materials handling:

- Loaded, assigned and idle percentages for each cart type.

In the actual assessment of performance, only production rates and throughput times were significant. In the absence of graphical output, the only method of establishing the cause of poor performance was the other measures. These allowed the robustness of the system to change in certain factors to be assessed.

8.7.2 Preliminary Analysis

As the objective of the model was to study the effect of ATH, it was necessary that a set of parameters for the component handling sub-system be established. This was needed to isolate the effects of the tool handling from the component handling to as high a degree as practical, by providing more than adequate component handling capacity.

For this preliminary analysis use was made of the queuing network model CAN/Q [Solberg, 1980A]. The parameters established from this analysis comprised the number and speed of the component carts, together with the work in progress levels required to sustain near theoretical maximum levels of production. From this, it was assumed that the tool carts were of similar speed to the component ones.

8.7.3 Experimental Procedure

The first run of the complete PATHSIM simulator was a long run with periodic "snapshot" report and results generation. This allowed the point at which the system began to show steady state behaviour to be established. This allowed run in and duration periods to be fixed so that realistic length runs with adequate statistical integrity can then be made for minimum use of computer resources.

The use of the above technique does not remove the need for parallel runs with different random number seeds. However, it does reduce the need for this duplication, allowing its use to be concentrated where small differences in output information are observed.

8.8 RESULTS

Seven main sets of experiments were carried out, aimed at establishing basic operational parameters for the system under study and to what extent it is reasonable to generalise these results.

The first set of experiments concerned the number of tool carts. The results are shown in Figure 8.7. These show, as would be expected, that production increased as the number of carts was increased. The rate of this increase reduced as more carts were added. The effect upon average throughput times was negligible, showing an absence of cart congestion. The number of carts thus established to give maximum production was used as the "base case" for future comparisons.

Second, the conjecture that a reduction in the number of tool carts could be achieved by increasing their speed was tested. This conjecture was supported by the results as shown in Figure 8.8, within a narrow band around an optimal cart speed. Component throughput times increased sharply with low cart speeds.

The tool kits available to the system form another potential constraint. To analyse this effect, the number of tool kits of all types was varied. The results, shown in Figure 8.9, show the diminishing effect of adding additional kits.

Obviously not all tool kits are crucial to system operation. To identify the critical tool types, defined as those kits where any reduction in their number causes a significant adverse effect upon total system performance, a series of experimental runs was made. The results are given in Figure 8.10. Of the eight tool kit types in use, three were shown to be most critical. These will be the 'critical tool kits' referred to below.

Since certain tool kits will be more heavily utilised than others, the use of priorities applied to the transport and/or regrinding of these kits seems to be a logical step. Figure 8.11 shows the effect of applying these priorities to the tool kits associated with each component family. The effect of larger tool magazines at workcentres should reduce the average waiting time for tools and so increase production as well as significantly reducing throughput times. Figure 8.12 shows the effect of larger tool magazines by allowing more tool kits to reside at each workcentre.

As one of the major objectives of this section of work was to examine the relationship between the component and tool handling sub-systems; accordingly the effect of changing certain component input parameters was investigated. The effect of changing inter-batch arrival intervals, batch sizes and the number of component types being produced was investigated. These results are given in Figures 8.13 - 8.15.

8.9 ANALYSIS OF RESULTS

Since a manufacturing system is usually provided with an adequate number of processing units to achieve the desired level of production, assessment of the performance of the complete system can be based on its output parameters. The two major measures of output are the number of components produced and the throughput times achieved.

To consider first the number of tool carts. As expected, there is an optimal number with less carts providing an inadequate level of service, whilst additional carts increased system congestion and so slowly reduced output from the system. Tool cart speed was shown to be very significant, even with an excessive number of carts, reducing their speed significantly reduces production. Hence, the use of faster carts will permit fewer carts to be used.

Additions to the number of tool kits that are available increases production, but this falls off rapidly for a given set of tool regrind times. The effect of increasing tool regrind times is very significant and a large number of additional tool kits are required to support extended regrinding times.

With a good level of service provided by tool carts and adequate output from the regrind facility, only 10% of components waited for tools. Those components that waited spent on average only 2 to 3 minutes waiting. Clearly in this case assigning priorities to the regrinding and/or tool transport queues is unnecessary. When either the number of tool carts or the level of service provided at the regrinding area is reduced, then assigning priorities appears to be a potentially beneficial option. The results do not support this supposition and almost no noticeable benefit occurred from the use of these priorities.

In contrast, the use of larger tool magazines at processing units produced a significant increase in output from the system. This simple solution, as highlighted by traditional techniques, is unfortunately a less economic alternative than more complex control logic. The use of these magazines can be equated with the use of inter-processing unit buffering for components, in that they both provide a degree of decoupling between successive processing units. This is achieved by allowing each processing unit to be more independent and operate for longer periods without need for service from the appropriate handling sub-system.

The level of interaction between the two handling sub-systems is important. Varying the parameters dealing with the input of components to the system caused the type of results that were obtained to be significantly different. This could produce results that accorded with a system not constrained by a tool sub-system.

8.10 CONCLUSIONS

The analysis described in this chapter answers some basic questions about both the effect of tool handling on manufacturing systems, and about the control of such tool handling sub-systems. As analytical solutions to the problems of these complex systems are not yet possible, conclusions need to be generalised from the results of simulation models, which are almost by definition rather specific. With this rider, a set of conclusions can be drawn.

The addition of an automated tool handling system to a non optimal flexible manufacturing facility has been shown not to affect the overall system performance to any significant degree. System performance was robust to changes in control parameter changes within the automated tool handling system.

Although generally robust, system performance was very sensitive to two surprising measures - tool regrinding times and the size of processing unit tool magazines. Drawing comparisons with component handling is valid, in that measures reducing the need for rapid response by the handling system are both the most beneficial and the most critical to system performance.

The generalised simulator written during the course of this work, called PATHSIM, provides a tool for the preliminary analysis of systems falling within its scope. It also provides a vehicle for future work, such as in the area of more complex control algorithms.

9.0 AUTOMATED TOOL HANDLING - A PRACTICAL STUDY

9.1 INTRODUCTION

This chapter follows on from the previous one and describes the application of automated tool handling, as defined earlier, to a real system concept. The differences between the specification applied to the theoretical study of these systems and the needs of real systems are shown to be significant. Certain parameters not considered previously become crucial whilst others are either constant or neglected.

The transfer of the concepts developed within a mainly theoretical model to this more realistic system is of especial interest. Some of the specific ideas developed showed themselves to be extremely useful in a practical environment. The flexible manufacturing system described is currently being implemented by a major automotive manufacturer.

9.2 DESCRIPTION OF THE MANUFACTURING SYSTEM

9.2.1 General Description

The manufacturing system used for the work described in this chapter was intended to machine a wide range of casting and forging dies used for the manufacture of automotive components. These dies wear out during use and undergo a number of refurbishments before being finally scrapped. This work is currently performed upon a wide range of ageing conventional machine tools. Additionally, some of this type of work is currently sub-contracted.

The project objectives were to reduce the lead times for both new and refurbishment operations. Additional benefits would accrue through reduced work in progress, faster engineering changes and increased in house work content. An opportunity for change over occurred due to the change in production process that was envisaged to the greater use of Electro Discharge Machining (EDM) techniques. This presented a window of opportunity for the use of advanced manufacturing technology.

The basic system configuration consisted of three 6-axis CNC machining centres, 3 automated EDM machines, a washing machine and various buffer and manual load/unload stations. These units are linked by an AGV materials handling system for both components and tooling. A fully automated tooling system is to be used, which is described in greater detail below. The complete system is to be under the overall control of a central computer with other computers in a hierarchical arrangement to control sections of the system. See Figure 9.1 for a layout of the system concept.

The workload on the system can be predicted some time in advance, as die wear out is fairly predictable. This allows some optimisation of the workload to be attempted to try and balance the overall system utilisation. This is especially useful due to the workload on the EDM units where components have either extremely long or negligible machining times, giving a potential for extremes of workload on these units.

The initial objectives of the simulation exercise were to confirm the basic equipment levels and define the levels of resources in terms of pallets, buffer stations and manual stations needed to sustain various levels of production. More detailed analysis of the control policies, mainly for the tooling sub-system, formed the second phase of the exercise.

9.2.2 The Tooling Sub-System

The tooling sub-system was envisaged to consist of four major physical elements - the tool warehouse, a manual tool service and regrinding area, the transport device - intended to be an AGV; and the tool handling within each of the three machining centres. An outline of the tool handling concept is shown in Figure 9.2. Obviously the tooling sub-system consists not only of physical elements, but also has a control and software element which is central to successful operation.

The original proposal was for tools to be moved individually by a robotic arm mounted on an AGV. Theoretically this would have meant that at any given time the robot/AGV combination could have been moving only a single tool. The objectives of this approach were to maximise productive use of the tooling whilst minimising the tool magazine requirements at the machining centres.

To achieve the desired objectives, close links would have been necessary between the actual NC machining part programs on the three machine tools and the tool handling sub-system. This would have been needed to correctly sequence the delivery, use and removal of tools throughout the duration of machining operations. Very tight control over the total tool inventory would have been possible provided that adequate tool transport capacity was available.

Analysis of the total tool requirement by function, as detailed in Appendix F, showed that there were 140 different tool types. Tooling rationalisation was suggested but rejected due to commercial considerations. To meet existing specifications and spares demand, the dies are needed as per current drawings. Future designs will be produced using a reduced set of tool types. Obviously the minimum number of tools is 140, one of each type. However, a more realistic figure is obtained by:

- | | | |
|----|---|-----|
| a) | Allowing for one tool of each type | 140 |
| b) | At least two of each tool type used on more than one component type. | +60 |
| c) | At least 25% of total number of tools where large usage is predicted. | + 8 |
| d) | Allow for single tool single component multiple usage. | + 6 |

This total of 214 tools represents a realistic minimum with good control and scheduling. Accordingly it represents an ideal case against which to judge the performance of less sophisticated tool scheduling systems.

9.3 THE MODELLING APPROACH

The first stage of the analysis was to examine the component sub-system. This was done initially as the number of major units was mainly dependent upon the component sub-system. The analysis was based upon the current total workload, i.e. that sub-contracted as well as that done internally. There were two stages of this analysis, a purely static one and one using CAN/Q. These are detailed in Appendices G and H respectively.

The static analysis was the base for the original equipment levels of 3 machining centres, 3 EDM units and a single washing machine. These levels were based upon between 80% and 85% of total demand being met by the system. Obviously no attempt could be made to quantify the number of pallets, and hence work in progress levels, needed to sustain these outputs.

The results from the CAN/Q model confirmed the above results, showing that work in progress levels of 15 to 20 would be sufficient to maintain the production of 80% to 85% of total demand. A single AGV with loaded time of approximately 25% was needed to meet the component movement requirements. This suggested that a second AGV would be needed to meet the tool handling workload.

Once the first stages of the analysis had been completed, and the general equipment levels confirmed, the next stage of the process was a more complex, integrated model covering both component and tool handling. However, developments of the tooling concept will be described first.

9.3.1 Development of the Concept - The Tooling Sub-System

The original concept of the tooling sub-system had several obvious drawbacks - it was technically high risk in both hardware and software terms, it had little or no ability to degrade, and it would have been inefficient in its use of the tool transport devices. Accordingly the original concept was refined using some of the systems concepts developed by use of the PATHSIM model.

The first refinement adopted was the use of the tool kit concept. This had the added advantage of simplifying the modelling of the system. However, the concepts used in PATHSIM were extended. As all the tools required for a given operation upon a given component were known, the actual build up of a tool kit from individual tools could be modelled and the usage of each tool type recorded. Where a particular tool would be worn before an operation was completed, two or more were specified to allow the kit to complete the entire operation.

One obvious refinement was a tooling rationalisation programme, see Appendix F. This situation had arisen due to the use of both imperial and metric units and was exaggerated by the fact that the majority of holes were for dowel locations purposes only. However, the alterations to drawings that would have been needed were so numerous that this step was not pursued.

The second refinement was a limited degree of scheduling of tools. Two areas were affected - tooling movement was requested as soon as a component was allocated to a specific machining centre; and tool wear was assessed upon the most quickly wearing tool in each kit.

In order to allow these measures to be adopted, the size of the tool magazines at the machining centres had to be enlarged in order to allow two tool kits to be accommodated simultaneously. However, the complex robot on an AGV could be replaced by a simpler handling shuttle.

The third refinement was to check upon tooling availability before a component was allocated to a machining centre. If the correct tooling was not available then the component was buffered and another one tried. Any components by passed in this way were given higher priority at the next attempt. This approach should tend to maximise processing unit utilisation at the expense of a greater variation in lead times and greater buffering requirements.

As these refinements were intended to produce a better compromise of control complexity and system robustness, they had the advantage of making the system easier to model. The actual modelling also tended towards a concept of a component sub-system and a tooling sub-system each with its own buffer. The balancing of these two buffers was an integral part of improving system performance. See Figure 9.3.

9.3.2 Development of the Simulation Model

Once again, the choice of the simulation package to be used was based upon availability and commercial considerations rather than being a technical decision. The package used was a three phase one, FORSSIGHT, then marketed by a subsidiary of the British Steel Corporation. Although not the same type of language used for PATHSIM, FORSSIGHT is also based upon FORTRAN and so not only concepts from PATHSIM, but also subroutines could be transferred.

The early stages of the analysis, although adequate on the component handling side, had shown the need to model the tooling side in more detail, and also to examine its relationship with the component handling scheduling system. A full simulation model was the only method of achieving these results.

The basic configuration of the model is in two major sections, each divided into smaller units. The physical model handles the mechanics of moving units around the system and is split into the processing units, the handling system and the tool warehouse/service functional groupings. The control model is the decision-making system and is divided into two unequal halves - the component section being far more significant than the tooling section.

The model was designed around this basic concept and considerable thought was given to the interfaces between the modules in order that progressive debugging of the model could be undertaken. This pre-planning was vindicated as the complete model was specified, written and tested in approximately six man weeks. The modular construction also facilitated the progressive development of the tooling control strategy.

9.3.3 Comparisons with PATHSIM

The most significant part of this model was the comparison between the features of a theoretical model and one for a basically similar system, which was needed for the planning stages of a real project. Several of the major parameters used in PATHSIM were totally neglected as they were fixed by physical factors. These included the number of tool carts, their speed, and all the component sub-system features.

The single greatest contribution from PATHSIM was the tool kit concept, which proved to be an extremely effective and powerful technique when applied to real systems. The benefits of simplicity of control within the simulation model would be transferred to the real control system leading to it being both simpler and more robust.

To review the two categories of parameter used in PATHSIM, first those considered as constant within PATHSIM.

- a) The assignment of operations to processing units is easier than within PATHSIM. However, the same principle of fixed routings was followed.
- b) The materials handling for components was well defined and not adjusted.
- c) The tool regrinding times for each kit were calculated and then kept constant.
- d) Tools were used for more than one component type according to the actual need for that type of tool. The strategy was to make up a tool kit and then to maintain it complete until its return to the tool warehouse. This is an enhancement to PATHSIM, anticipated at the time of writing PATHSIM, but one which needed considerable quantities of consistent, realistic data.
- e) A simple anticipatory tool change algorithm, as described above, was used. This was a second enhancement to PATHSIM, but represented a relatively minor change to the control strategy.
- f) Tool handling control and scheduling strategies were kept constant and alterations were not evaluated. This is an area where further in-depth investigation would be useful.

The parameters that were varied within the PATHSIM experimental programme were mainly kept constant during this experimentation. These factors included the number and speed of the tool carts, the tool kit regrinding times and priorities, and the input batch sizes for components and their priorities. The remaining parameter varied for PATHSIM, the number of tool kits, was also varied as one of the major parameters investigated during this experimental programme.

The major addition to the PATHSIM features was the use of individual tools within the model. This would allow the evaluation of various tooling rationalisation plans to be evaluated as well as giving the facility for establishing the number of tools of each type required to sustain any given production level. The incorporation of this feature was based upon the availability of detailed process planning data, which is a valuable benefit of the study of real systems.

Overall, PATHSIM proved to be an excellent foundation for the later and more detailed work. The modular format of PATHSIM allowed blocks of code to be transferred almost directly. The experimentation carried out using PATHSIM was shown to be less relevant, albeit interesting. The need for real data, especially process planning details, was demonstrated clearly. This quantity and quality of data is almost impossible to obtain except in the circumstances of a real project.

9.4 EXPERIMENTAL PROGRAMME

There were two major objectives to the experimental programme conducted on the full simulation model - to confirm the major items of equipment and operational strategy of the full system; and to analyse the operational factors of the tooling sub-system.

The first stages of work, involving a phased analysis of the component system is detailed within Appendices G and H. This component side, once operating satisfactorily, was fixed whilst the tooling system was investigated. Although this procedure did not permit an exhaustive examination of the interactions between the two sections of the system, it did provide a reasonably thorough analysis of the tooling system in the total system context. This method gave a good overview of the interactions between the component and tooling sub-systems within a reasonable number of simulation experimental runs.

The first parameter of the tooling sub-system to be examined was the number of tooling AGVs. Having established this fundamental parameter, the actual number of tools was examined. Several methods of restricting the overall number of tools, as distinct from the number of tool kits, were examined. All were disregarded due to the stage of process planning attained which was inadequate to precisely define the individual tools within each kit. Accordingly, experimental work was based upon control at the tool kit level.

Each tool kit was built up when required from individual tools. Limitations on the number of tools within the system were imposed by limiting the number of tool kits of each type. The number of tool kits, by type, and the number of individual tools, by type, actually used were recorded. By progressively reducing the number of tool kits of each type, the trade-offs between the output obtained and the level of tooling resources needed to support that output could be investigated. The comparison with the level of component buffering needed to support any output level is notable.

9.5 RESULTS

9.5.1 Component Sub-System

As already noted, the primary stages of the component side sub-system analysis are described in Appendix H. The later stages, where the number of pallets was investigated, are shown in Figure 9.4. The optimum number of pallets was established at 18. Additional pallets increased lead times with no significant benefits upon output, whilst reduced number of pallets cut output levels.

9.5.2 Tooling Sub-System

Using the component side parameters obtained as described above, the number of tool handling AGVs was examined. Adding a second AGV produced a reduction in output. Examination of the graphical output from the model showed clearly that a second AGV produced congestion in this restricted area. As changes to the physical layout in this area were not a preferred option, only one tool handling AGV was used for subsequent work.

The majority of the results were obtained from reducing the number of tool kits available. These results are given in Figures 9.5 and 9.6. With no limitations on tool kits, the system output averaged 2853 components per annum, with tooling requirements of 408 to 449 tools to support that output level. The number of tool kits of each type was then progressively cut to 2, giving reductions in total tool requirements to a range of 303 to 323, with no statistically significant reduction in output or change in lead times. A further reduction to only one tool kit of each type reduced tool requirements to a range of 207 to 212, but cut output and extended lead times.

As neither adjustments to the level of component buffering (controlled by the number of pallets), nor to the level of tooling produced any progressive changes, the utilisation of the processing units was examined for the results in question. No difference in utilisation was noticed, suggesting that the system was being constrained by factors other than those considered.

A probable explanation for the lost time waiting for components and/or waiting for tooling is the short processing times that are sometimes needed. This loss of capacity is caused by the handling system catching up with the needs of the processing units and being unable to supply the next component or tool kit before the previous one had completed processing. This conclusion was supported by examination of the graphical output.

9.6 ANALYSIS OF THE RESULTS

The results of this tool handling system study support those obtained from the PATHSIM model. PATHSIM showed that increasing the number of tool kits from a relatively low level had only a marginal effect upon output. The results described in this chapter showed that when alternative component selection is used when the correct tooling is not available, then a more dramatic effect occurs. The number of actual tools required fell significantly when the number of control units (tool kits) was restricted. This gave a marginal effect upon output coupled with a large reduction of the resources needed to support that output.

A parallel effect was noted for component handling - the number of pallets, and so components in the system, needed to support any given production level was lower than estimated by some 40%. As lead time is usually thought of as being related to work in progress levels, some effect on it was expected. This was not observed and the explanation is probably based upon the small fraction of time that components were waiting, as distinct from being processed.

There appears to be an effective capacity constraint created by the differences between certain short processing times and the response times attained by the handling systems. The loss of capacity due to the processing units waiting for components or waiting for tooling was reasonably constant as both output and the level of these resources provided varied. This conclusion is not what would be expected by a consideration of the problem, and its solution is not directly obvious. The two alternatives are to give higher priority to subsequent components when successive previous components at that processing unit have had short processing times or to increase the independence of the processing units by the use of larger components and/or tool holding capacity.

Neither of these options is especially attractive. The prioritising system would be complex and priority application did not achieve expectations when used within the PATHSIM model. As noted earlier, the use of anticipatory type tool change algorithms shows promise, although they were not considered due to their inherent complexity.

The use of multi-station pallet tables and/or larger tool magazines would increase capital costs, increase the work and tooling in progress leads, whilst at the same time increasing processing times by longer average component and/or tool access times.

9.7 COMMENTS AND CONCLUSIONS

When the planning of the manufacturing systems with both automated tool handling as well as automated component handling is considered, then there are few developed tools to assist. In particular, there is no parallel to the queuing network packages available for component handling systems.

There is a high level of interaction between the component and tool handling sub-systems, even when they are physically separate. The concept of components and tools within the system acting as resources for the processing units is a useful analogy and goes some way towards clarifying the importance of their interactions. Even more than with other advanced manufacturing facilities, these additional complexities highlight the need for a unique simulation based analysis of these systems. More conventional approaches cannot address the complexity found in those systems.

Some form of loss of utilisation of processing units occurs when short processing times place too rapid response requirements on the handling system. This applies to both component and tool handling. This is illustrated by the relative waiting times of the EDM units - with their long processing times, when compared to the machining units - with both short processing times and the need for service from two handling systems.

The level of agreement with the results of the PATHSIM model, which suffered from low utilisation rates, was very high. The most striking feature of this study was the small number of tools and the low work in progress levels needed to support design output levels despite high system complexity.

10.0 CONCLUSIONS

Comments and conclusions relating directly to specific sections of work have been incorporated at their appropriate place within the main body of this thesis. This chapter draws these together to provide general conclusions resulting from the entire work.

The central objective of this thesis has been stated as the provision, for a defined class of flexible manufacturing systems (FMS), of a framework for their systems analysis as an integral part of their complete design process. A necessary section of this work was the use of the framework for the investigation of certain systems with particular features of interest.

This thesis supports the view that manufacturing systems design should, in practice, be carried out in a systematic manner that can be analytically supported. Academic analysis, industrial research and general perception all provide little evidence of the actual industrial use of rigorous system design techniques. This naturally leads to the supposition that advanced manufacturing systems are planned in a similar way to their conventional counterparts. This is not due to a lack of appropriate supporting analysis tools, as detailed investigation has shown that an adequate frame of reference, and sufficient tools in the form of computer based aids, do exist for this field of manufacturing systems design.

The use of these available analysis tools for practical examples, as well as for academic analysis purposes, has demonstrated that there is an adequate hierarchical range currently available and capable of industrial use. This range is sufficient to provide a well structured approach for manufacturing systems design. The need for this level of structured planning is confirmed by the usual consensus that further development of advanced manufacturing techniques, in the direction of the unmanned factory, is and will continue to be, constrained by financial rather than technical factors. In brief, ultimate technical capability is outstripping commercial requirements. This illustrates the need for comprehensive, and indeed exhaustive, planning for future investment in order to maximise the benefits gained whilst minimising the risks involved.

Both industrial and theoretical investigation indicated a significant potential hazard in the inappropriate use of the simpler modelling tools for more detailed analysis. This investigation was facilitated by the use of several different analysis tools for the same system, so allowing a meaningful comparison to be made. These shortcomings were highlighted by the weakness of the queuing network based model CAN/Q when used for more detailed system design, especially when work in progress levels were low. These findings strengthen the view that the progressive, hierarchical application of the various tools is required to obtain their maximum utility.

One of the central conclusions of this thesis emerges from the preceding points. This is, that although an adequate set of analysis tools does exist, their application in an indiscriminate fashion is not merely of little value, but can be positively disadvantageous. Accordingly it is apparent that the use of these tools must be carefully planned, so that they are used following the hierarchical approach that has been described. This will also achieve the maximum utility from each of these planning and analysis tools.

Wide ranging commercial considerations have necessitated moves towards ever lower levels of work in progress. This tendency causes manufacturing systems to cease to be collections of isolated units and become complete, integrated entities. This is in fact the principle organisational difference between FMS and conventional manufacturing facilities. Analysis of these integrated entities cannot be easily governed by the application of strict rules, although general principles still apply widely. The combination of these low levels of work in progress and the need to achieve the best results as judged by complex sets of performance measures, have demonstrated the necessity of individual detailed systems planning analysis for FMS. The use of simulation models provides the best, if not the only, route for this detailed planning.

It is now apparent that the design challenge of FMS is uniquely demanding, due to their inherent integrated nature and the resulting control complexity. Analysis of alternative manufacturing system design philosophies supports this view. It is illustrated by research into one central area of FMS design, namely pooling. This work did not provide support for the generally held view that the maximising of pool sizes inevitably maximises system performance. Following on from this, it is apparent that heuristics and policies developed for conventional systems cannot simply be transferred to FMS design procedures. Again taking pooling as an example, it was shown to be beneficial in certain circumstances, but its usefulness was restricted by practical limitations of financial viability and technical robustness. This was a typical system parameter in that its behaviour is altered by low work in progress levels.

One of the major factors affecting the levels of pooling that are either desirable or practical is processing unit tool magazine capacity. Additionally, the application of automated tool handling (ATH) to already complicated manufacturing systems adds another layer of complexity to their analysis. This thesis highlights a major difficulty in any decomposition of the tool and component handling sub-systems to allow their separate consideration. Extensive evidence has been presented of the high level of complex interaction between such sub-systems. This interaction renders attempts at their decomposition of little practical value. The parallel can be drawn with low work in progress levels, another factor forcing the use of a progressive approach for complete systems design.

Initial academic analysis of a FMS with ATH supported the intuitive conclusion that the use of ATH can only reduce the overall performance of a manufacturing system. It follows that, in order to minimise this reduction, a complete systems approach is needed. This view is supported by the unexpectedly large impact of certain parameters upon system performance. These parameters include tooling regrind, or service, times and the capacity of processing unit tool magazines. It is worth noting that these parameters have parallels on the component side of the system. This initial level of analysis provided a basic set of information about the factors which govern the performance of system which include ATH. However this stage of the analysis was constrained by a lack of real data.

The extension of ATH analysis to a real system emphasised the lack of any developed tools for use at the early stages of the ATH systems design process, such as is provided by CAN/Q for the early stages of component flow analysis. Accordingly, the ATH sections of the academic model, known as PATHSIM, were extended and coupled to a detailed component side model to provide an overall analysis tool of some depth for a planned manufacturing system. This route provided the most cost and time effective route for generating an useful model. The results from this second ATH model supported the general conclusions obtained from the complete PATHSIM model. The successful transfer and use of analysis concepts generated within an academic model to a real application is worthy of note. This second model was then used to reduce the adverse effects of ATH on system performance to a level at which they were not a barrier to its use, and indeed not significant in the context of the total system.

A great deal of additional research will be necessary to provide a detailed understanding of the operation of ATH systems and their role within complete manufacturing facilities. This thesis provides an introduction to this analysis and establishes the major parameters affecting system performance. The overall configuration of ATH so as to maximise its effectiveness, whilst providing a high degree of robustness to variations in system status, is a complex procedure. The degree to which any given parameter impacts upon overall performance is specific to each application. Once again the need for individual detailed analysis is brought out.

Detailed investigation of several manufacturing systems indicated the existence of some form of critical ratio between minimum processing times and service times, whether for components or tooling. Below this ratio, the utilisation of processing units is reduced as they are idle awaiting the delivery of either components or tooling. Above this ratio, the level of work in progress increases for marginal, if any, performance advantage. This ratio is affected by many factors, including the frequency of components with short processing times and the levels of buffer storage (components and tooling) at the processing units.

The use of automated tool handling was not found to have an especially negative effect upon system performance, however this concept of a critical ratio between processing and servicing times offers an explanation for the sensitivity of certain system performance measures to the unexpected factors of tool servicing times and tool magazine capacities. Solutions to reduce effective service times are available, often involving the use of additional buffering facilities, but they involve extra expense and increased control complexity.

In summary, the demands imposed by commercial factors have led to modern manufacturing systems becoming much more complex and integrated. This process is exemplified by such features as low work in progress and the use of ATH. This thesis provides a general framework for the systems planning and analysis of a certain class of manufacturing systems within that larger family known as FMS. This framework is illustrated by several examples. The main points raised are the need to use currently available analysis tools in a planned hierarchical manner; the problems arising from excessive use of the simpler tools; and the difficulty of transferring existing manufacturing system design concepts to FMS planning. The systems impact of the use of ATH was examined in some detail and shown to require the use of integrated systems analysis, as does the use of the other advanced technologies, to ensure that potential benefits are realised.

11.0 SUGGESTIONS FOR FUTURE WORK

The hierarchical approach to the simulation of manufacturing systems has now been proven in both academic and industrial use. There exists a need to allow all of these tools to access the same data, which would be progressively enhanced and refined as a project progressed. This integration of existing tools is more important than the development of new ones, as those currently available more than meet current functional needs.

The systems integration effects generated by low levels of work in progress are now recognised, perhaps more readily by industry than by academics. Currently industry has difficulty in defining these effects and still more so in generating solutions. The concepts of the trade-offs between work in progress levels and processing unit utilisation are complex and need to be addressed from a theoretical viewpoint.

Similar systems integration effects were noticed in the organisational and operational aspects of pooling. The pooling concept has been investigated by the use of queuing network theory and unique solutions developed, this thesis suggests that the theoretical base of that work is not completely sound. Accordingly, opportunities exist for the detailed treatment of this area using simulation based methods to develop a more generally applicable set of procedures, as well as investigating the reasons for the failure of queuing network theory.

The combination of systems for both component and tool handling offers a new set of problems. The interactions between the handling systems and the processing units that they serve are a little explored area. The concept of a critical ratio between processing and service times, and their relative influence in determining processing unit interference time, is a topic suitable for more detailed research work. Obviously there is also scope for more investigation of operational strategies using the models that have already been developed.

A great deal of work has been done, and is being done, on the modelling of combinations of component and tool handling systems. However, this work is almost totally system specific and there exists a need for a theoretical treatment in order to understand the operation of these systems.

In conclusion, the bulk of the increasing amount of work in the field of analysis and modelling of manufacturing systems is industrially originated and targeted at specific systems. A more general treatment of the theory of such systems and their behaviour is needed. Ideally this should be coupled with investigation into the actual planning of these systems worldwide and how industrial requirements of their planning systems can best be met.

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APPENDICES

APPENDIX AAN EXAMPLE OF SYSTEMS INTEGRATION EFFECTS

Consider a manufacturing system with three stages producing a variety of components. On a particular day, of 8 working hours, 80 components are required, all of the same type. The first stage is an automatic processing unit which produces 20 components per hour, but needs a 4 hour set-up. The second stage is purely manual with an output of 10 components per hour. The third stage is a semi automatic machine which processes components in batches of 16 and requires cleaning and set-up of 36 minutes per batch prior to a processing time of one hour for that batch. Figure A.1 shows the system, together with the output from each unit and the buffering needed.

The calculated outputs over the 8 hour day give perfect balance between the different units, yet a total buffering of 56 units is needed. This represents a buffering requirement of 70% of the daily output and this assumes no additional disruption from manual needs breaks, shift patterns and equipment breakdowns.

An alternative view is that if the system started empty, then it would be nearly 5 hours into the working day before the first component was completed by the system. Yet the system needs 8 hours of work from each unit to complete the required 80 components. If buffers of at least the sizes indicated were available and demand was constant, then this workload assumption would be accurate. The point is made even clearer if consideration is to be given to the impact of low work in progress upon a conventional "one operation per week" manufacturing facility.

APPENDIX B

DESCRIPTION OF THE POOLING SIMULATION MODEL

OUTLINE

The simulation model was built using the BASIC language on a CBM PET computer. The model was built up using a series of registers, and moving 'components' between these registers, according to a set of pre-determined flow rules.

Figure B.1 shows a tabular representation of the system showing the registers involved for each pooling unit. The method of operation is that a component is moved from one register when a next subsequent register can accept it. A time is associated with each register so that when a component is loaded into a register that time is decremented, in time increment blocks, until it is zero, when the component is ready to be transferred again, if the next register can accept it; if not a wait state is used until the component can be transferred.

The order in which components are loaded into the system is defined by a separate set of scheduling rules derived from the balance of required production of components, and the requirement for maximum utilisation of the processing units.

A modular approach was used, each station being treated as a separate entity, with its own individual set of registers. When a component is ready to leave the set of registers associated with a station, the state of the next register is checked and the component transferred to the next suitable appropriate vacant register or held until a suitable register is vacant.

ASSUMPTIONS

A modular method was used where a module comprises the (use of the) materials handling system from the previous processing unit, any pre-station buffering and the processing station itself. This places constraints upon the complexity of the control and scheduling rules that can be used.

It is assumed that no component would return to any processing station. This led to the load and unload stations being split, even though in reality they may be at the same location.

The use of a coarse (5 second) time increment was mainly to reduce the quantity of processing involved and to speed up model execution. This meant that all processing and travel times were only accurate to the nearest 5 seconds. This increment could be varied for other applications, either upwards to further increase the processing speed or downwards to increase the precision of the model and its output.

Originally breakdowns were completely neglected, both of the processing units and of the materials handling system. Later a subroutine was written which generated random breakdown occurrences and their duration. These were then inserted in the model by switching machines 'off' and 'on' at the appropriate times. A similar technique could be applied to the materials handling system.

A two phase approach was used, as it was considered that the increased processing speed allowed more than balanced the increased work in the ordering of the activities.

Due to the high degree of flexibility allowed within the system, BASIC statements can be patched in to cover any specialised features needed, so almost any of the above constraints could be avoided. However, the basic concept of a fairly simple system must not be forgotten, and if many enhancements are required, the use of a model written in a general purpose simulation language would be a better option. The present method of treating all the processing stations in a similar manner also ensures the maximum simplicity of the model.

The concept of this model has undoubtedly been overtaken by the development of simulation packages during the course of the work described in this thesis. However, its utility for the initial analysis of the pooling problem and its usefulness for the communication of simulation concepts during the early stages of the learning curve mean that it retains a role within this work.

APPENDIX C

FUNCTIONAL DESCRIPTION OF THE PATHSIM MODEL

The model consists of four types of modules - load station(s), processing unit(s), unload station(s) and the central tool warehouse. These modules are all linked by two separate materials handling systems. These modules will be briefly described.

THE PROCESSING UNIT MODULE

A block diagram of a processing unit module is shown in Figure 8.2. As can be seen, the tool and part handling is similar. No specific differentiation is made between processing units. This split is made by the input data, which determines which part type can be processed at which station(s), and by the tools that are made available. It is possible that some classes of machine, e.g. a wash, may not require any tools, and this has been allowed for. It is assumed that there will be adequate space in the tool magazines as their capacity is expressed in tool kits, not directly in numbers of tools.

A part is transferred to the machine via an on shuttle and from it via an off shuttle, both of these are capacity limited queues. The queues of carts waiting at these shuttles are assumed not to interfere with one another.

A set number of tools is held in each station magazine, and are matched with parts as they arrive for processing. Processing times are obtained from the input data. When a part has been processed, the life of the tool is reduced by one and it is returned to the magazine. Tool life is assumed to be a constant number of operations. When a tool is worn, it is transferred to the tool off shuttle to await replacement. Tool breakage is neglected. This is reasonable with modern tool life equations, and the conservative life ratings that are used in automated systems, where consistent tool life is more important than ultimate tool performance. The replacement process is initiated by a worn tool being put into the off shuttle. A tool arriving at the tool on shuttle is automatically transferred to the tool magazine. It is assumed that there are no set-up times between different types of part.

THE LOAD STATION MODULE

Figure 8.3 shows a block diagram of the load station. At intervals, a batch of parts is created and enters the system if the number of parts in the system is less than or equal to the defined maximum work in progress level. When the batch is introduced, its type is decided, and its attributes are assigned. Transport requests are made as each part in the batch completes the load activity, which represents the loading of the part on a pallet or fixture. The parts are then moved as carts become available.

THE UNLOAD STATION MODULE

A block diagram is given as Figure 8.4. Once the parts have been unloaded from their cart, the cart is then released and the part enters an activity representing removal from its pallet or fixture. Part statistics, such as time in system, are collected.

THE TOOL WAREHOUSE MODULE

A block diagram is given as Figure 8.5. Tool carts carrying worn tools are unloaded, the tools queue to be reground, are reground, and are then placed in the warehouse until required. It is assumed that completely worn out tools are replaced on a like for like basis, and that this process has no significant effect upon the regrinding time.

Tool replacements are initiated by the processing units, the appropriate tool kit is transferred to the warehouse off shuttle, and a request for transport to the processing unit is made.

THE MATERIALS HANDLING SYSTEMS

There are two separate materials handling systems, one for tools and one for parts. They are assumed to be completely independent. Each tool cart can carry only one tool kit at a time, each part cart can carry only one part at a time. Cart flow is uni-directional, for convenience, the two systems are assumed to flow in the same direction between machines.

The cart control system used is the assignment system. A cart is either idle (and hence empty); assigned (and empty); or loaded. As a cart becomes idle it either receives its next assignment or waits until another movement is needed. Idle carts remain in the queue following the workcentre where they were unloaded, unless they are 'pushed' along by assigned or loaded carts. Carts always complete their assignment, there is no on going re-assignment procedure.

This is straightforward for the parts which circulate around the system. The tools, however, merely shuttle between machines and the tool warehouse. A tool change is initiated by a processing unit requiring a worn tool to be replaced. When a replacement tool is available in the warehouse, a transport request is made. A tool cart then transfers the new tool to the appropriate processing station, picks up the worn tool, and returns back to the tool warehouse, without servicing any other stations. This also requires that there are always at least two tool kits of every type somewhere in the system.

DISCRETE EVENT SUBROUTINES - SYSTEM CONFIGURATION

These subroutines are used only for system initialisation, data input, if a fault condition arises, and by the SLAM processor for simulation control.

Program MAIN and Subroutine EVENT (I)

These are used by the SLAM processor for the correct organisation of the model sequencing and subroutine calls.

Subroutine INTLC

This subroutine reads in the data from the data file PATDATA, checks it for correct format, and then echoes it. Also, certain system status arrays are initialised.

Function USER(IFN)

These functions contain the inter- and intra-workcentre travel time data.

Subroutine FAULT(N)

This subroutine is called if an error is detected within the model, such as a data format error. A brief description of the error and its location are then printed out. This subroutine should not be confused with the SLAM subroutine ERROR, which detects SLAM errors. FAULT(N) detects logical errors in the model, not SLAM errors.

DISCRETE EVENT SUBROUTINES - PART MOVEMENT CONTROL

Unless otherwise noted, these subroutines are used by all the workcentres apart from the tool warehouse.

Subroutines BSET, LOAD and PSET

These three subroutines are used by the load station for introducing new parts. BSET introduces a batch entity, and determines the batch quantity. PSET sets the part attributes, and finally LOAD complete the process by loading a cart with the part, as a cart becomes available.

Subroutine NCPAS

Finds the nearest idle part cart to meet a transport request, then calls PLINK to link the cart and part.

Subroutine PATB

Updates attributes of a part after it has been unloaded at an on shuttle.

Subroutine PCCL

Ensures that the part off shuttle does not exceed its capacity by allowing a part to enter the off shuttle only if space is available.

Subroutine PCON

Makes the routing decision for the part cart at the part on shuttle, based on the destination of the part that the cart is carrying.

Subroutine PCOF

Makes the routing decision for the part cart at the part off shuttle, based on the destination of the part that the cart is carrying.

Subroutine POPN and PCRT

These two subroutines control the movement of part carts through the inter-workcentre track section. They ensure that correct cart order is maintained when idle carts are pushed by an assigned or loaded cart.

Subroutine PCSD

Updates part cart attributes after unloading a part at an on shuttle, and then assigns that part cart to the first pending part transport request (if any).

Subroutine PLINK

From a part movement request, links a part with the part cart found by NCPAS, then assigns that part cart to the destination of the part.

Subroutines UNLD and UNCK

These two subroutines are used by the unload station only. UNLD collects the statistics from the newly completed part, and sets the appropriate cart status back to idle. UNCK unloads the part and removes it from the system.

DISCRETE EVENT SUBROUTINE - PART AND TOOL MOVEMENT CONTROLSubroutine UPDT

This routine is unique in that it controls both part and tool movement. A part/tool combined transaction that has just completed processing is split into its components - part and tool. Part attributes are updated, the next workcentre is assigned, a part transport request entered, and the part filed in the appropriate off shuttle. Tool attributes are also updated, and it is either re-filed in the tool magazine, or, if worn, in the tool off shuttle. In this latter case, tool transport and tool required requests are entered.

DISCRETE EVENT SUBROUTINES - TOOL MOVEMENT CONTROL

Unless otherwise noted, these subroutines are used by all the processing workcentres.

Subroutine NCTAS

Finds the nearest idle tool cart to meet a tool transport request, then calls TLINK to link the cart and tool.

Subroutine TATB

Updates attributes of a tool after it has been unloaded at an on shuttle.

Subroutine TCCL

Not currently used, allows for a capacitated tool off shuttle.

Subroutine TCON

Makes the routing decision for the tool cart at the tool on shuttle, based on the destination of the tool that the cart is carrying.

Subroutine TCOF

Makes the routing decision for the tool cart at the tool off shuttle, based on the destination of the tool that the cart is carrying.

Subroutine TOPN and TCRT

These two subroutines control the movement of tool carts through the inter-workcentre track section. They ensure that correct cart order is maintained when idle carts are pushed by an assigned or loaded cart.

Subroutine TCSD

Updates tool cart attributes after unloading a tool at a processing station on shuttle, and then re-assigns the tool cart to the tool waiting at that processing unit off shuttle.

Subroutine TWHCS

Updates tool cart attributes after unloading a tool at the tool warehouse, then assigns that tool cart to the first pending tool transport request (if any).

Subroutine TLINK

As a result of a tool movement request, this subroutine links a tool with the tool cart found by NCPAS, then assigns that tool cart to the destination of the tool.

Subroutines TLUP and TOOLF

These two subroutines are used by the tool warehouse only. TLUP resets the tool life after it has been reground, checks to see if that tool is required at a workcentre. If so, TLUP submits a tool transport request and calls NCTAS to find an idle tool cart. The tool is then placed in the tool warehouse. TOOLF searches the tool warehouse for a required tool and assigns it if one is found.

APPENDIX DPATHSIM DATA INPUT FILEStructure

| Indicates comment lines not included in the actual data file.

System identifier (optional)								
	Total number of stations	Number of part carts	Number of tool carts	Number of part types	System work in progress level	Off shuttle load time	On shuttle unload time	
sys	10	7	3	3	60	0.80	0.80	

-- -- For each station								
Station identifier (optional)								
	Station number	Part on shuttle capacity	Part off shuttle capacity	Part on shuttle bypass (0=N, 1=Y)	Part off shuttle bypass	Tool on shuttle bypass	Tool off shtle bypass	
st1	1	2	2	1	1	1	1	

Part side previous stations (LAYOUT array)								
	First previous station	Second previous station						
:	:	:	:	:	:	:	:	
p	9	8	7	6	5	4	3	2 Last prev sta

Tool side previous stations (LCONFIG array)								
	First previous station	Second previous station						
:	:	:	:	:	:	:	:	
t	10	7	6	5	4	3	2	Last previous station

st2	2	2	2	1	1	1	1	
p	1	9	8	7	6	5	4	3
t	1	10	7	6	5	4	3	
:	:	:	:	:	:	:	:	:
s10	10	2	2	0	0	1	1	
	0	0	0	0	0	0	0	0
t	7	6	5	4	3	2	1	

-- --

```
--  --  For each part
|Part identifier (optional)
|      |Part number
|      |      |Batch size
|      |      |      |Number of operations
pt1    1      3      3

      |Operation time - first workcentre
      |      |Operation time - second workcentre
      |      |      |      |      |      |
      |      |      |      |      |      |      |Op time - last workcentre
      |      |      |      |      |      |      |
0.00    0.00    3.00    2.50    0.88    0.00    11.12
```

```
--  --  --  --  For each operation
|Operation identifier (optional)
|      |Operation number
|      |      |First alternative workcentre
|      |      |      |Second alternative workcentre
|      |      |      |      |Third alternative workcentre
|      |      |      |      |      |Final alternative workcentre
op1    1      4      3      0      0
op2    2      5      0      0      0
op3    3      7      0      0      0
--  --  --  --
```

```
pt2    2      3      4
5.15    5.43    3.87    3.87    0.88    7.42    0.00
op1    1      2      1      0      0
op2    2      4      3      0      0
op3    3      5      0      0      0
op4    4      6      0      0      0

pt3    3      4      4
5.15    5.43    3.87    3.87    0.88    3.52    3.52
op1    1      2      1      0      0
op2    2      4      3      0      0
op3    3      5      0      0      0
op4    4      6      7      0      0
--  --
```

```
feor
feof
```

Example Datafile

sys	10	7	3	3	60	0.80	0.80	
st1	1	2	2	1	1	1	1	
p	9	8	7	6	5	4	3	2
t	10	7	6	5	4	3	2	
st2	2	2	2	1	1	1	1	
p	1	9	8	7	6	5	4	3
t	1	10	7	6	5	4	3	
st3	3	2	2	1	1	1	1	
p	2	1	9	8	7	6	5	4
t	2	1	10	7	6	5	4	
st4	4	2	2	1	1	1	1	
p	3	2	1	9	8	7	6	5
t	3	2	1	10	7	6	5	
st5	5	2	2	1	1	1	1	
p	4	3	2	1	9	8	7	6
t	4	3	2	1	10	7	6	
st6	6	2	2	1	1	1	1	
p	5	4	3	2	1	9	8	7
t	5	4	3	2	1	10	7	
st7	7	2	2	1	1	1	1	
p	6	5	4	3	2	1	9	8
t	6	5	4	3	2	1	10	
st8	8	2	2	1	1	0	0	
p	7	6	5	4	3	2	1	9
	0	0	0	0	0	0	0	
st9	9	2	2	1	1	0	0	
p	8	7	6	5	4	3	2	1
	0	0	0	0	0	0	0	
s10	10	2	2	0	0	1	1	
	0	0	0	0	0	0	0	0
t	7	6	5	4	3	2	1	
pt1	1	7	2					
	0.00	0.00	4.12	4.12	11.12	11.12	11.12	
op1	1	4	3	0	0			
op2	2	5	6	7	0			
pt2	2	7	3					
	10.58	10.58	6.54	6.54	7.42	7.42	0.00	
op1	1	2	1	0	0			
op2	2	3	4	0	0			
op3	3	6	5	0	0			
pt3	3	8	3					
	10.58	10.58	6.54	6.54	0	7.42	7.42	
op1	1	1	2	0	0			
op2	2	4	3	0	0			
op3	3	7	6	0	0			
feor								
feof								

APPENDIX EPATHSIM CONTROL ALGORITHMSSystem Control Algorithms

Initial work on FMS control had highlighted the fact that the control algorithms used would be critical for good system performance. Six areas required consideration:

- a) Part introduction in PATHSIM. Parts are introduced in batches. The choice of which batch type to select is based on a user specified sequence of part types to be introduced. Another alternative rule that could easily be implemented would be choice by random selection.
- b) Part assignment in PATHSIM. There has been a great deal of work done on the job shop assignment problem, and this has been extended to FMS. It has been shown, in the context of studying a system that is now operational, that providing that the priorities of specific parts, as opposed to part types, are not important, then simple first in, first out is almost as effective as any other method (Houshmand, 1983). Accordingly, this method was adopted for selection from queues at on shuttles to processing units.
- c) Transport Devices. Two classes of scheduling rules can be identified relating to the control of independent addressable type materials handling vehicles, such as automated guided vehicles (AGV). These two rules are the workcentre initiated rule - where one cart has to be selected to perform a task, when more than one idle cart is available; and the vehicle initiated rule - the choice of which station to service, when more than one is waiting for service as a cart become idle.

Transport Device Assignment

This is the first rule above, it is initiated by workcentres, and is basically a cart search. The algorithm used is the "nearest idle cart" one. Although this is not optimal, it has the benefit of tending to avoid "locking situations". This is where a system becomes frozen as carts are carrying parts which cannot be unloaded, and the unload areas are occupied by other parts that are themselves waiting for cart service.

Transport Request Priorities

This is the second type of scheduling rule, it is vehicle initiated, and is choice of which station to service when there is more than one request for service as a cart become idle. Two different algorithms were used, one for the part carts and one for the tool carts.

- a) For the part carts, the method originally adopted was to store all the transport requests and service them on a first come, first served basis. however, a "locking situation" developed, so the priority of the requests list was adjusted to give a higher priority to parts leaving the system. This prevented the occurrence of "locking".
- b) Tool cart transport requests were also serviced on a first come, first served basis, except for certain cases, where the use of priority assignments to certain types of requests was used.

The latter two algorithms are specific to systems which include ATH, whereas the previous ones are general to FMS. These two classes of algorithms have been treated as if they were independent. It is unlikely that this is completely so, but their interdependency is assumed so small as to be insignificant.

- d. Tool introduction. This is a confusing term, it refers to the way tools are reintroduced into the tool warehouse, following regrinding. It corresponds to the introduction of parts into the system. In the model a first in, first out approach to the regrinding operation was usually used. The merits of this are its easy implementation and a lack of data on which to justify a more complex algorithm. A priority approach to regrinding is considered in the work described in the main body of the text.
- f. Tool despatching. The despatching of tools in most cases is a trivial problem. An adequate number of tools should be provided so that an (expensive) machine is not idle due to waiting for an (inexpensive) tool. This is occasionally not the case, some tools, such as multi-spindle drilling heads, are expensive, as well as being infrequently used, so that competition for their use could arise. In this case, the station that first requested service is dealt with first.

Algorithms used by PATHSIM

Three variations were used during the experimental programme conducted using the PATHSIM model.

1. A cart delivers a new tool to a workcentre, in response to a worn tool filing a "tool required request". The worn tool is then loaded onto the same cart and returned to the tool warehouse.
 - a) Carts will not become idle at a workcentre (other than the tool warehouse). The carts after unloading a new tool will be instructed to pick up the "corresponding" worn tool in the appropriate "off shuttle".
 - b) Carts will become idle only at the tool warehouse and will then search the transport request file.
2. Tool transport request priorities. High priority given to requests for new tools to be taken to a workcentre. Low priority given to requests for worn tools to be taken back to the tool warehouse. Two transport requests will need to be filed at each movement:
 - a) The first will be exactly the same as in 1.
 - b) The second request will be of lower priority, to take the worn tool back to the warehouse.

Carts can become idle anywhere in the network, not just at the warehouse.

3. This will be exactly the same as variation (2), except after a cart unloads a tool on a workcentre off shuttle, it will inspect the tool off shuttle queue at that workcentre and determine if there are any worn tools requiring transport back to the warehouse. If there are, the tool transport request file will be searched for that worn tool's request - that request will then be serviced. If not, the cart will search the tool transport request as in alternative (2).

If there are more than one tool transport requests at a given workcentre, the cart will service the requests in first in, first out order.

APPENDIX F

TOOLING ANALYSIS OF THE DIE FMS

CATEGORY	PLANNED	SUGGESTED	REDUCTION
BORING TOOLS	11	8	3
COUNTER SINKS	9	3	6
- 60°	4	3	1
- 90°	4	4	-
- CARBIDE	5	4	1
DIE-CUTTERS	3	3	-
DRILLS	31	20	11
- 90°	2	2	-
- 90° COUNTERSINK	4	3	1
- CARBIDE	9	6	3
- CENTRE	3	3	-
HOBBS	4	4	-
MILLS			
- END	19	11	8
- FACE	3	3	-
- FORM	5	5	-
- SHOULDER	4	4	-
REAMERS	5	5	-
TAPS	15	11	4
	140	102	38 ~ 27%

APPENDIX GWORKLOAD MODEL FOR THE DIE FMS

COMPONENT TYPE	ANNUAL VOLUME TIME	ANNUAL MACHINING	ANNUAL EDM TIME	ANNUAL WORK TIME	ANNUAL MANUAL STATION TIME
1	1300	17810	-	9100	19500
2	1237	27461	-	25977	55666
3	1786	91086	-	12502	26790
4	1787	83274	-	12509	26805
5	242	16504	7914	5082	7260
6	1787	36634	-	12509	26805
7	127	5192	-	1778	3810
8	272	3645	-	3808	8160
9	272	16483	-	3808	8160
10	272	6446	-	1904	4080
11	273	9446	-	5733	12285
12	140	13328	5404	2940	4200
13	147	15009	-	1029	2205
14	147	18831	-	2058	4410
15	147	16082	-	2058	4410
16	148	49743	-	3108	6660
17	148	34676	-	4144	8880
18	148	9635	-	1036	2220
19	60	20658	86922	2100	3600
20	60	4872	20502	1680	2700
21	61	24363	102517	2562	4575
22	61	27700	116559	2562	4575
23	61	12249	51545	1708	2745
24	61	17775	74799	2135	3660
25	61	18270	76872	2135	3660
26	62	1376	4799	1736	2790
27	726	29621	64977	15246	21780
28	446	1873	-	3122	6690
29	1586	21887	-	11102	23790
30	1586	19984	-	11102	23790
31	174	2558	4802	2436	2610
32	1586	8882	-	11102	23790
33	326	3293	24645	2282	9780
34	101	1939	3303	1414	1515
35	355	16650	-	2485	5325
36	356	12033	-	2492	5340
37	356	11214	-	2492	5340
38	356	23567	-	4984	10680
39	356	25596	-	7476	16020
40	356	3721	-	2492	5340

COMPONENT TYPE	ANNUAL VOLUME	ANNUAL MACHINING TIME	ANNUAL EDM TIME	ANNUAL WORK TIME	ANNUAL MANUAL STATION TIME
41	39	3721	-	546	1170
42	39	1322	-	273	585
43	39	3569	-	546	1170
44	40	5208	-	560	1200
45	40	196	-	280	600
46	40	5812	-	560	1200
47	40	3888	-	560	1200
48	45	189	2880	630	675
49	39	3721	47229	819	1170
50	39	1322	11139	546	1170
51	39	3569	54962	819	1170
52	39	5078	62275	819	1170
53	39	191	27538	546	1170
54	39	5667	39963	819	1170
55	40	3888	42128	840	1200
56	326	-	20864	2282	4890
TOTALS	20455	835617	954537	219373	437911
Utilisation at 100% Internal Content*		258% 3 units at 86%	295% 3 units at 98%	68% 1 unit	135% 2 units at 68%
Utilisation at 80% Internal Content*		206% 3 units at 69%	236% 3 units at 78%	54% 1 unit	108% 2 units at 54%
Utilisation at 70% Internal Content*		181% 2 units 90% 3 units 60%	206% 3 units at 69%	47% 1 unit	95% 1 units at 95% 2 units at 47%

* 1 year is 324,000 mins

APPENDIX HCAN/Q ANALYSIS FOR THE DIE FMS

Station Performance Measures

Station Number	Station Name	Server Utilisation	Av. No. of Busy Servers
1	SETTING	.195	.778
2	M/C TOOLS	.646	1.938
3	EDM	.997	2.992
4	AGV	.242	.242

Work-in-Progress = 15 Batches

Mean No. of Ops. to Complete a Batch = 5.513

System Performance Measures

System Run Time = 103 Hour(s)

Work-in-Progress = 15 Batches

Production = 119.856 Batches
= 119.954 Parts

Average Throughput Time = 773.428 Minutes

Processing = 294.347 Minutes

Travelling = 12.46 Minutes

Waiting = 466.622 Minutes

System Performance Measures

Production of Each Product Type

	No. of Batches	No. of Parts
ONE	7.31	7.31
TWO	7.31	7.31
THREE	15.756	15.756
FOUR	15.756	15.756
FIVE	15.756	15.756
SIX	15.756	15.756
SEVEN	2.4	2.4
EIGHT	3.064	3.064
NINE	3.064	3.064
TEN	3.064	3.064
ELEVEN	3.064	3.064
TWELVE	2.883	2.883
THIRTEEN	2.883	2.883
FOURTEEN	2.883	2.883
FIFTEEN	2.883	2.883
SIXTEEN	2.883	2.883
SEVENTEEN	2.883	2.883

System Performance Measures

Production of Each Product Type

	No. of Batches	No. of Parts
EIGHTEEN	2.883	2.883
NINETEEN	1.207	1.207
TWENTY	1.207	1.207
TWENTY ONE	1.207	1.207
TWENTY TWO	1.207	1.207
TWENTY THREE	1.207	1.207
TWENTY FOUR	1.207	1.207
TWENTY FIVE	.113	.113
TWENTY SIX	.04	.04
TWENTY SEVEN	.084	.084

System Performance Measures

Functions of Work-in-Progress

W.I.P. (Batches)	Production (Batches)	Average Throughput Time (Minutes)
1	20.143	306.807
.	.	.
.	.	.
10	117.383	526.486
11	117.382	574.229
12	118.385	623.083
13	119.021	672.71
14	119.688	722.878
15	119.856	773.428
16	119.964	824.245
17	120.034	875.251
18	120.079	926.387
19	120.109	977.615
20	120.128	1028.91
.	.	.
.	.	.
Inf	120.162	Inf

The Bottleneck Station is 3 EDM

FIGURES

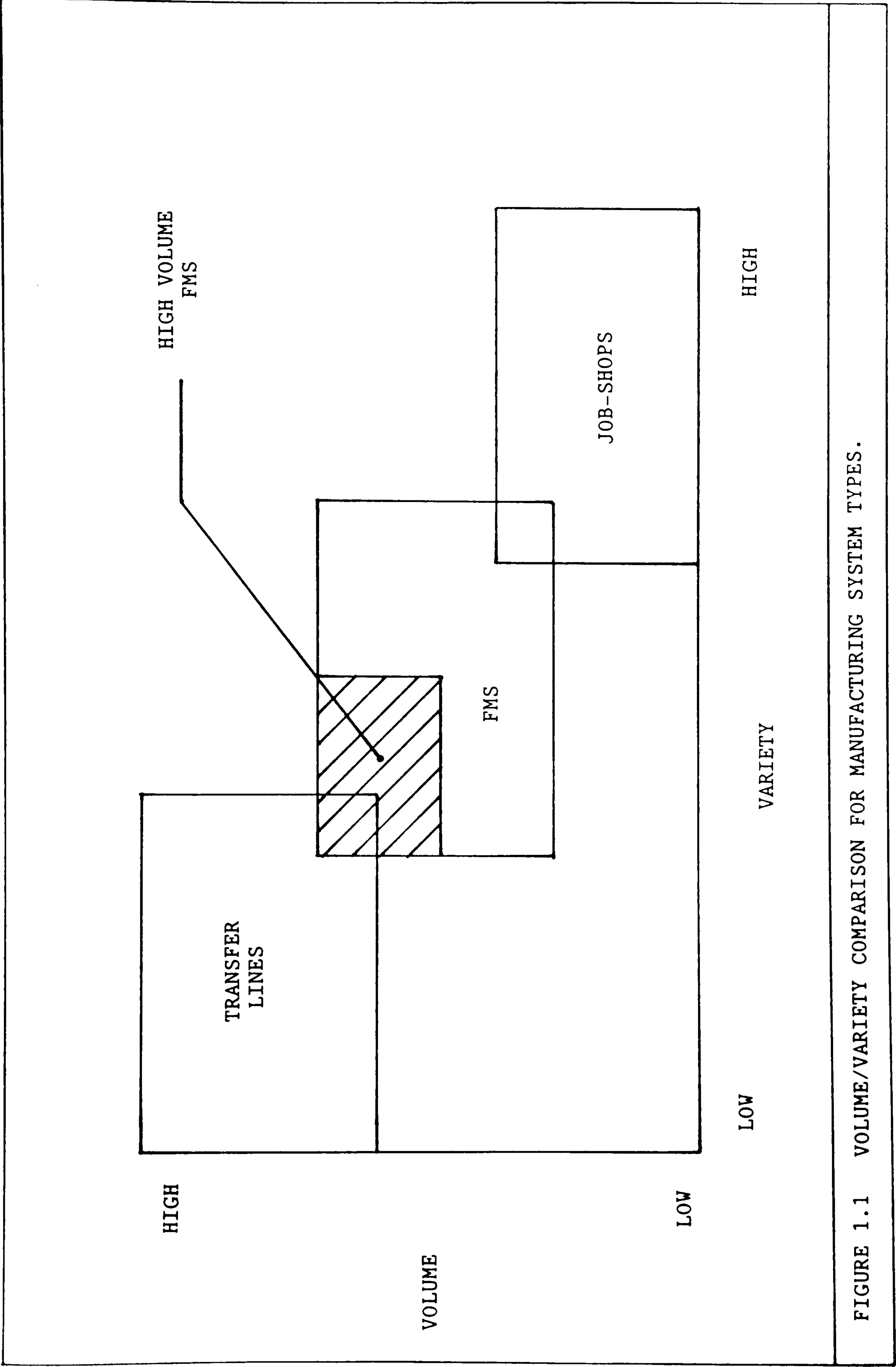


FIGURE 1.1 VOLUME/VARIETY COMPARISON FOR MANUFACTURING SYSTEM TYPES.

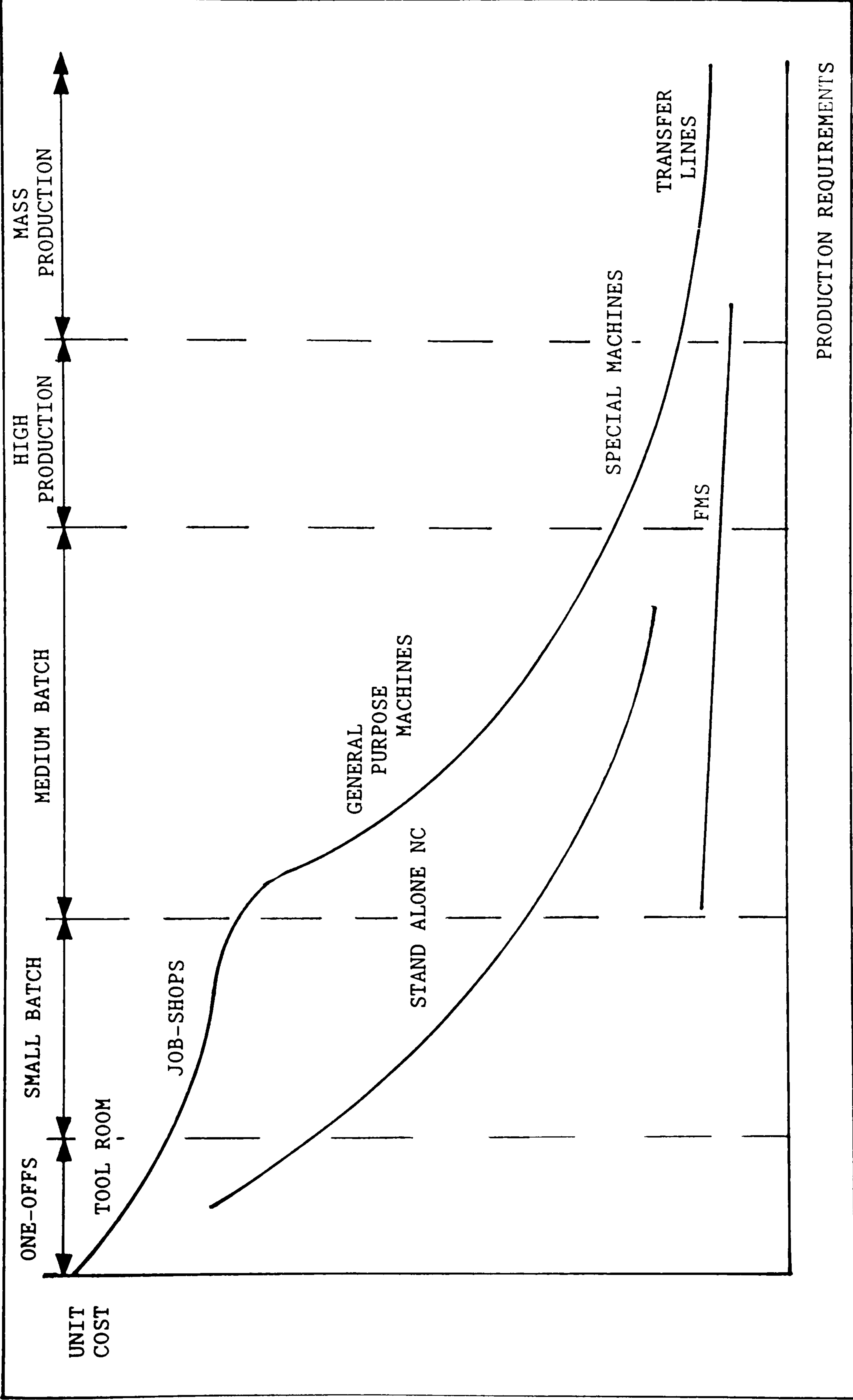
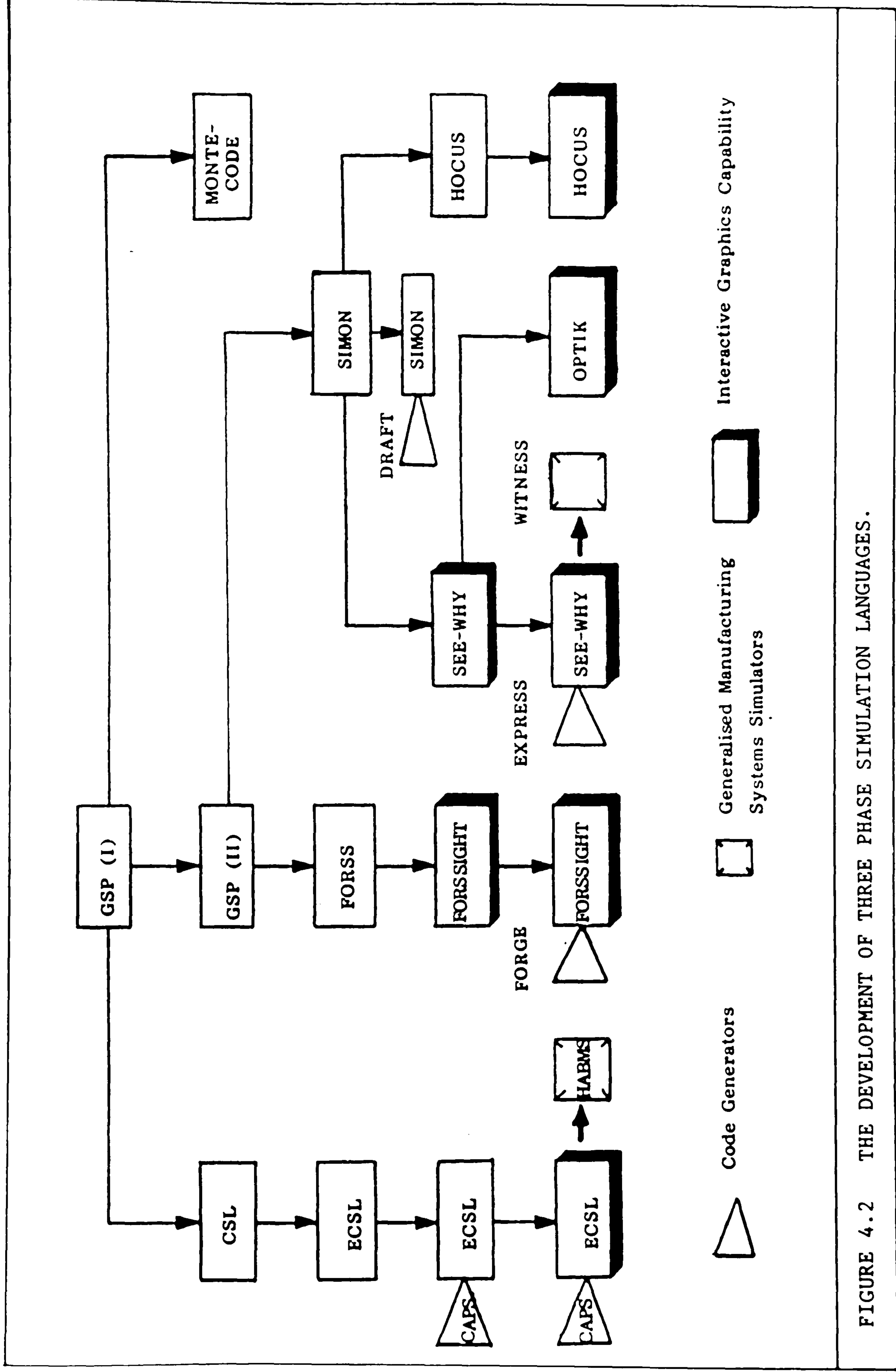


FIGURE 3.1 COST/PRODUCTION COMPARISON FOR MACHINING FACILITIES.



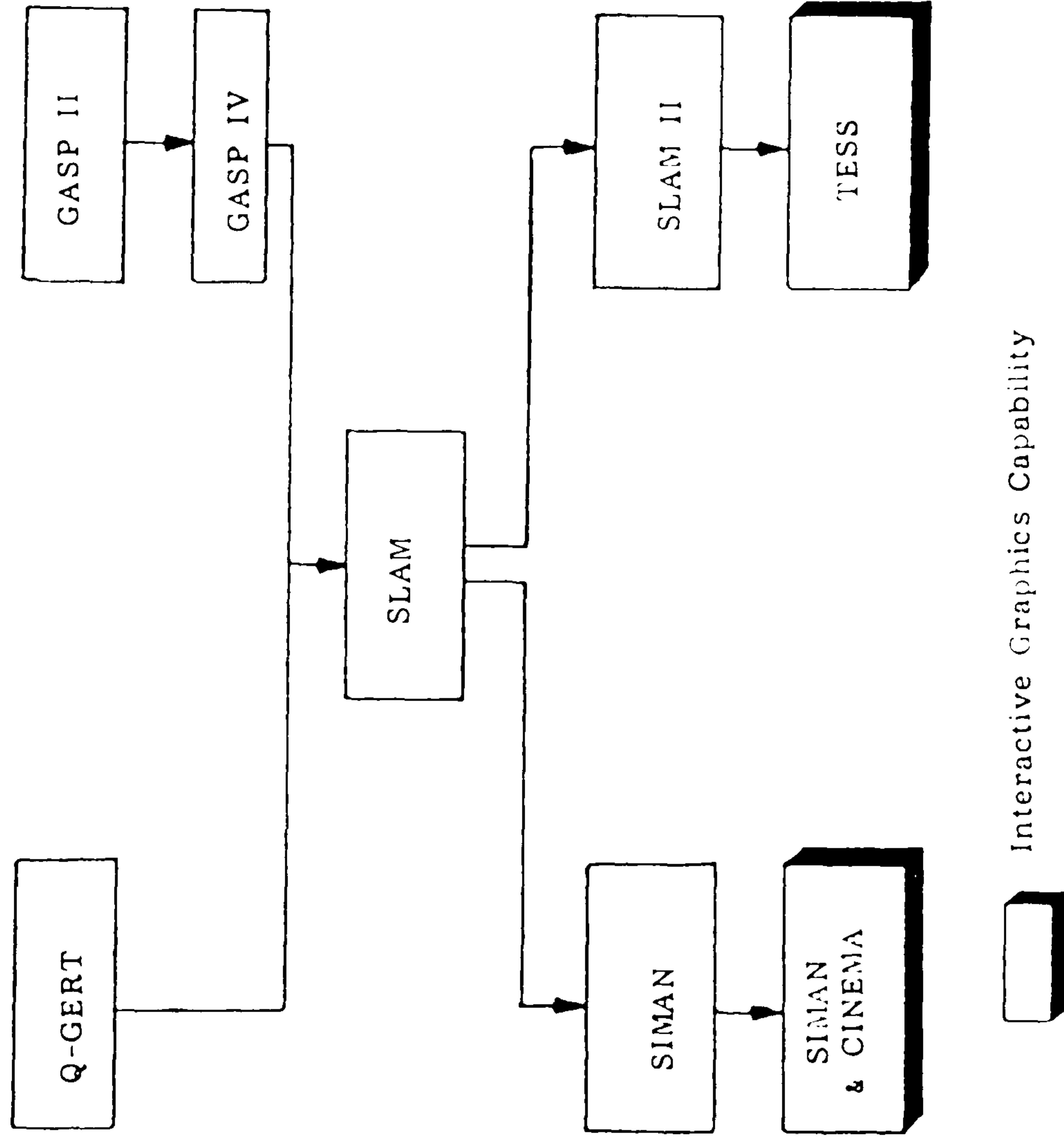


FIGURE 4.3 THE DEVELOPMENT OF GASP BASED SIMULATION LANGUAGES.

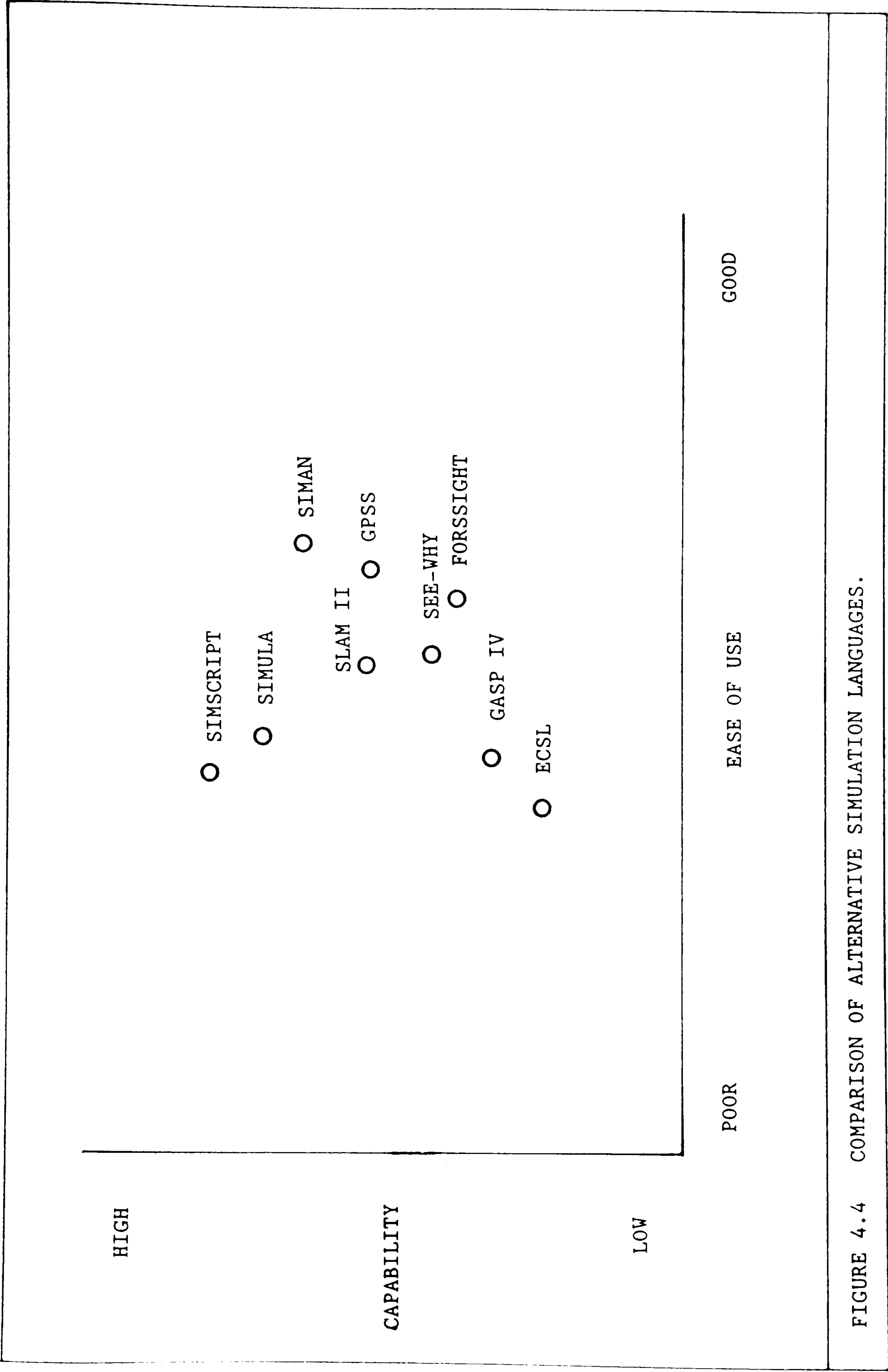


FIGURE 4.4 COMPARISON OF ALTERNATIVE SIMULATION LANGUAGES.

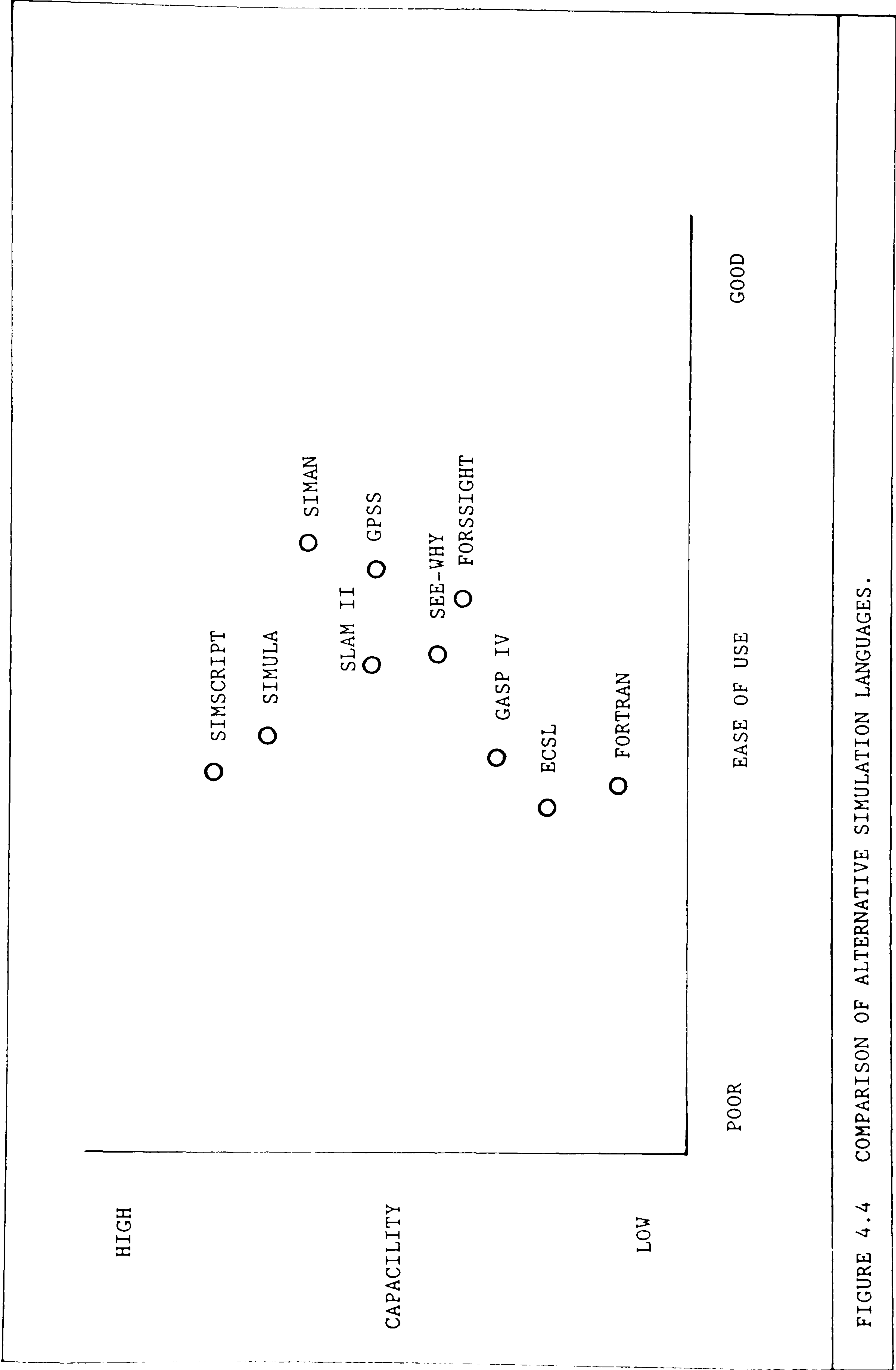
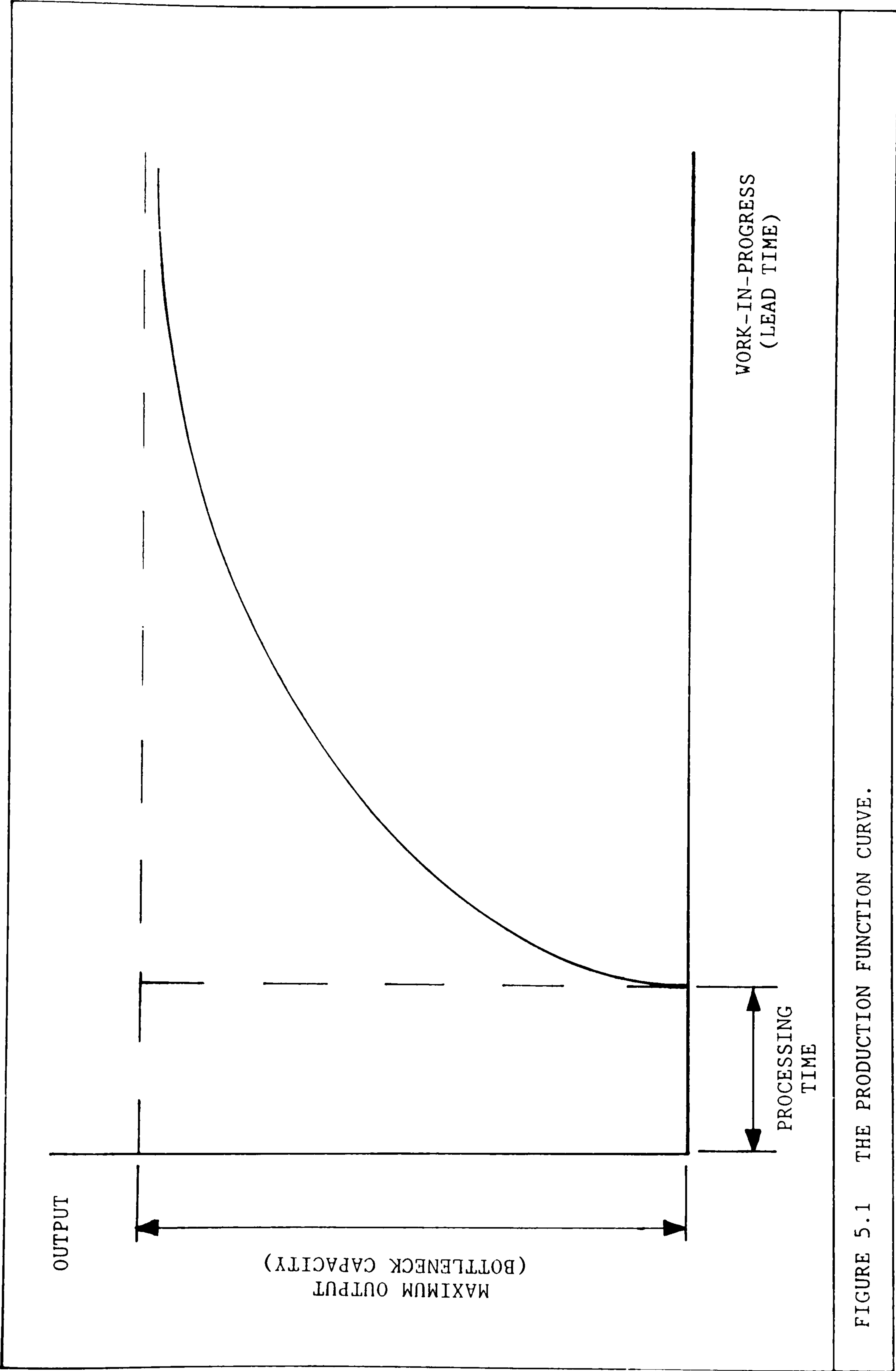


FIGURE 4.4 COMPARISON OF ALTERNATIVE SIMULATION LANGUAGES.



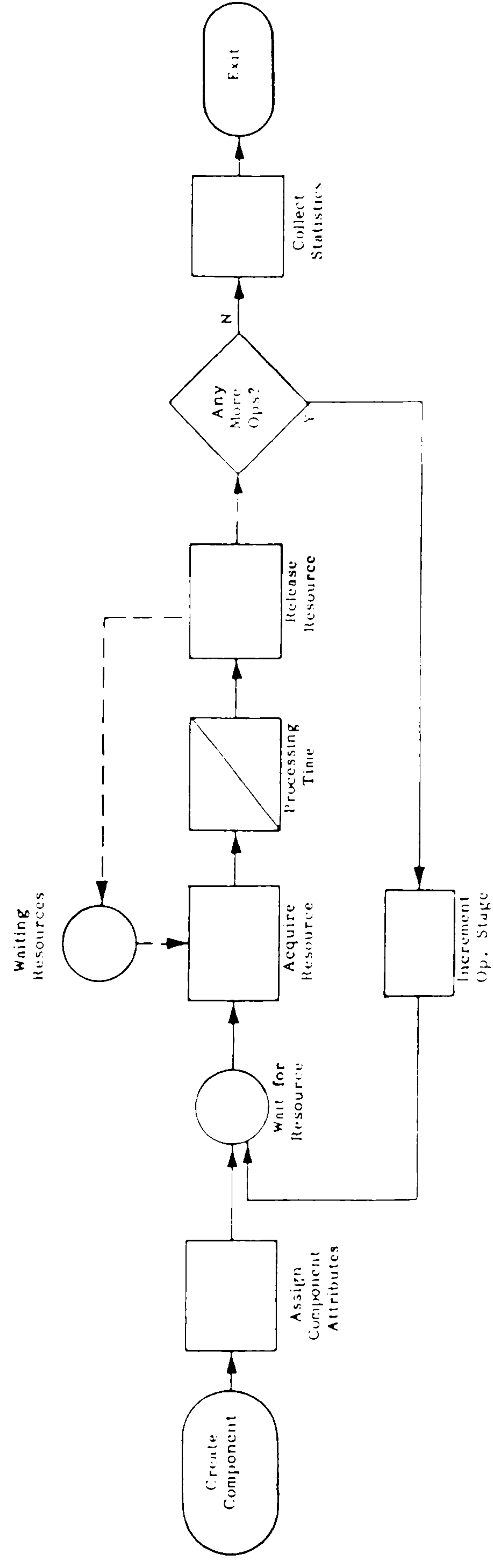


FIGURE 5.2 A TYPICAL NETWORK DIAGRAM.

SUMMARY REPORT

TIME = CUR(TIM) = 14400.000
RUN = CUR(RUN) = 1

NODE STATISTICS: LAST STARTED AT TIME = 0.000
RESOURCE STATISTICS LAST STARTED AT TIME = 0.000
NODE STATISTICS COLLECTION TIME SINCE LAST CLEAR = 14400.000
RESOURCE STATISTICS COLLECTION TIME SINCE LAST CLEAR = 14400.000

	NODE NAME	NODE NUMBER	NODE COUNT COUNT(*)	NODE IN NODE
QUEUES	INSPECTION W	2	2324	0
	REPAIR WAIT	7	575	6
ACTIVITIES	INSPECTION	3	2124	1
	TRAVEL TO RE	5	5777	12
	RECYCLE	6	5120	6
	REPAIR	8	569	1
SINKS	GOOD DISHWAS	4	1770	
SOURCES	DISHWASHERS	1	1796	

NODE STATISTICS

ACTIVITY NODES ACTIVITY TIME						
NODE NUMBER	NAME	MEAN MEAN(TIM,*)	STANDARD DEVIATION STD(TIM,*)	SUM CSUM(TIM,*)	SMALLEST SMA(TIM,*)	LARGEST LAR(TIM,*)
3	INSPECTION	3.93619	1.97410	21116.2	3.75983	18.5020
5	TRAVEL TO RE	10.0000	.000000E+00	87350.0	10.0000	10.0000
6	RECYCLE	10.0000	.000000E+00	81340.0	10.0000	10.0000
8	REPAIR	14.9212	5.00635	14155.2	12.7664	40.0612

SINK NODES TIME IN SYSTEM						
NODE NUMBER	NAME	MEAN MEAN(NET,*)	STANDARD DEVIATION STD(NET,*)	SUM CSUM(NET,*)	SMALLEST SMA(NET,*)	LARGEST LAR(NET,*)
4	GOOD DISHWAS	141.425	359.775	250322.	3.75983	3641.77

RESOURCE STATISTICS

NUMBER(S) OR TYPE	NAME	STATE NUMBERS	STATE NAME	TIME IN STATE	PERCENT OF OBSERVED TIME	FRACTIONAL UTILIZATION
5	REPAIRMAN 1	1	IDLE	236.316	1.6411	
		4	CAPTURED IN AN ACTIVITY	14163.7	98.3533	
		3 AND 4	TOTAL BUSY	14163.7	98.3533	
		1 TO 4	TOTAL PRESENT	14400.0	99.9998	.983539

FIGURE 5.3 TYPICAL OUTPUT FROM A NETWORK DIAGRAM SIMULATION MODEL.

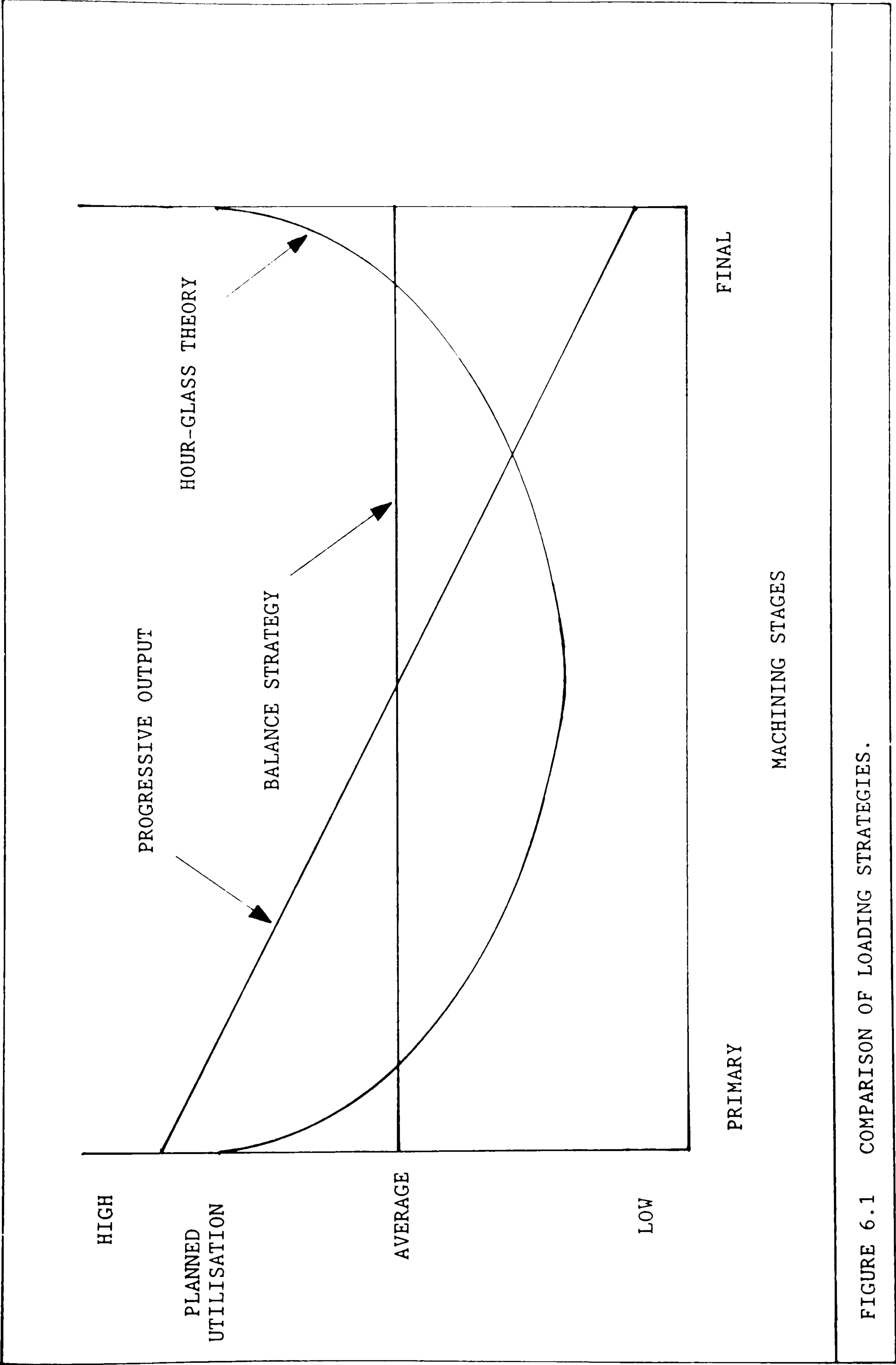


FIGURE 6.1 COMPARISON OF LOADING STRATEGIES.

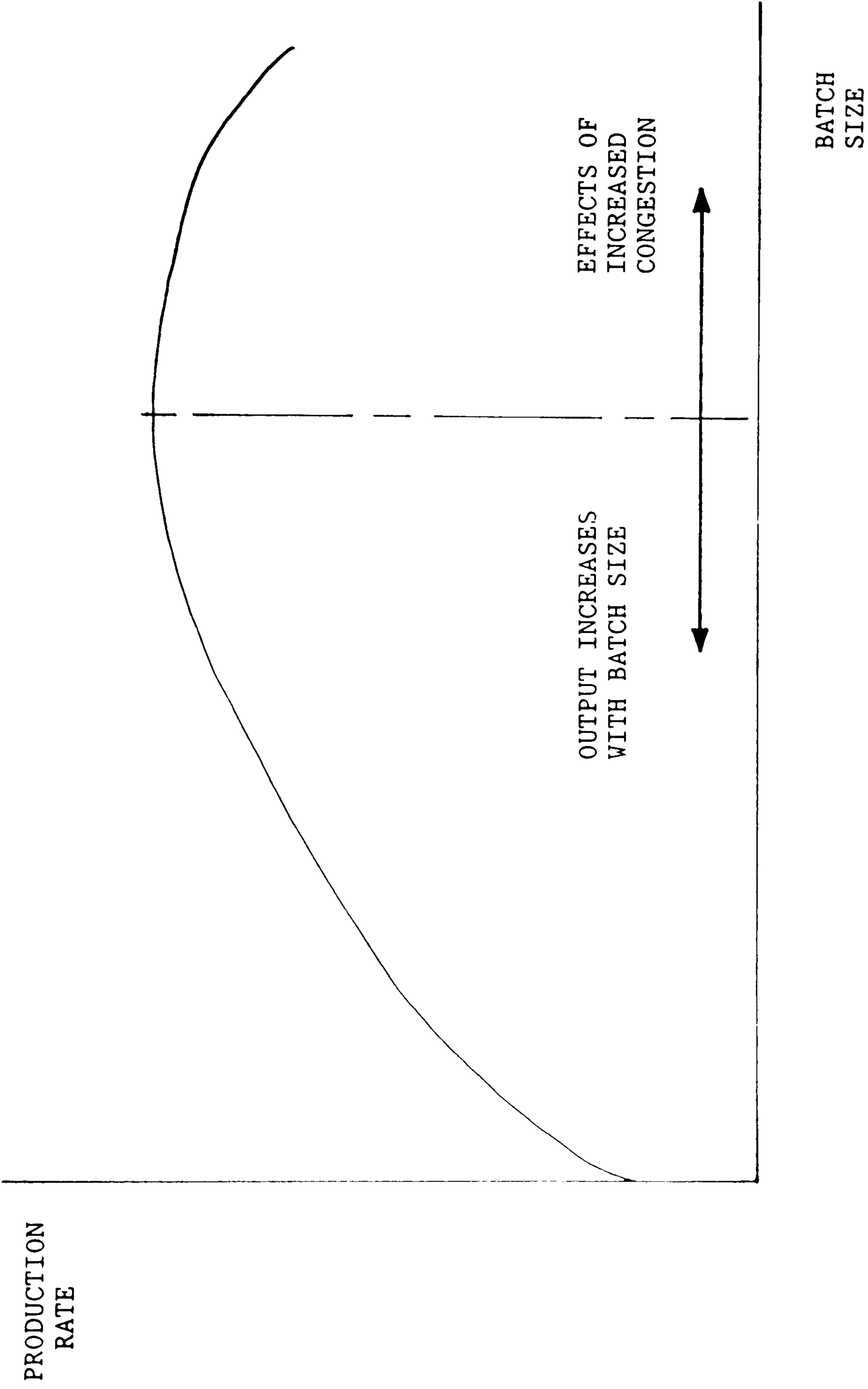


FIGURE 6.2 BATCH SIZE INFLUENCE UPON PREDICTED SYSTEM OUTPUT.

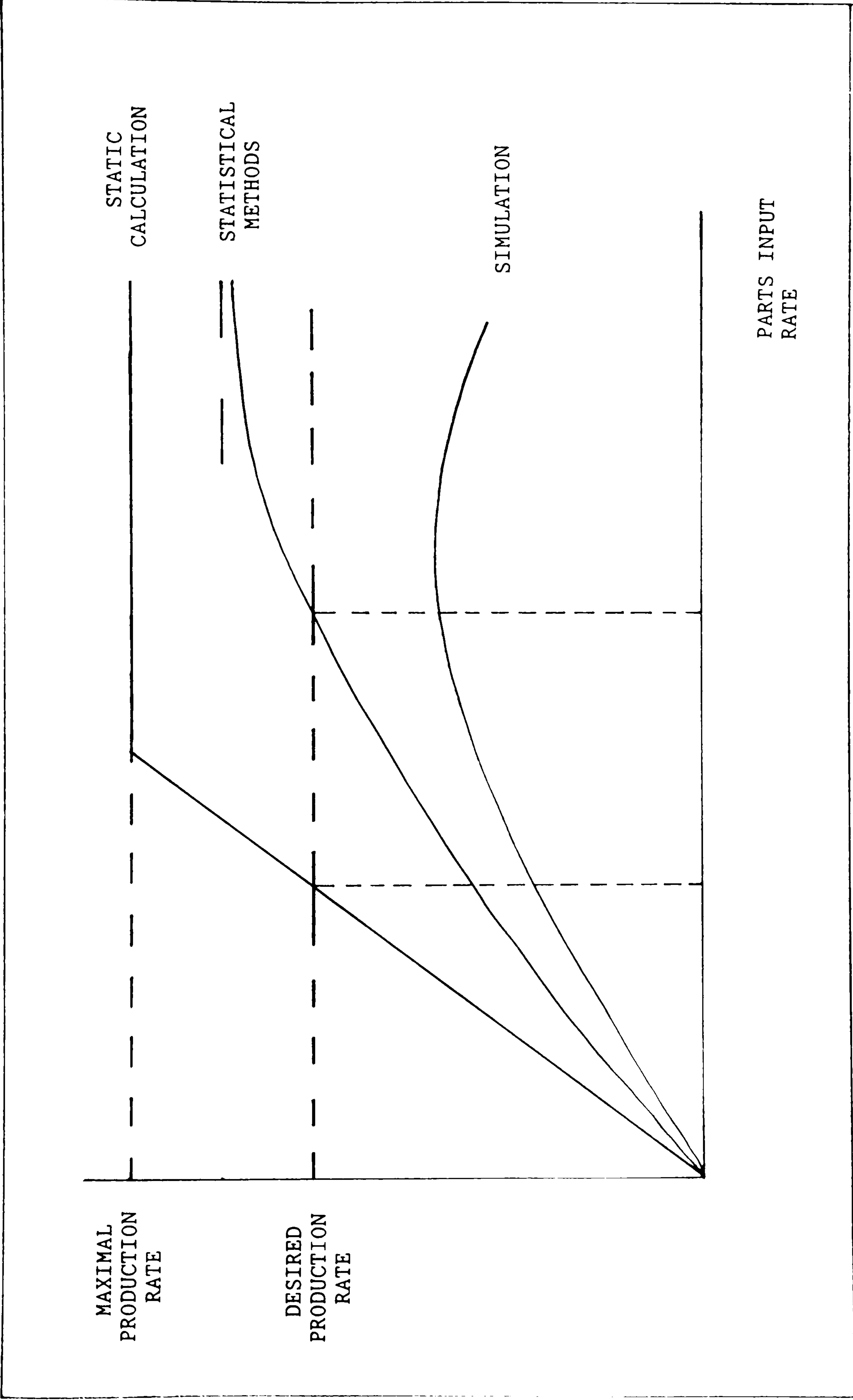


FIGURE 6.3 COMPARISON OF DIFFERENT ANALYSIS TOOLS UPON PREDICTED SYSTEM OUTPUT.

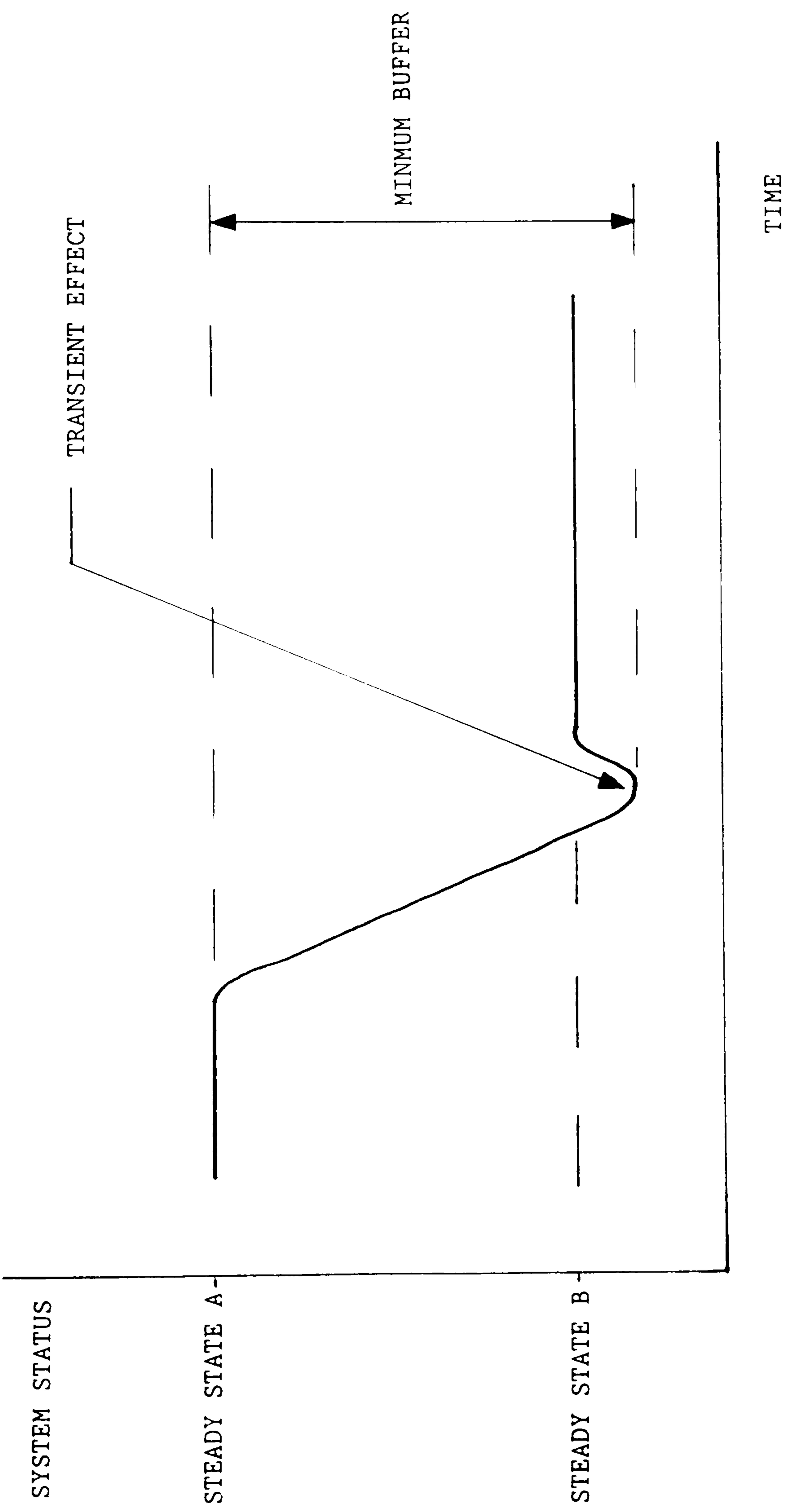


FIGURE 6.4 CONTROL THEORY EFFECTS APPLIED TO MANUFACTURING SYSTEMS.

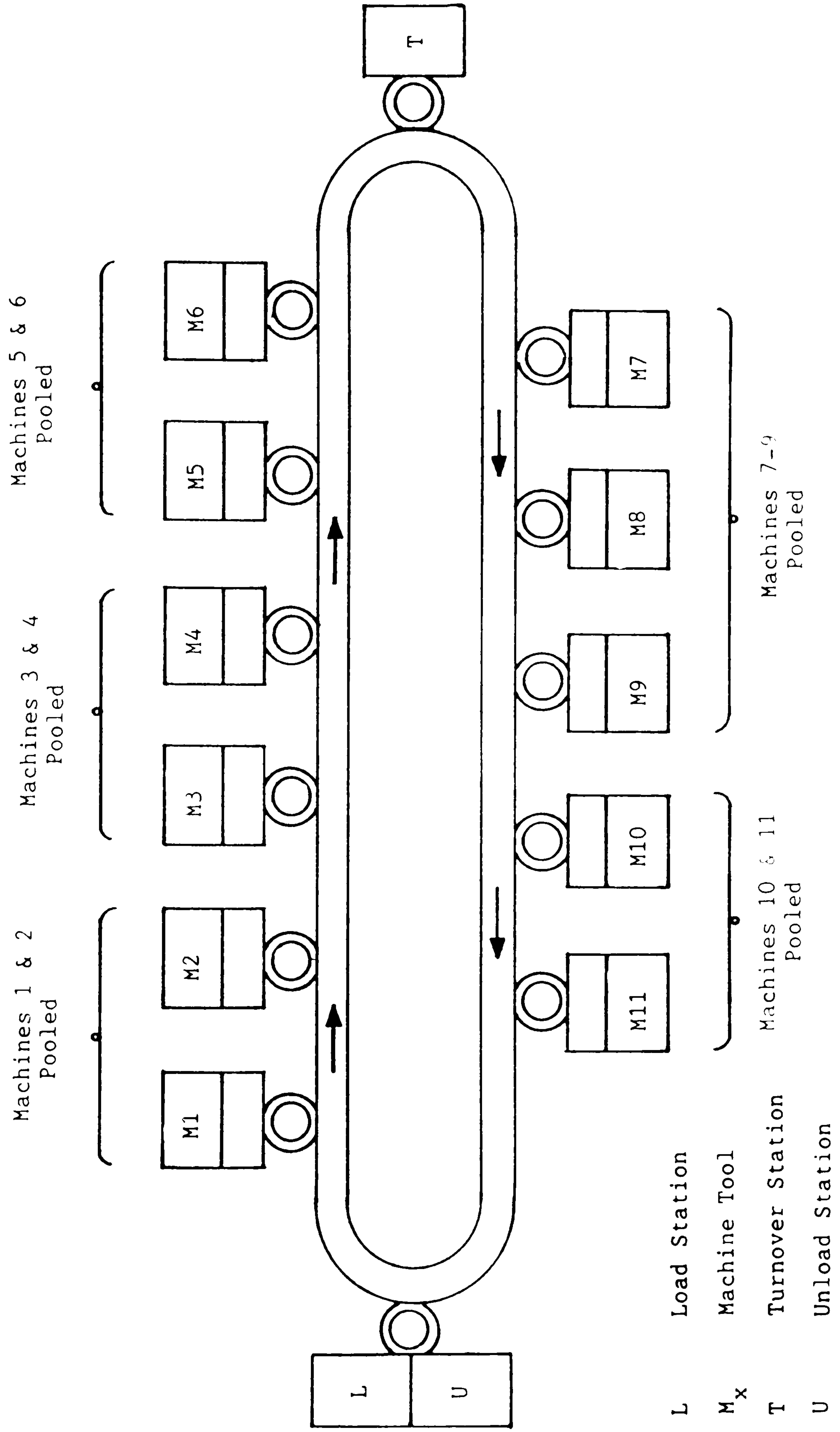


FIGURE 7.1 CONVEYOR BASED FMS - LEVEL A POOLING ARRANGEMENT.

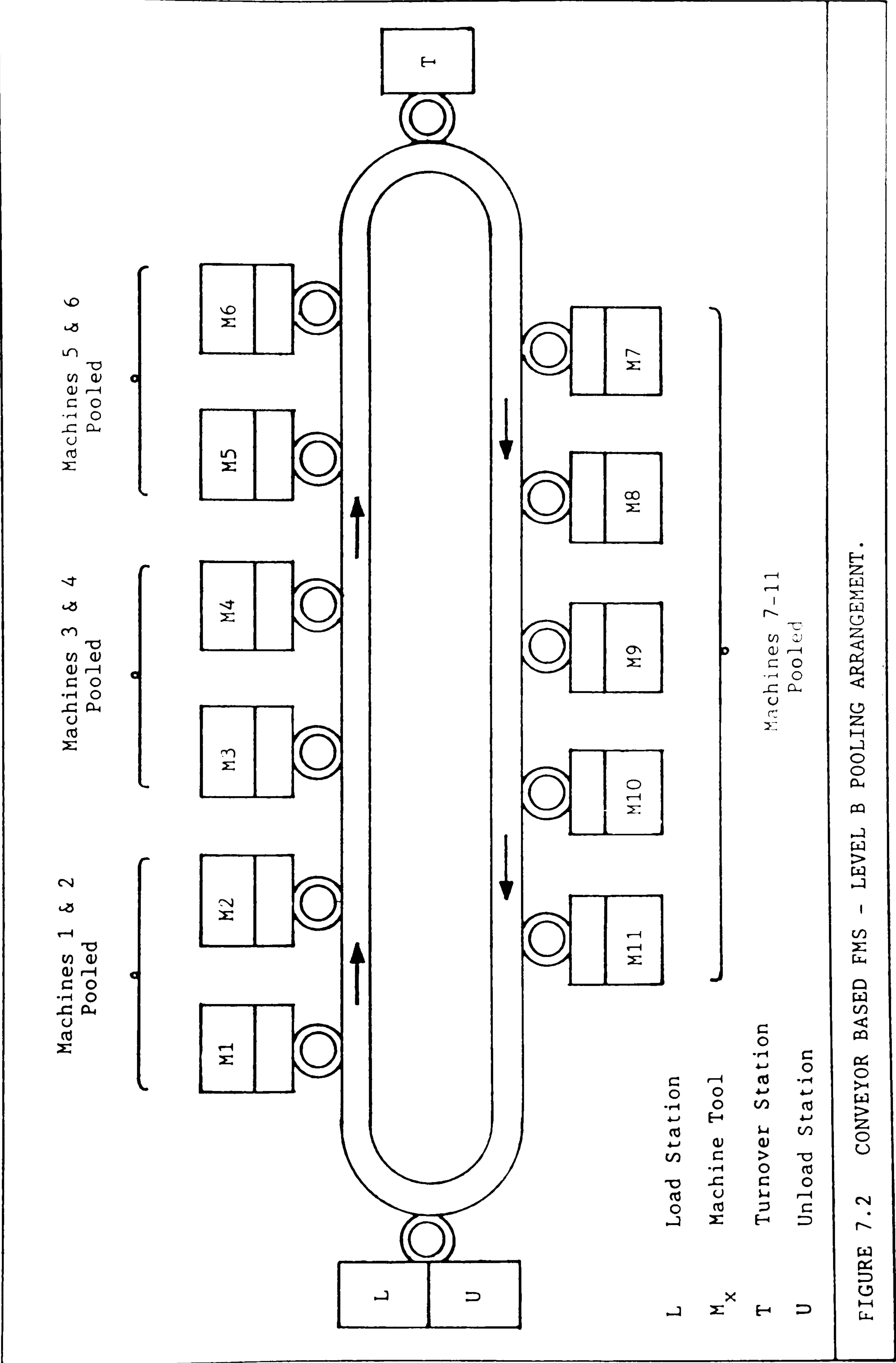


FIGURE 7.2 CONVEYOR BASED FMS - LEVEL B POOLING ARRANGEMENT.

Machines 1-4
Pooled

Machines 5 & 6
Pooled

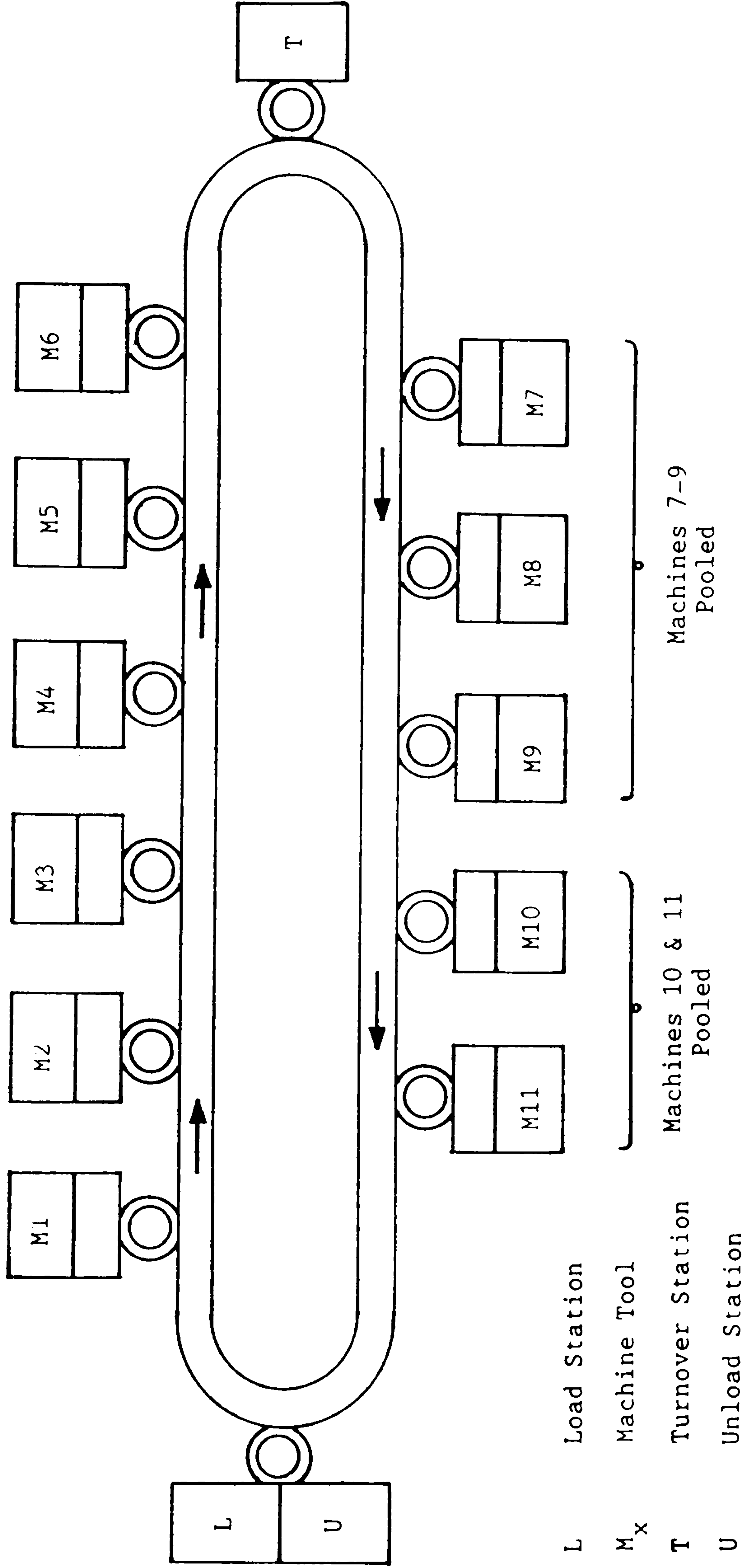


FIGURE 7.3 CONVEYOR BASED FMS - LEVEL C POOLING ARRANGEMENT

Machines 1-4
Pooled

Machines 5 & 6
Pooled

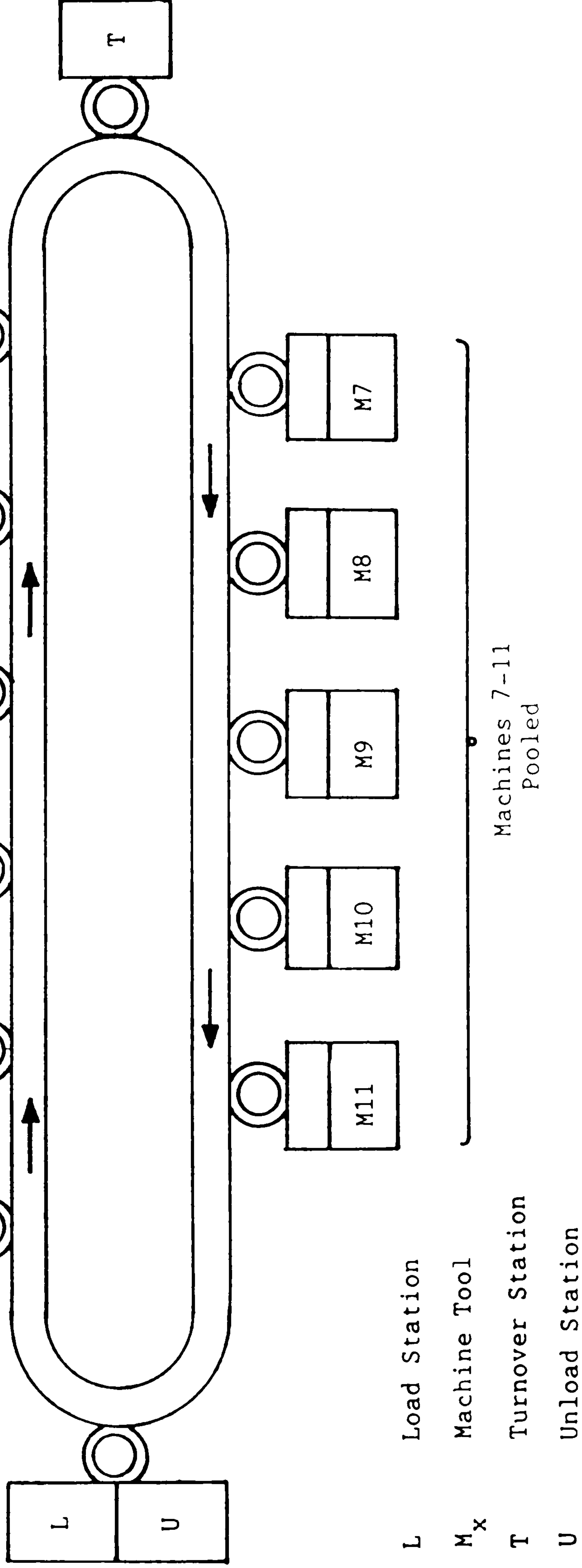


FIGURE 7.4 CONVEYOR BASED FMS - LEVEL D POOLING ARRANGEMENT.

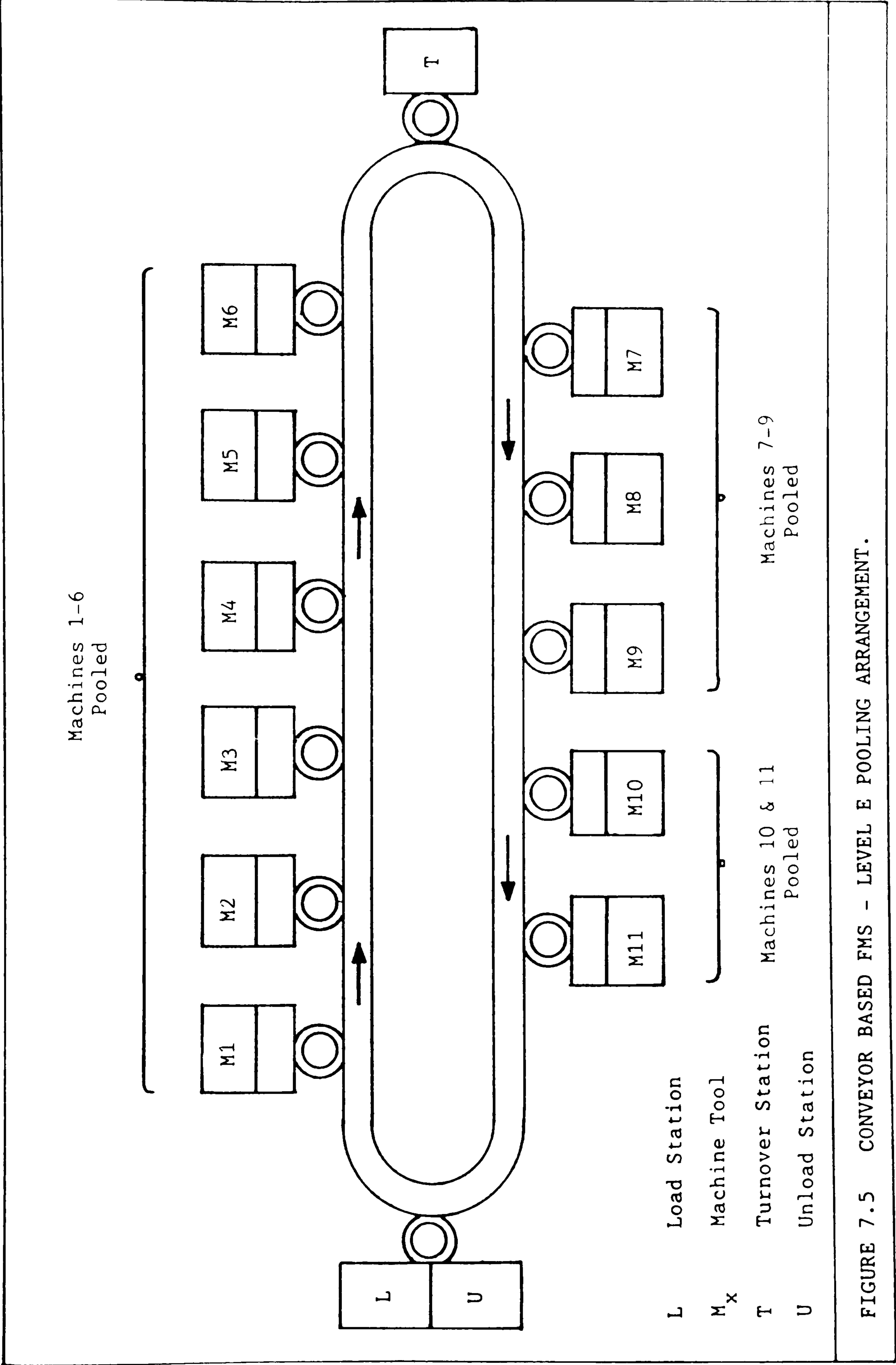


FIGURE 7.5 CONVEYOR BASED FMS - LEVEL E POOLING ARRANGEMENT.

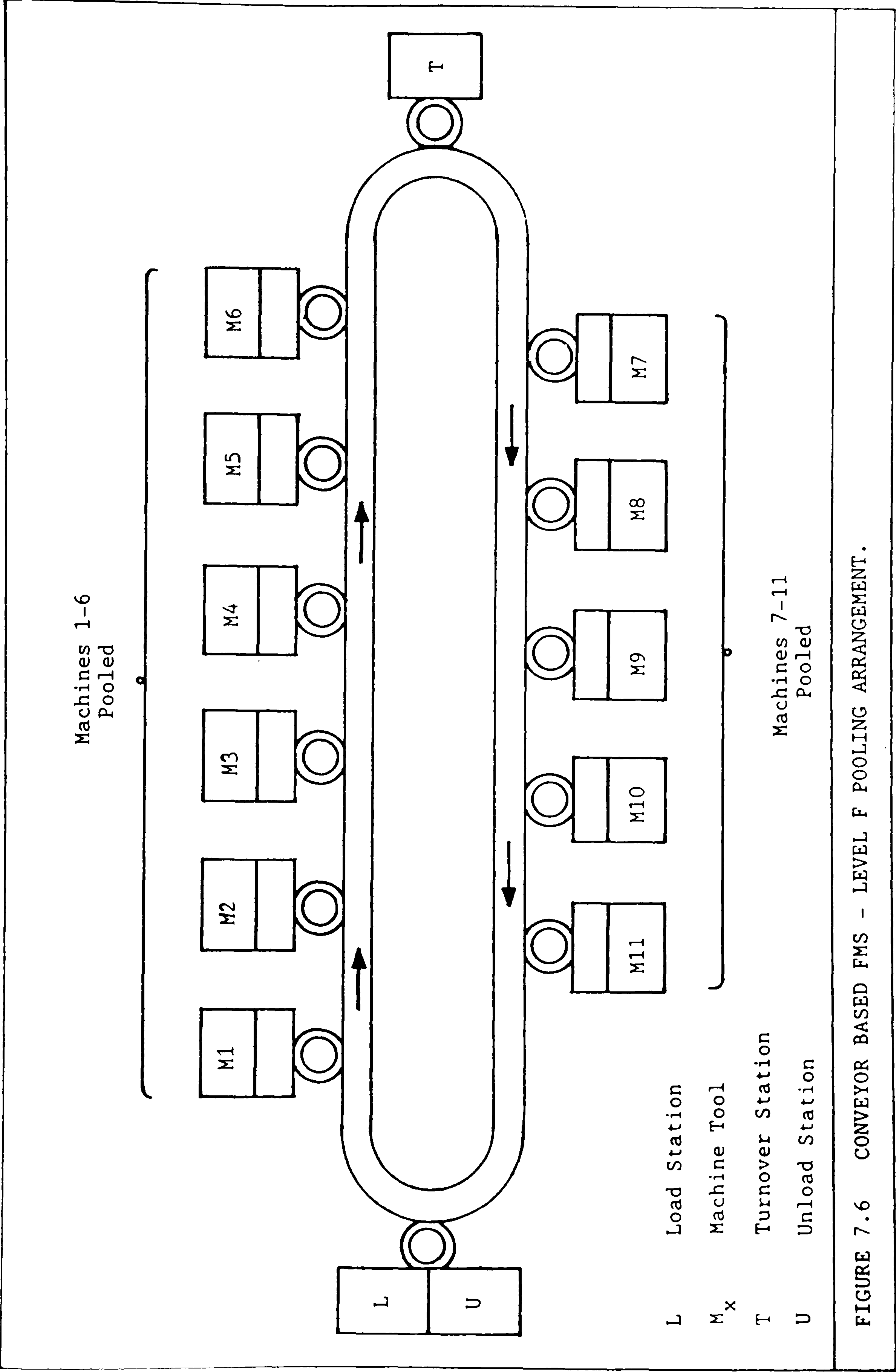


FIGURE 7.6 CONVEYOR BASED FMS - LEVEL F POOLING ARRANGEMENT.

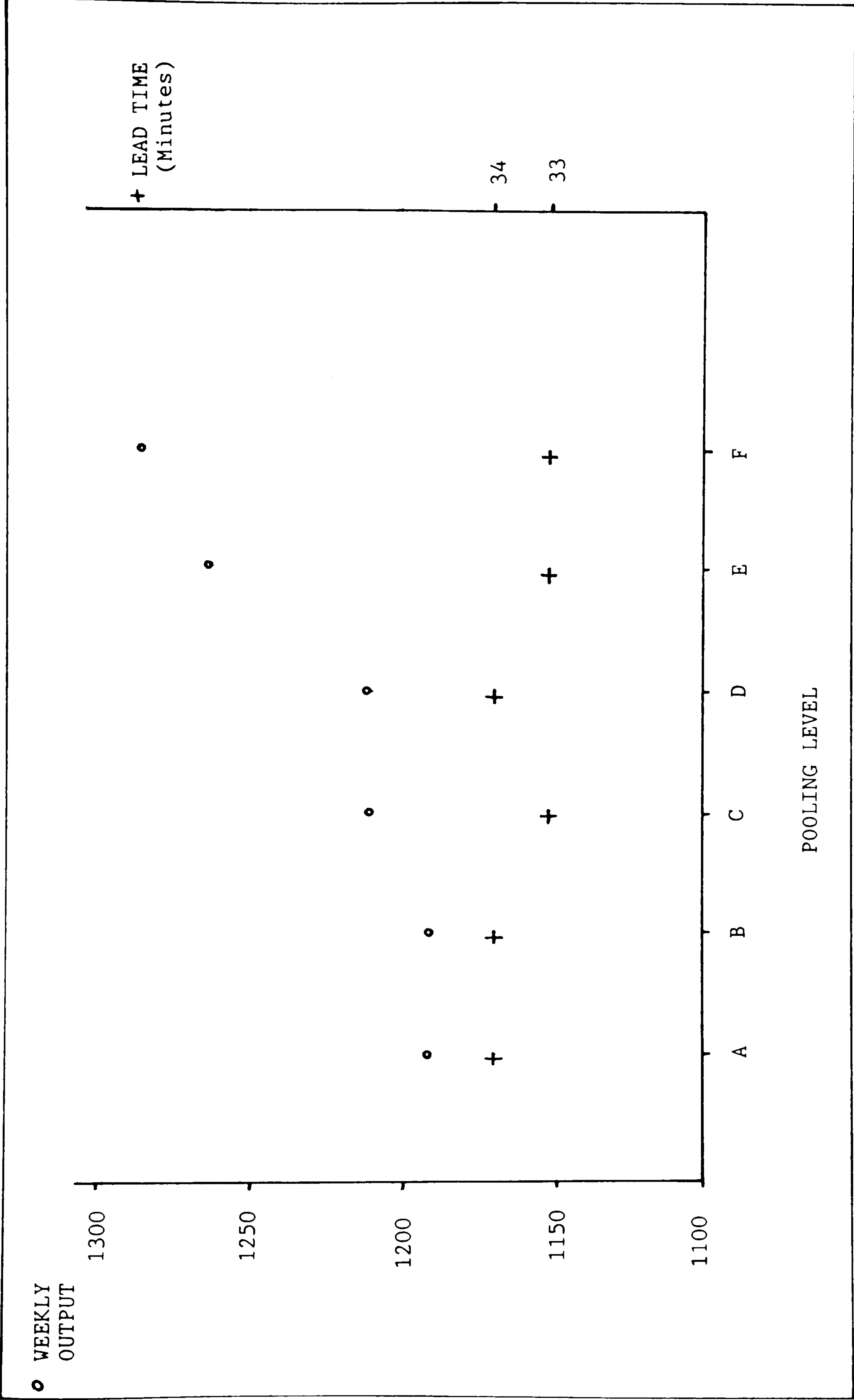


FIGURE 7.7 WORKLOAD MODEL RESULTS.

POOLING LEVEL	M A X I M U M W O R K I N P R O G R E S S				
	10	21	42	INF	
A OUTPUT LEAD TIME	587 25	910 33	1091 55	1189 INF	
B OUTPUT LEAD TIME	599 24	938 32	1109 55	1189 INF	
C OUTPUT LEAD TIME	621 24	962 31	1140 53	1210 INF	
D OUTPUT LEAD TIME	625 23	1001 30	1163 52	1210 INF	
E OUTPUT LEAD TIME	630 23	1022 30	1202 50	1288 INF	
F OUTPUT LEAD TIME	646 22	1081 28	1241 49	1288 INF	

FIGURE 7.8 QUEUING MODEL RESULTS SUMMARY.

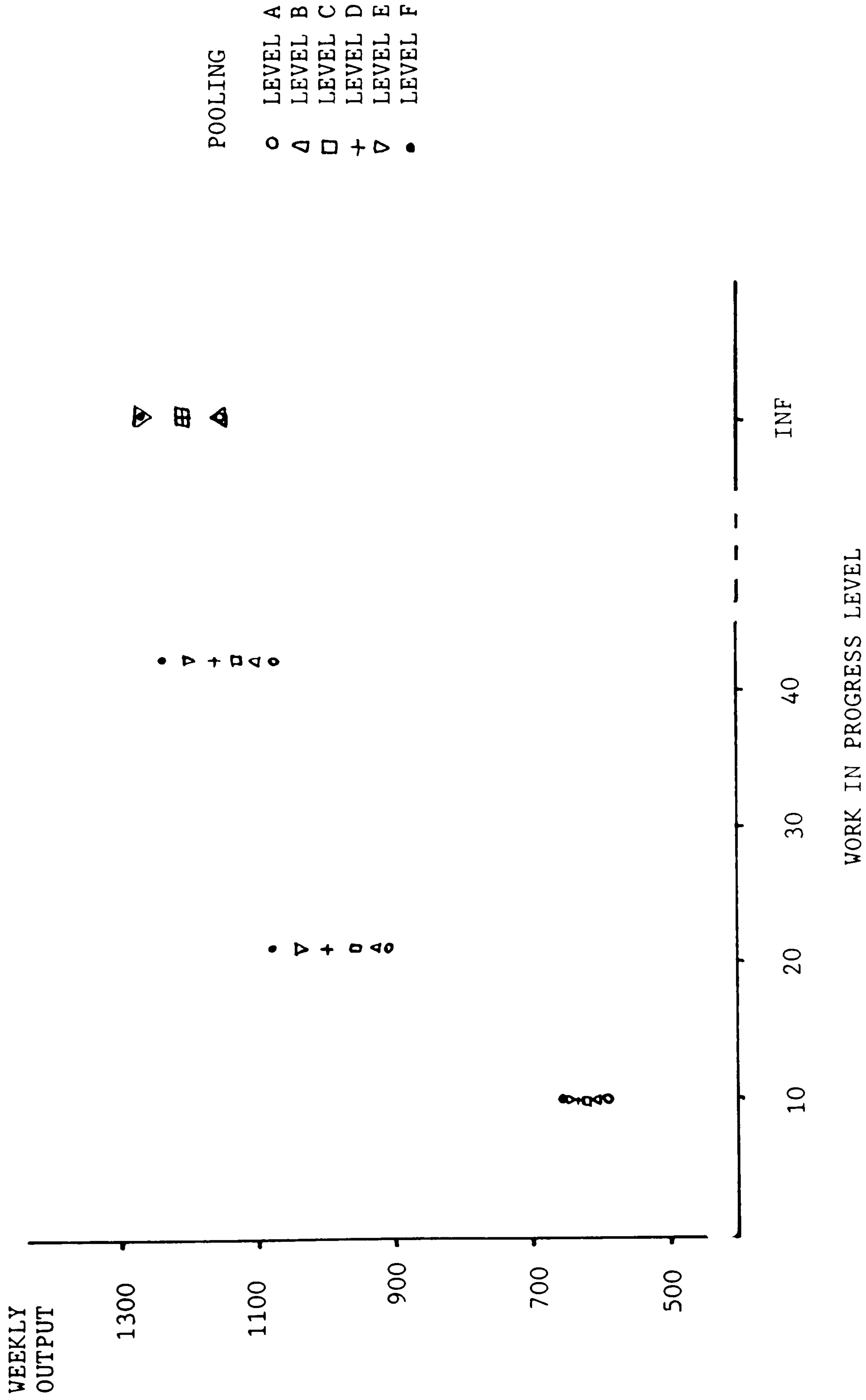


FIGURE 7.9 QUEUING MODEL RESULTS - OUTPUT ANALYSIS

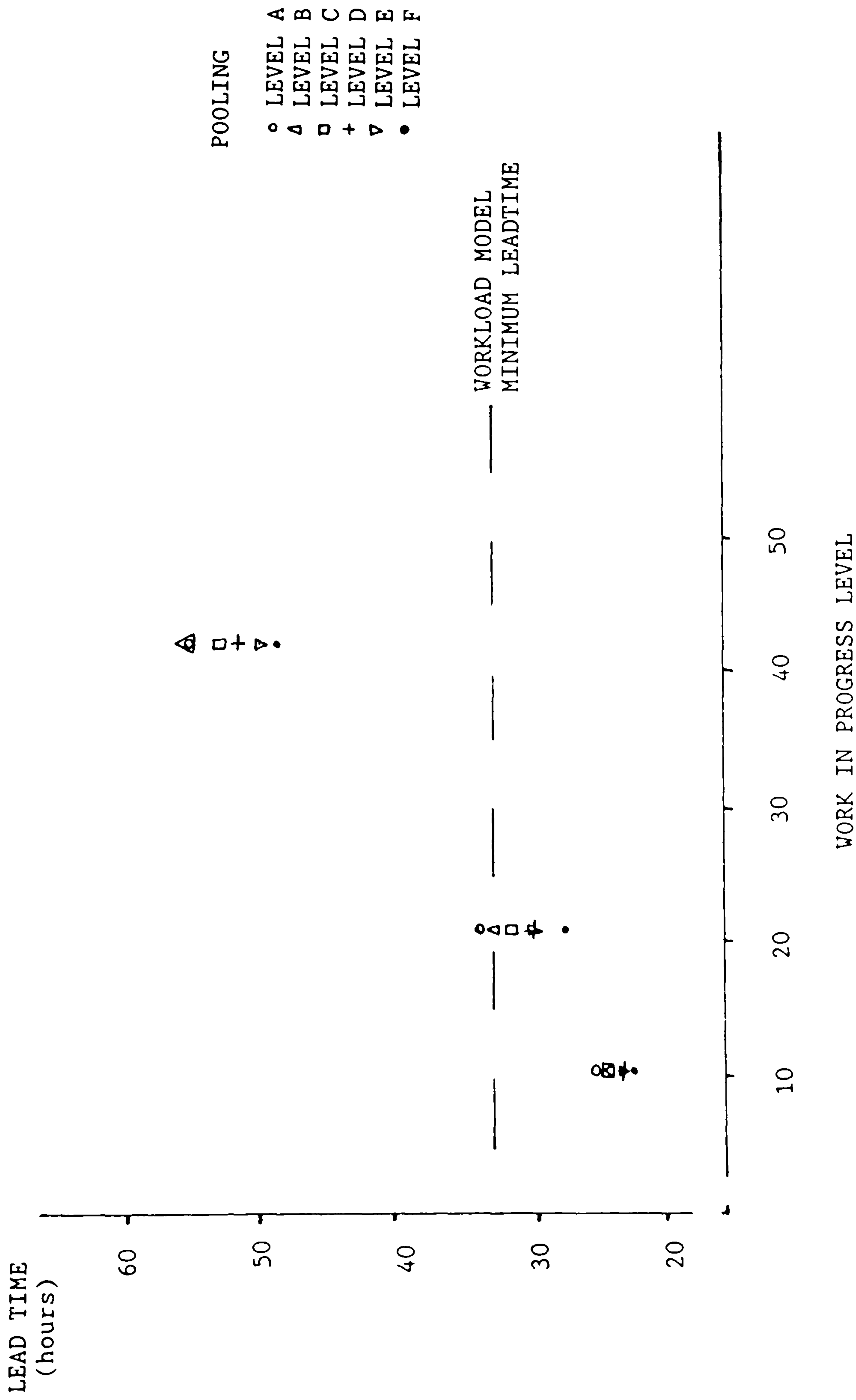


FIGURE 7.10 QUEUING MODEL RESULTS - LEAD TIME ANALYSIS.

POOLING LEVEL	M A X I M U M W O R K I N P R O G R E S S						
	21	22	23	24	25	26	42
A OUTPUT LEAD TIME	1151 44	1161 45	1186 47	1189 48	1189 50	1189 52	1190 85
B OUTPUT LEAD TIME	1150 44	1163 46	1189 46	1189 48	1189 50	1189 52	1189 85
C OUTPUT LEAD TIME	1159 44	1159 46	1181 47	1179 49	1179 51	1179 53	1179 85
D OUTPUT LEAD TIME	1166 43	1163 45	1177 47	1179 49	1179 51	1178 53	1178 86
E OUTPUT LEAD TIME	994 51	997 53	994 56	991 58	994 60	995 63	997 101
F OUTPUT LEAD TIME	998 51	993 53	989 56	994 58	995 60	992 63	991 102

FIGURE 7.11 SIMULATION MODEL RESULTS SUMMARY.

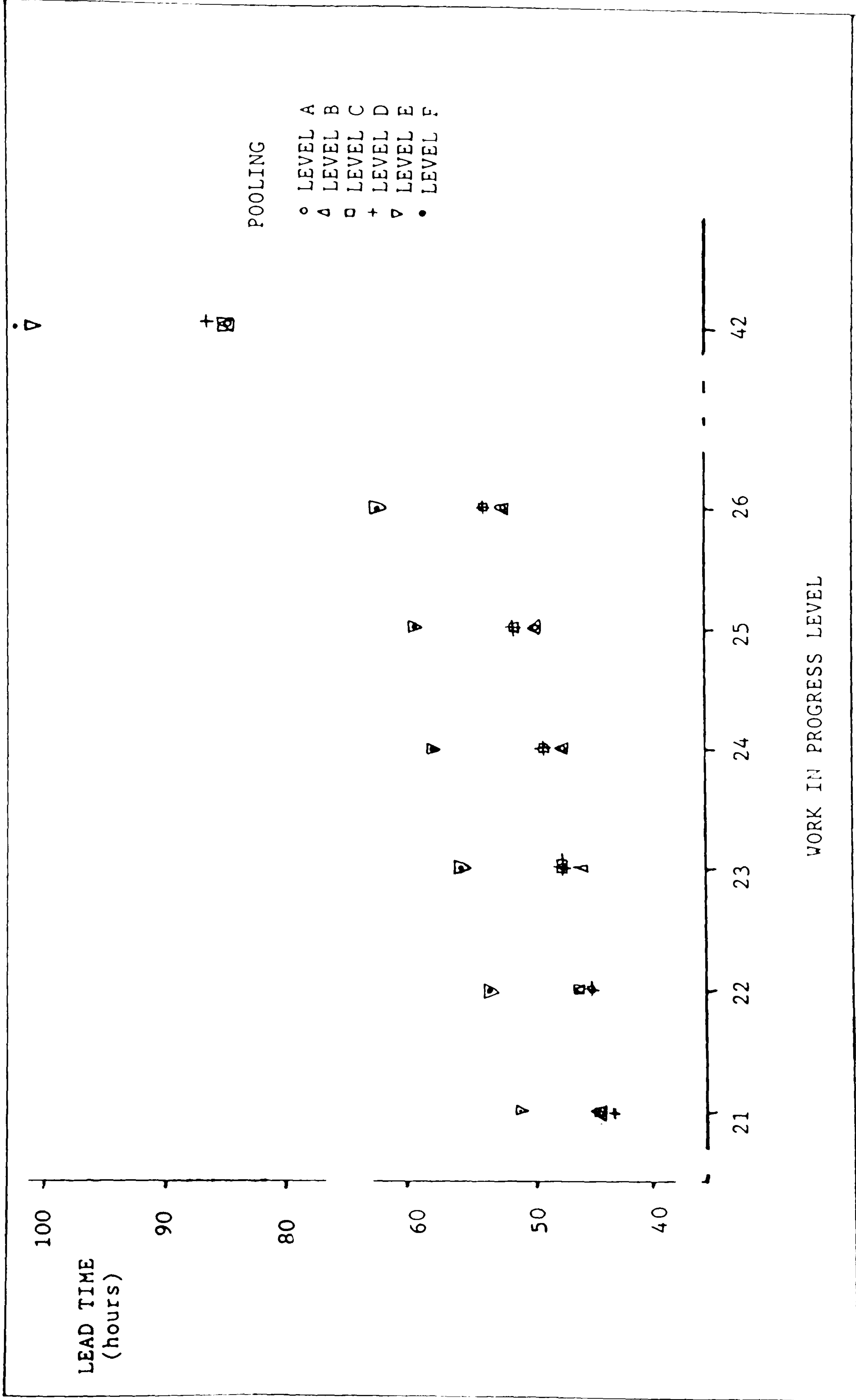


FIGURE 7.12 SIMULATION MODEL RESULTS - LEAD TIMES ANALYSIS.

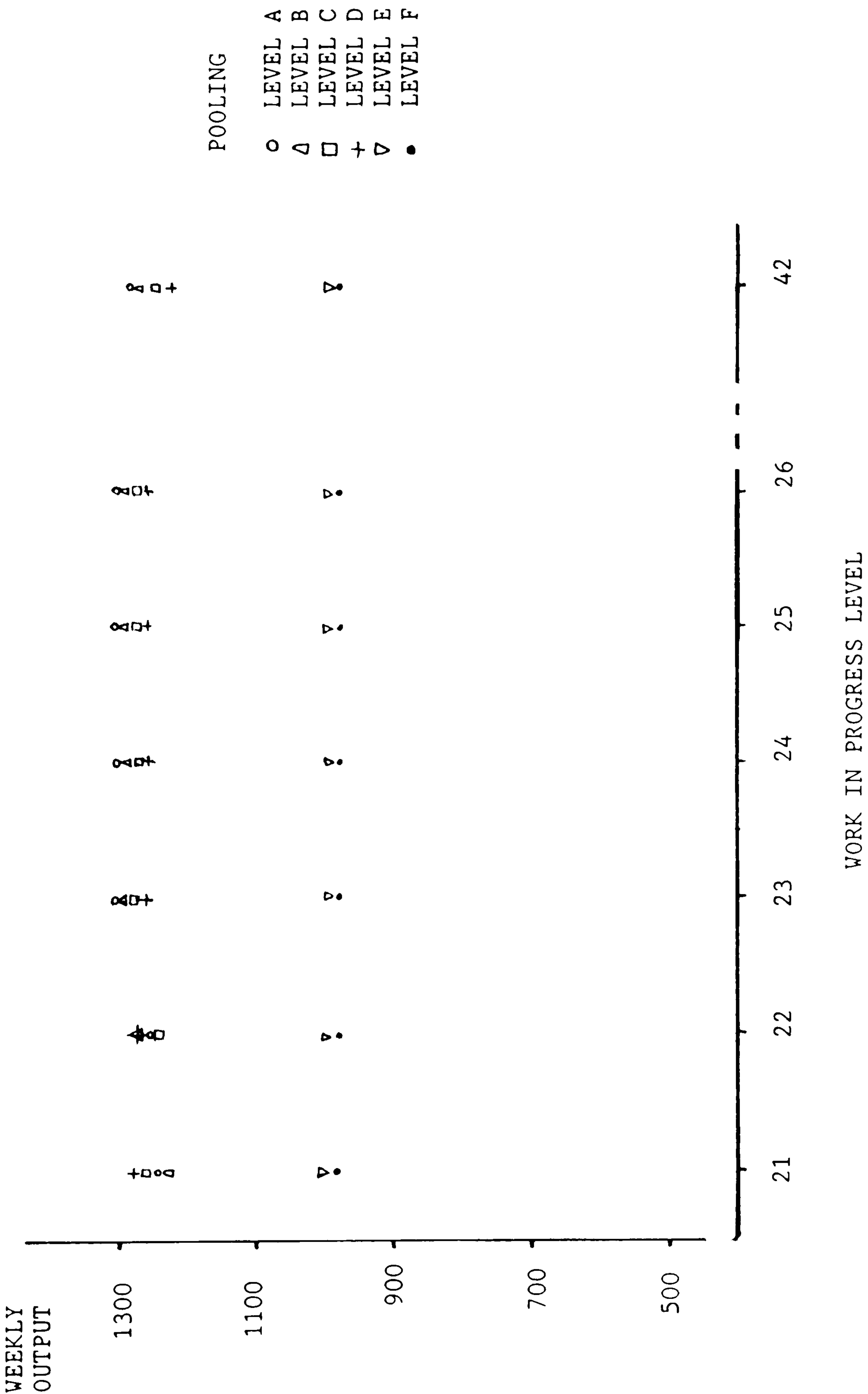


FIGURE 7.13 SIMULATION MODEL RESULTS - OUTPUT ANALYSIS.

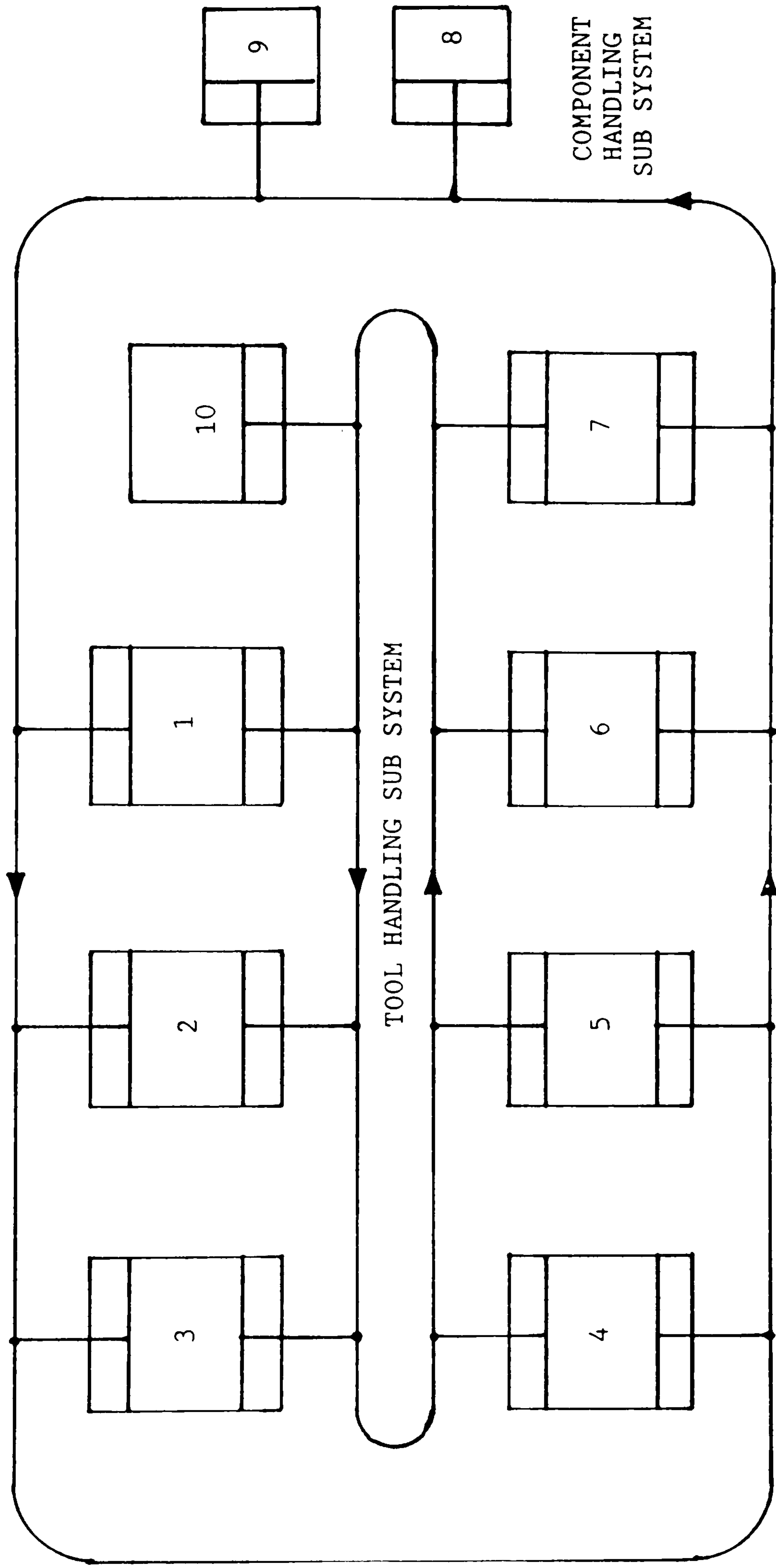


FIGURE 8.1 PATHSIM MODEL NETWORK BLOCK DIAGRAM.

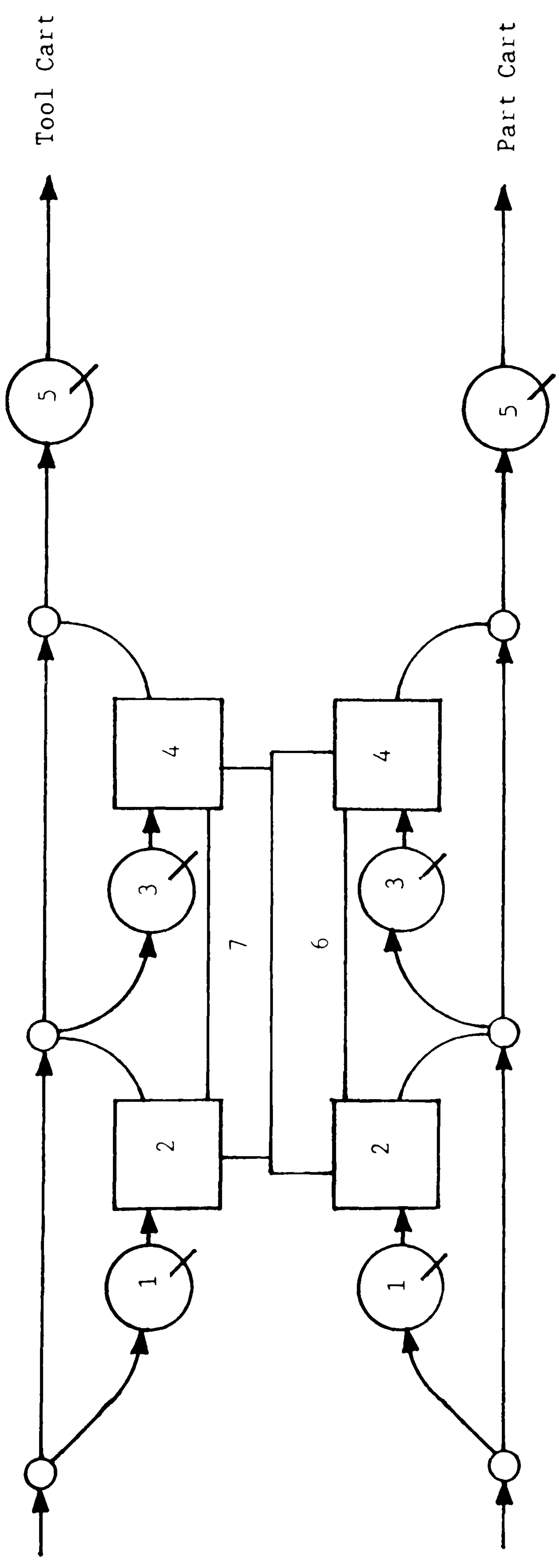
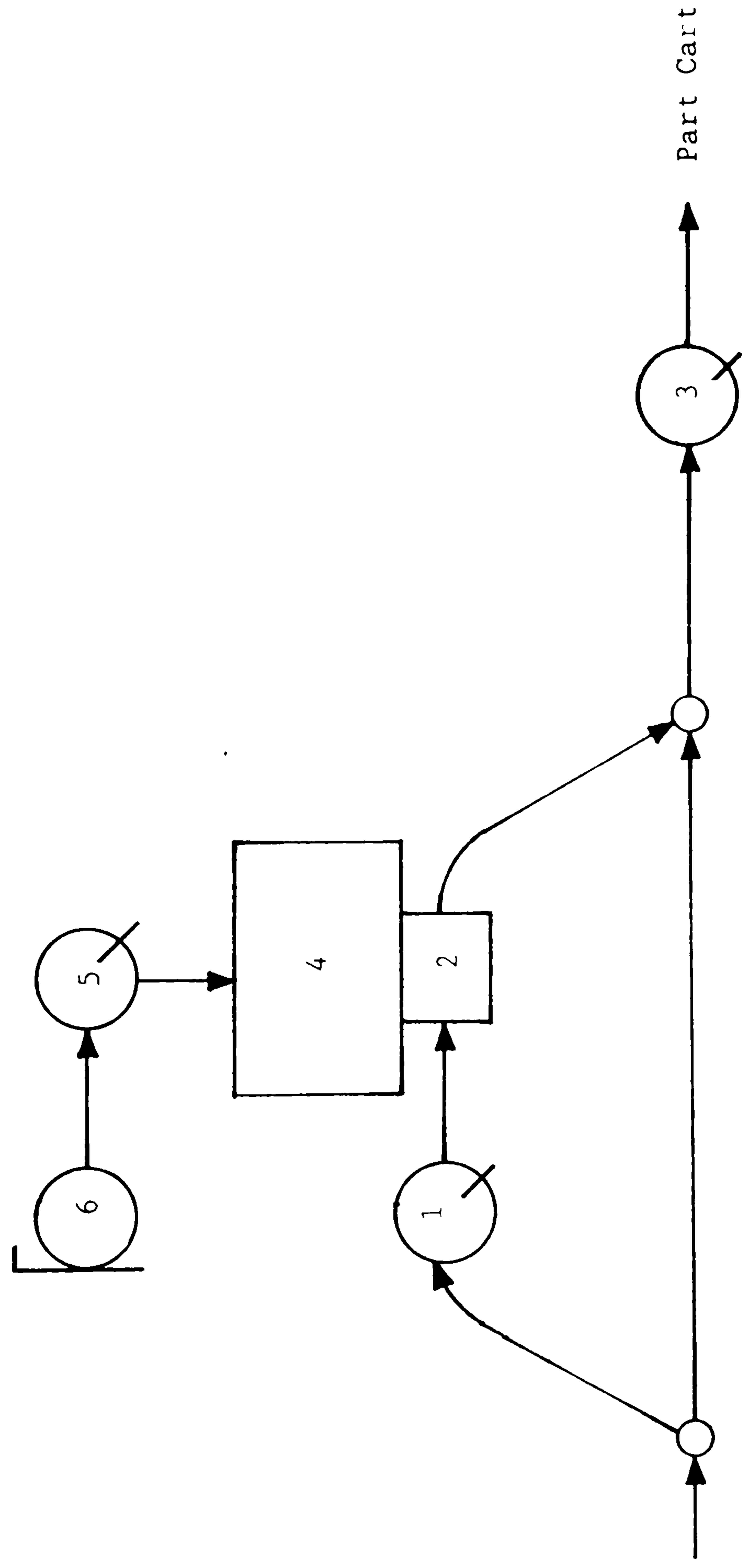


FIGURE 8.2 PATHSIM MODEL PROCESSING UNIT MODULE BLOCK DIAGRAM.



- 0. Cart decision point
- 1. queue of empty carts awaiting loading
- 2. Load shuttle
- 3. Queue of idle carts between modules
- 4. Load station
- 5. Queue of parts awaiting loading
- 6. Batch creation mechanism

FIGURE 8.3 PATHSIM MODEL LOAD STATION MODULE BLOCK DIAGRAM.

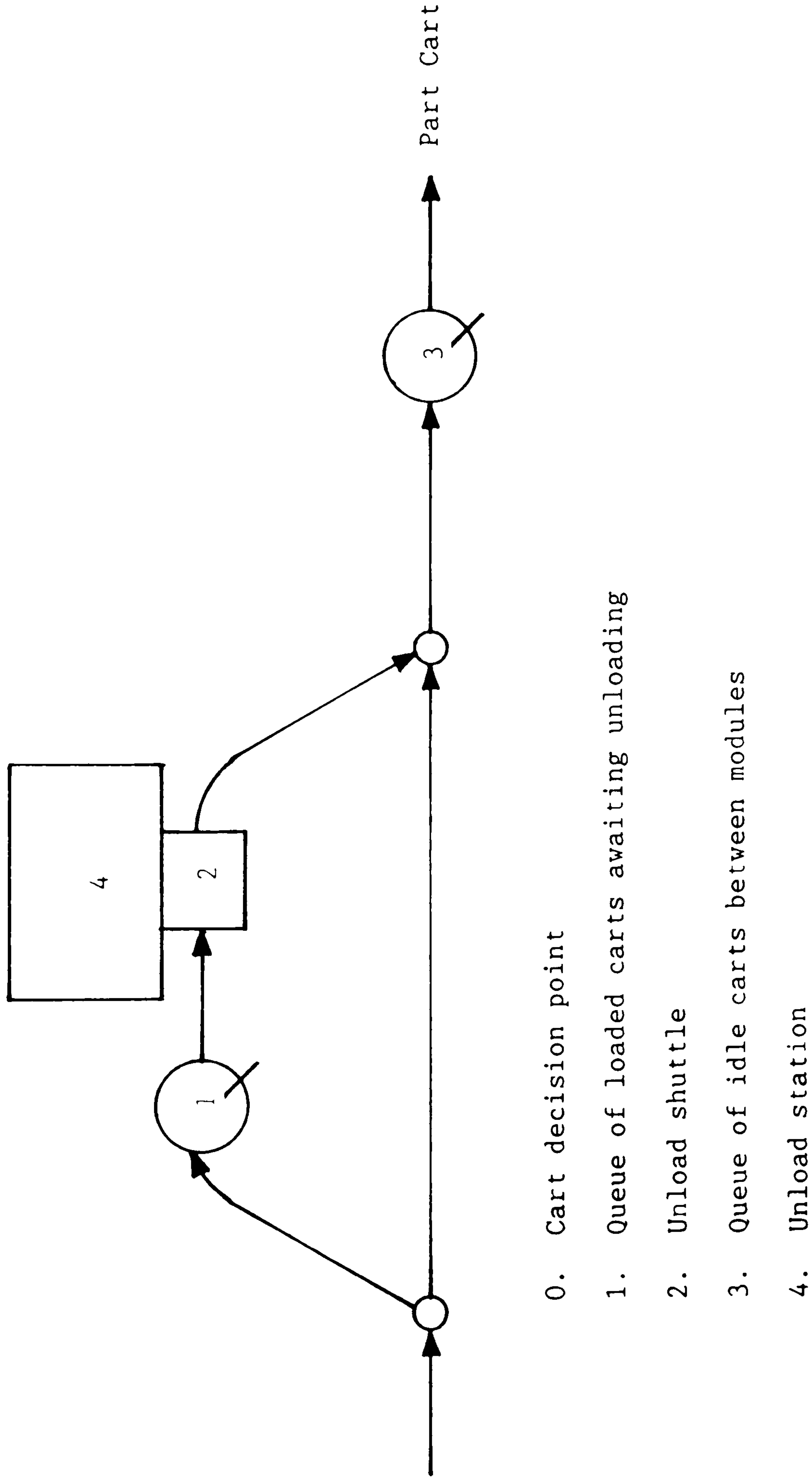
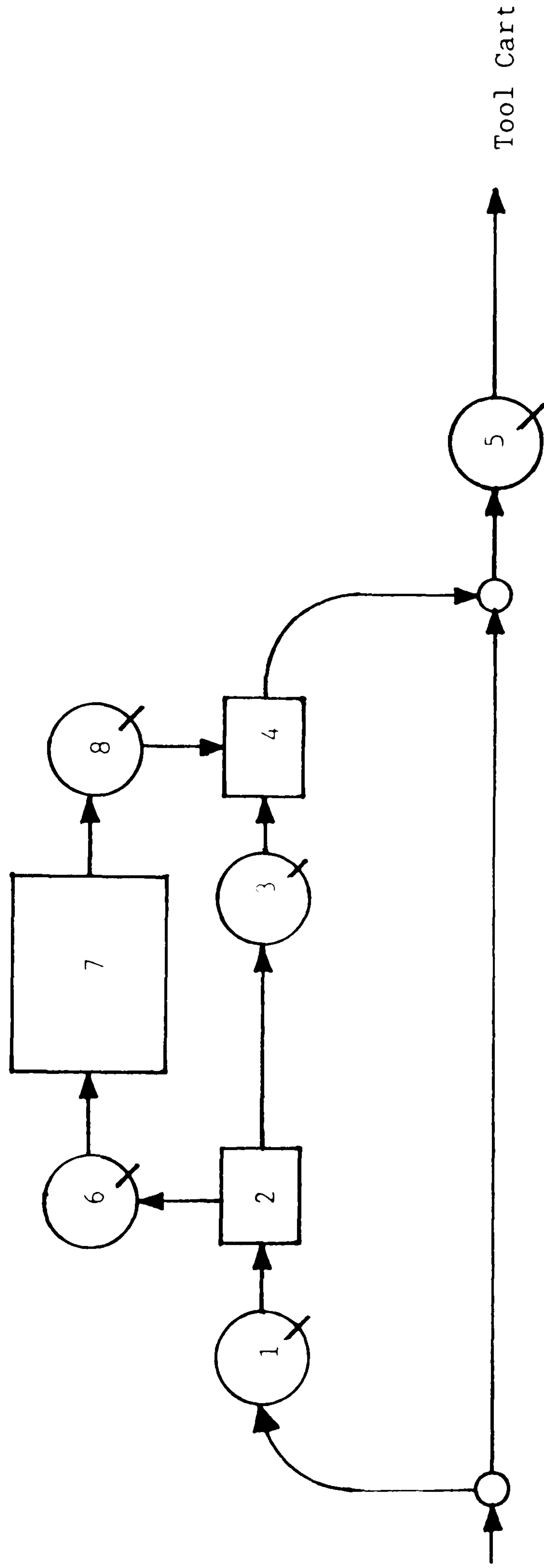
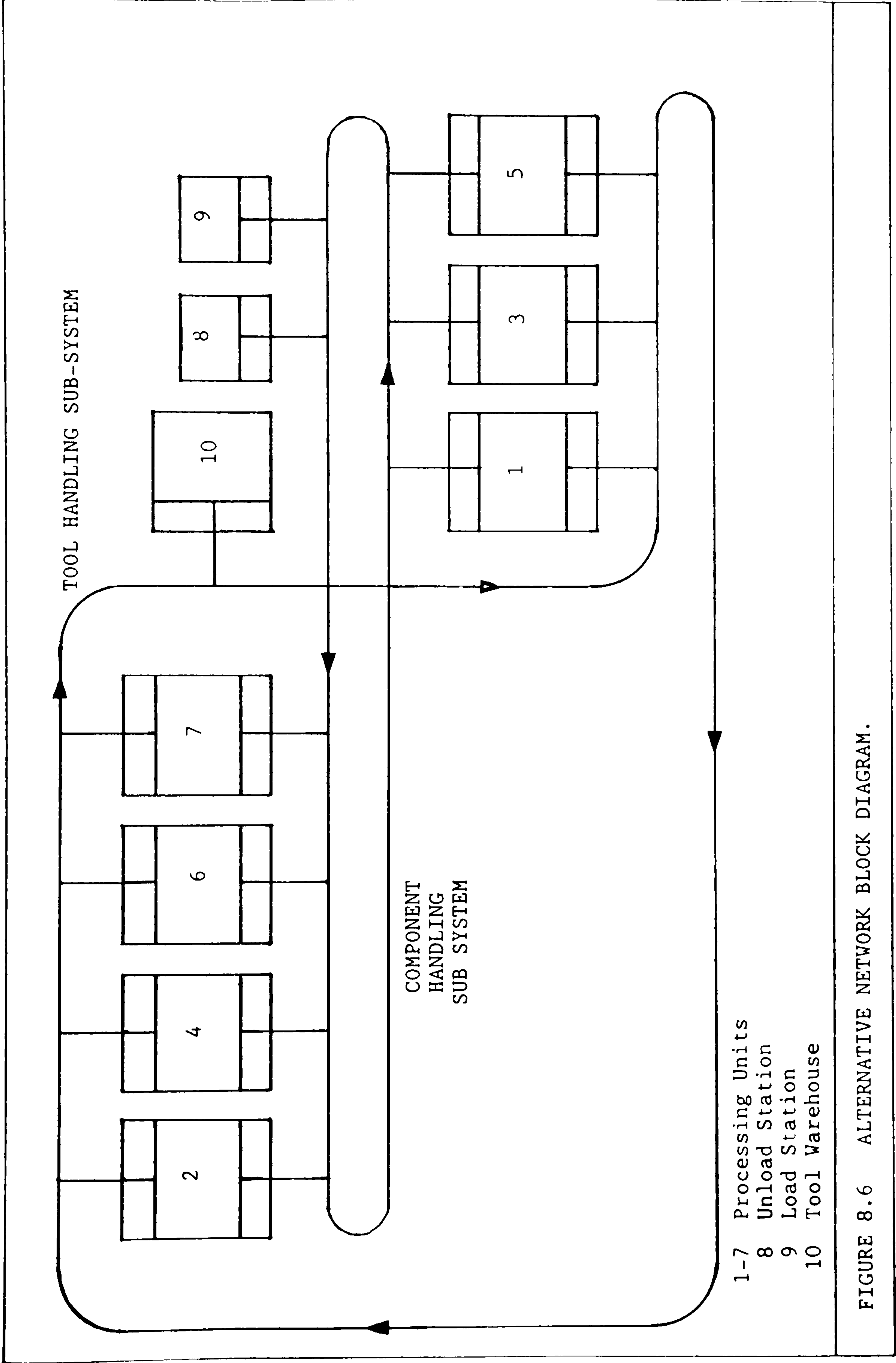


FIGURE 8.4 PATHSIM MODEL UNLOAD STATION MODULE BLOCK DIAGRAM.



- 0. Cart decision point
- 1. Queue of loaded carts awaiting unloading
- 2. Tool on-shuttle
- 3. Queue of unloaded carts awaiting loading
- 4. Tool off-shuttle
- 5. Queue of idle carts between modules
- 6. Queue of tools awaiting regrinding
- 7. Regrinding operation
- 8. Tools in warehouse awaiting allocation

FIGURE 8.5 PATHSIM MODEL TOOL WAREHOUSE MODULE BLOCK DIAGRAM.



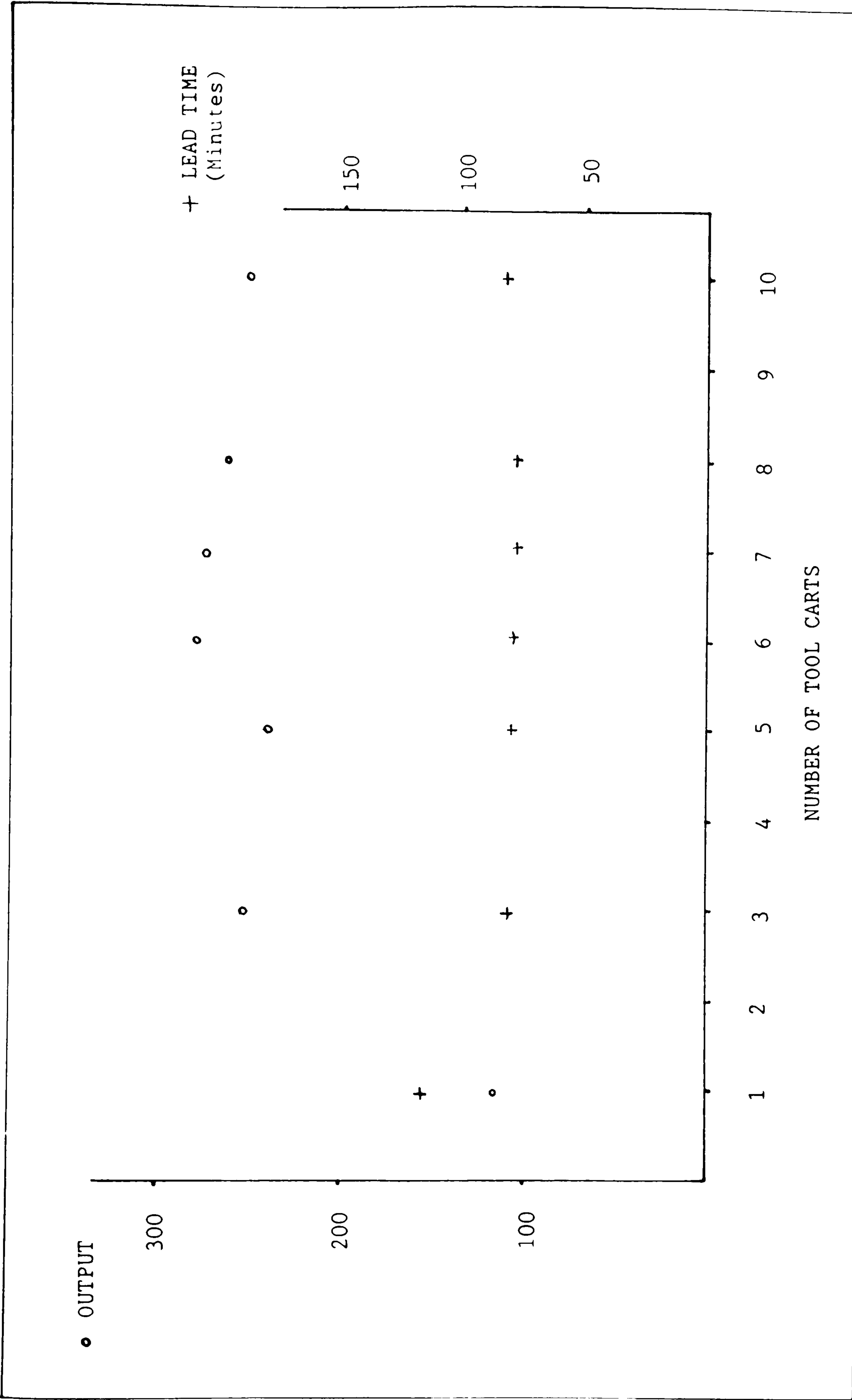


FIGURE 8.7 PATHSIM MODEL RESULTS - NUMBER OF TOOL CARTS.

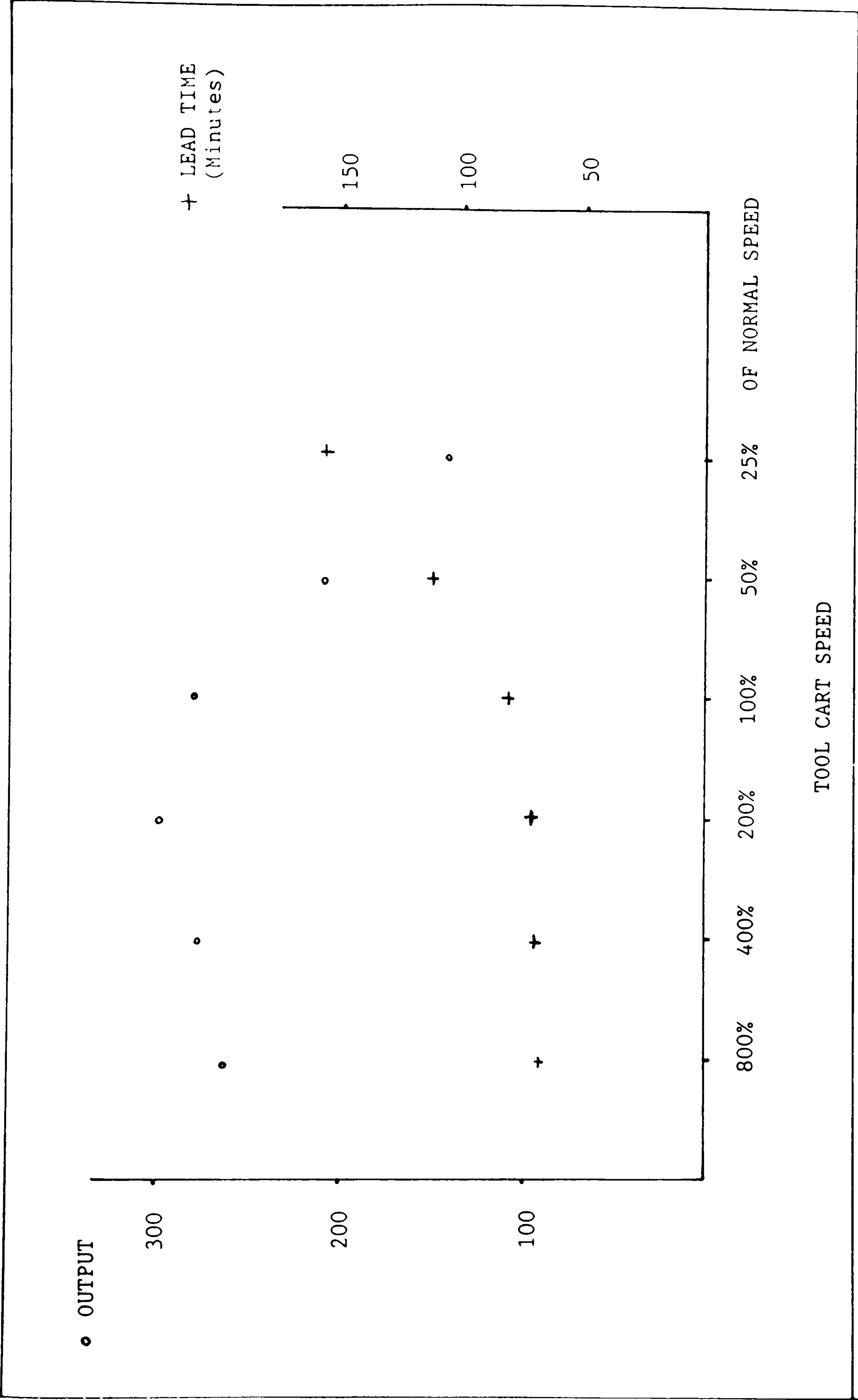


FIGURE 8.8 PATHSIM MODEL RESULTS - TOOL CART SPEED.

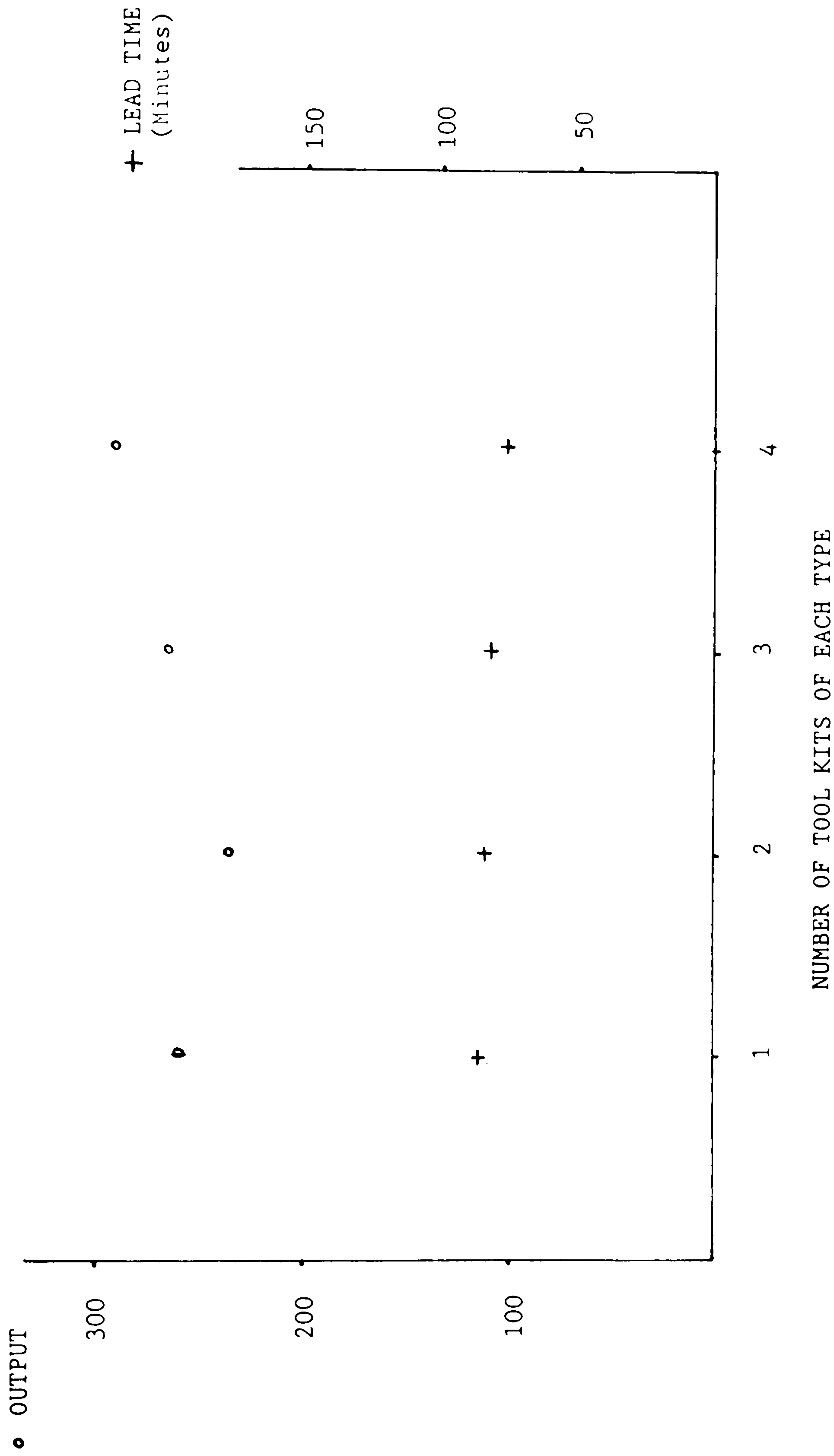


FIGURE 8.9 PATHSIM MODEL RESULTS - NUMBER OF TOOL KITS.

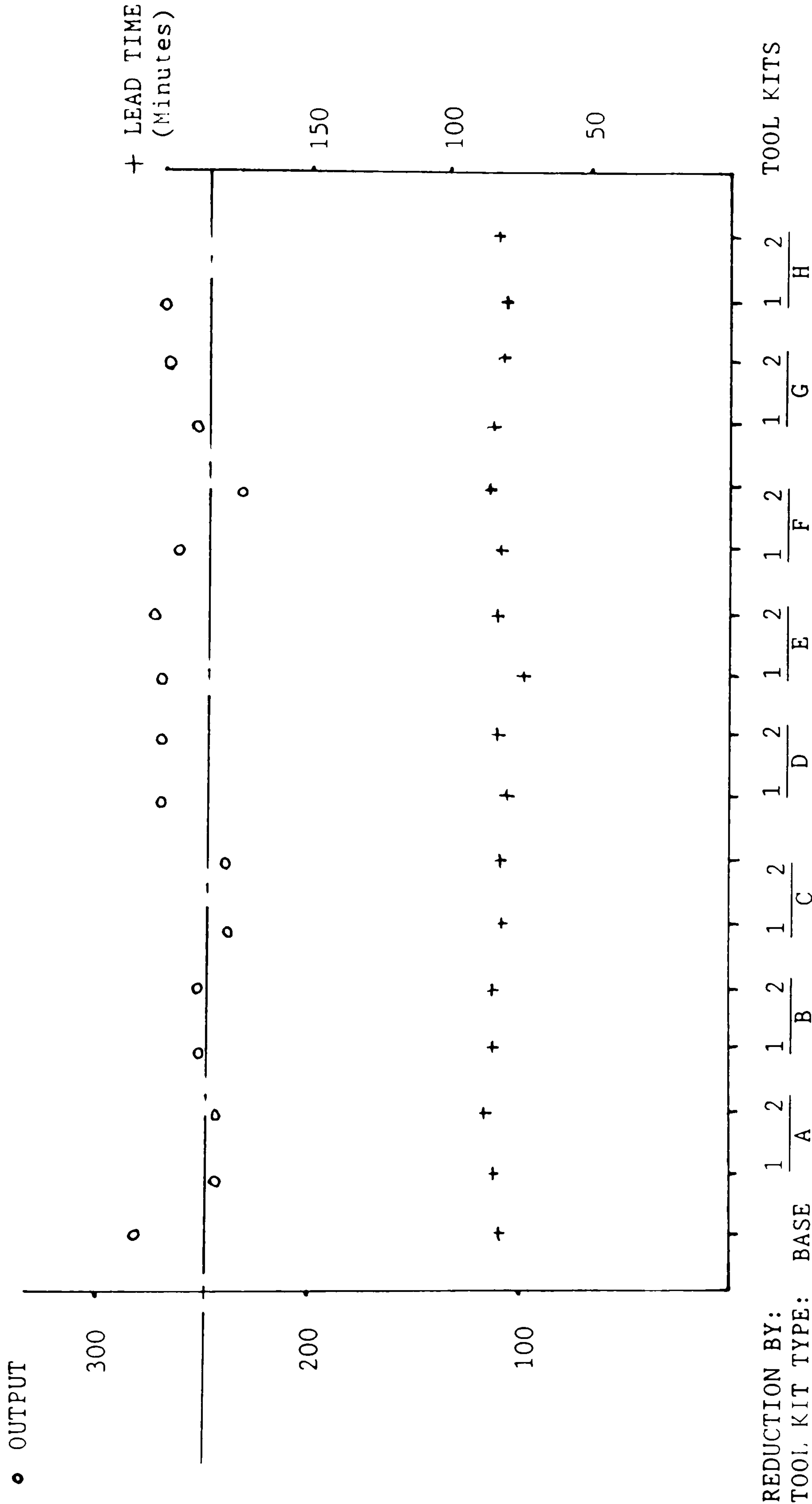


FIGURE 8.10 PATHSIM MODEL RESULTS - IDENTIFICATION OF CRITICAL TOOL KIT TYPES

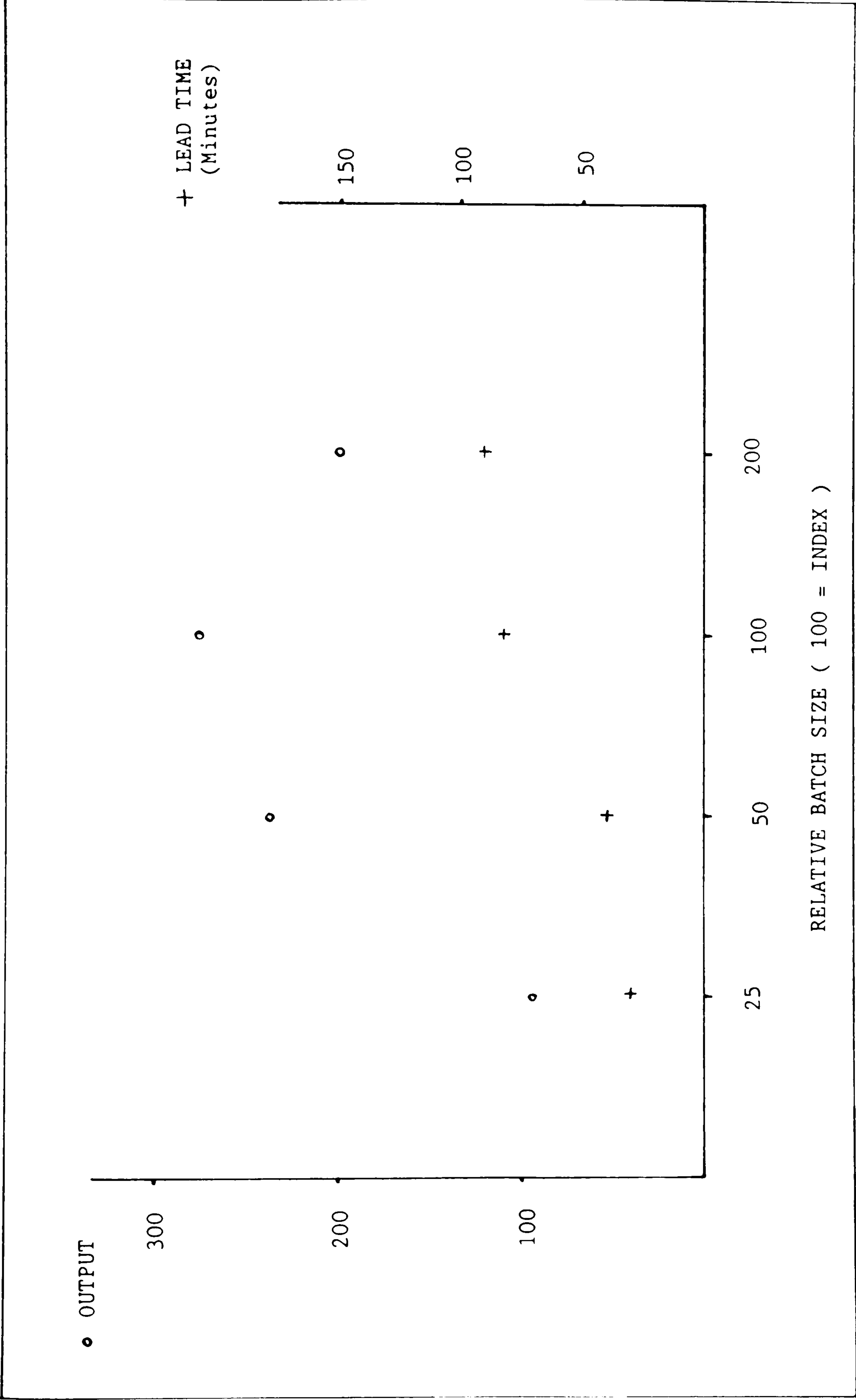


FIGURE 8.13 PATHSIM MODEL RESULTS - COMPONENT BATCH SIZE.

NB. Output is by component, not by batch.

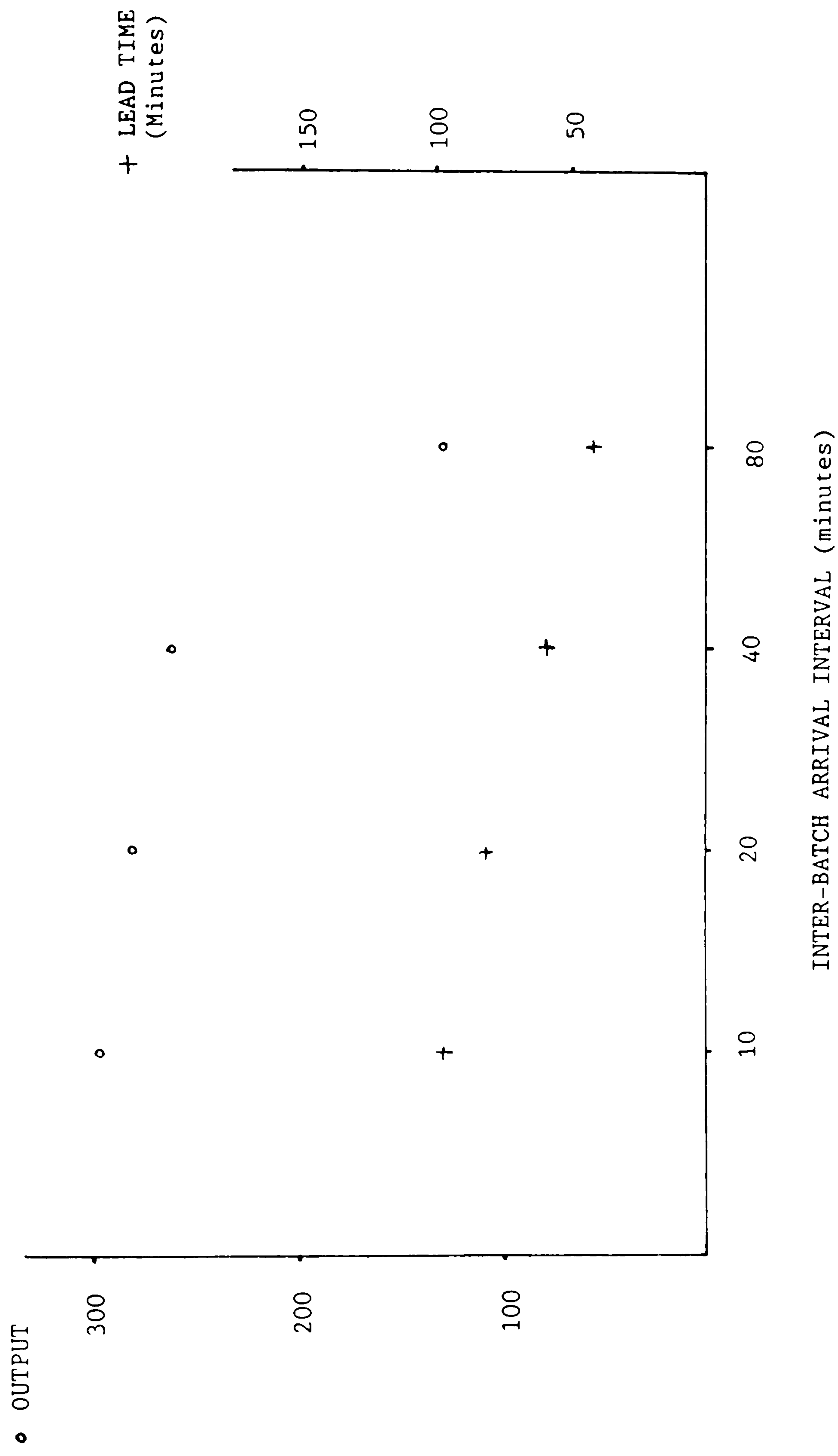


FIGURE 8.14 PATHSIM MODEL RESULTS - COMPONENT BATCH FREQUENCY.

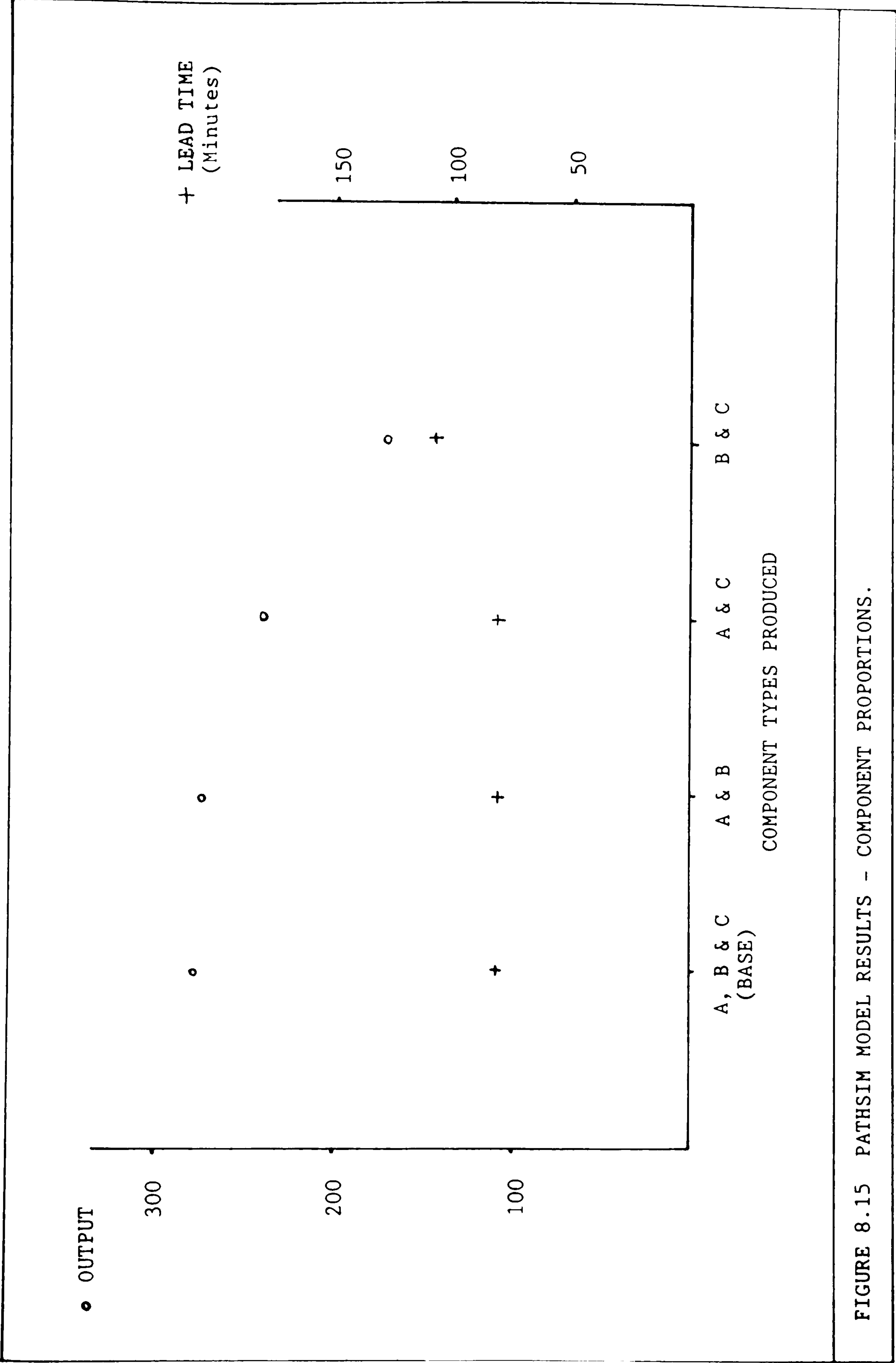


FIGURE 8.15 PATHSIM MODEL RESULTS - COMPONENT PROPORTIONS.

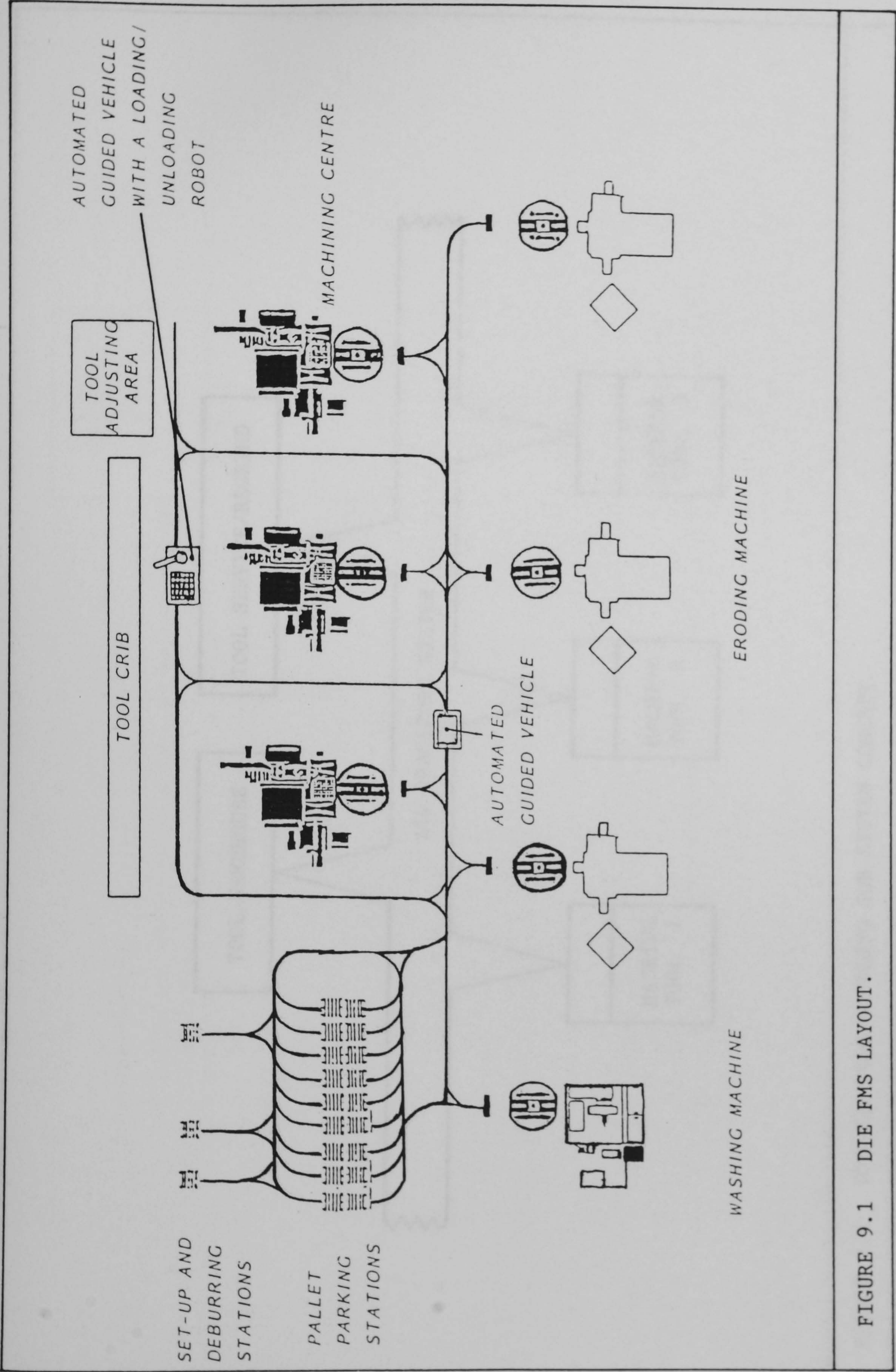


FIGURE 9.1 DIE FMS LAYOUT.

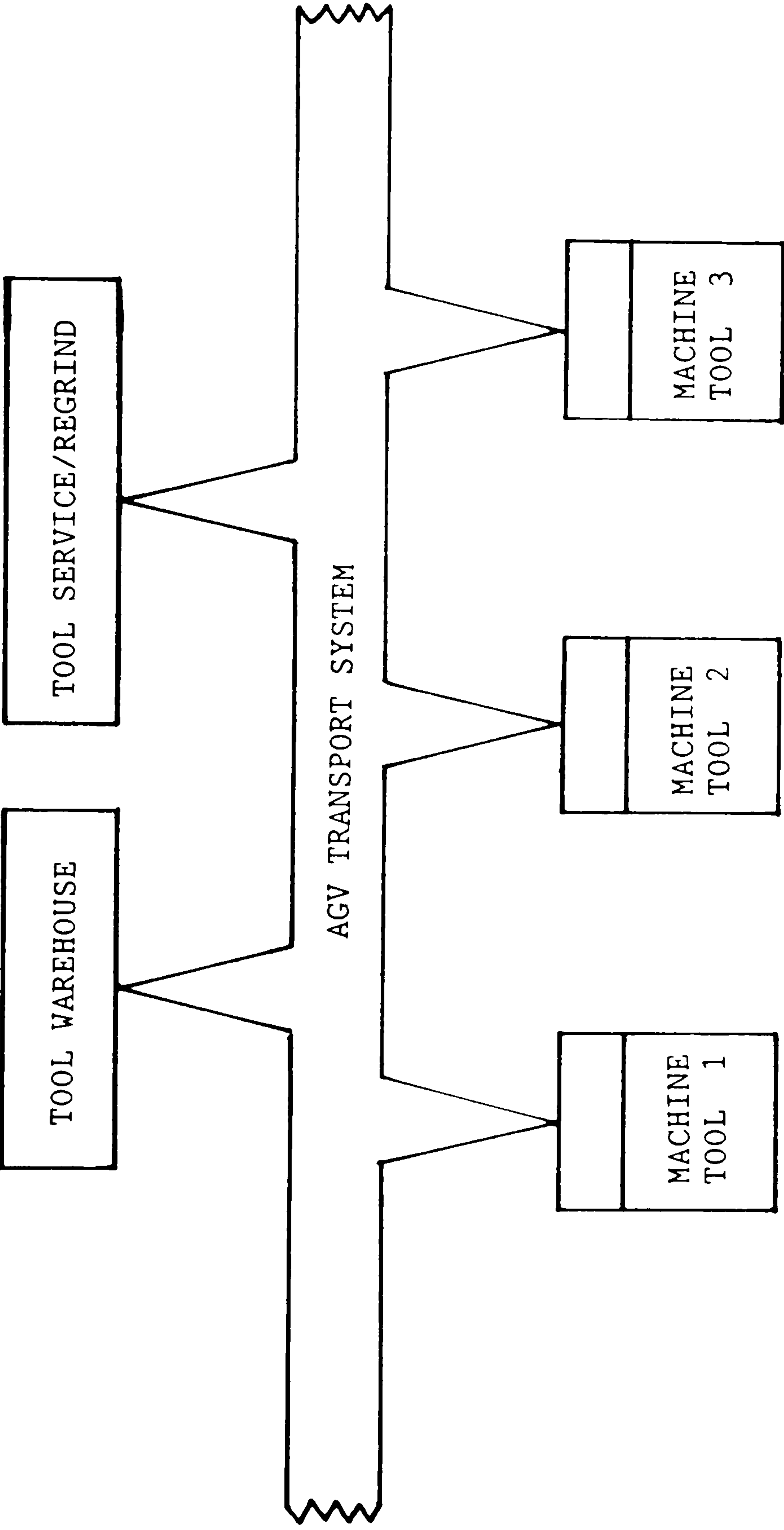


FIGURE 9.2 DIE FMS TOOL HANDLING SUB-SYSTEM CONCEPT.

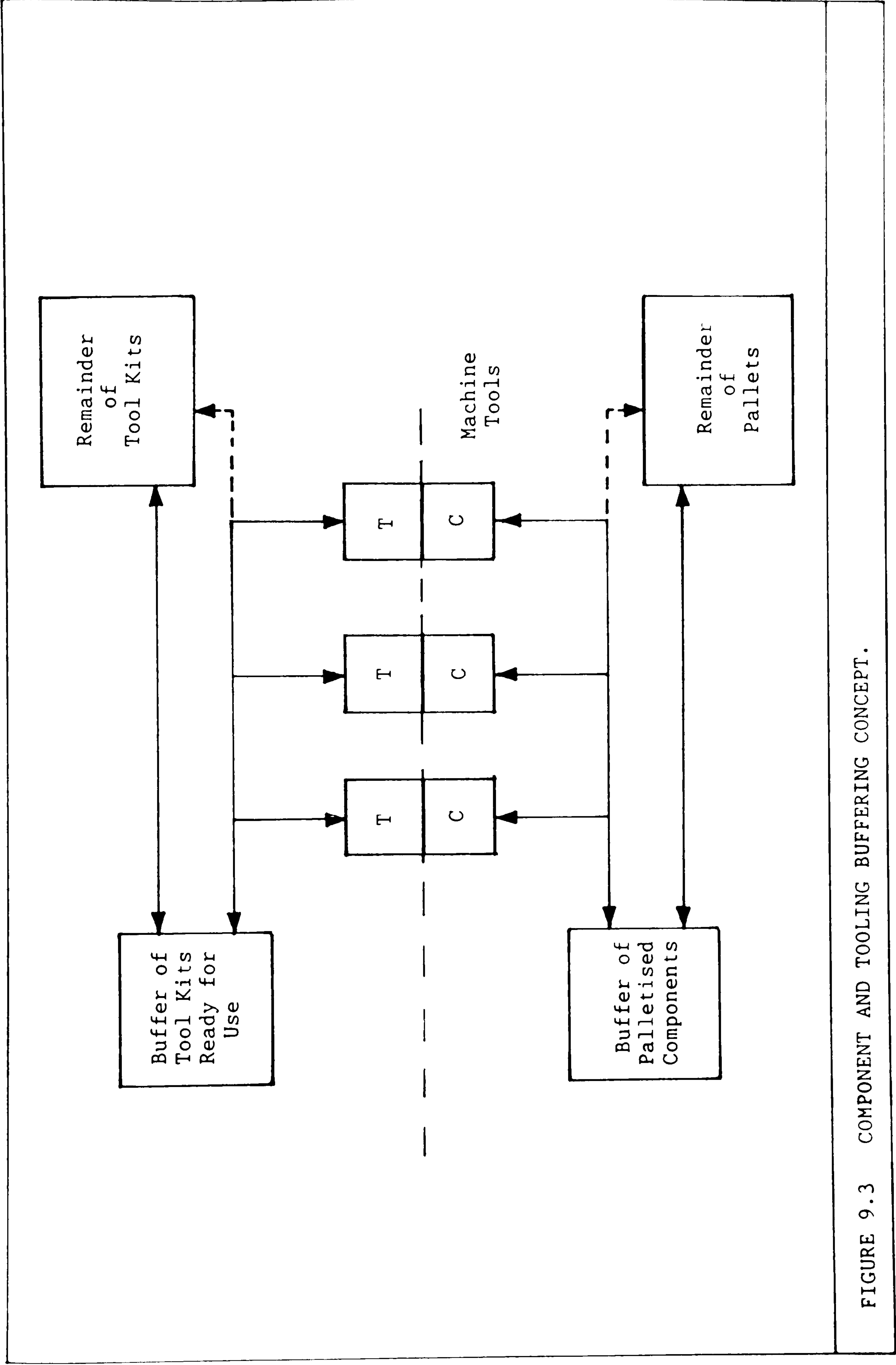


FIGURE 9.3 COMPONENT AND TOOLING BUFFERING CONCEPT.

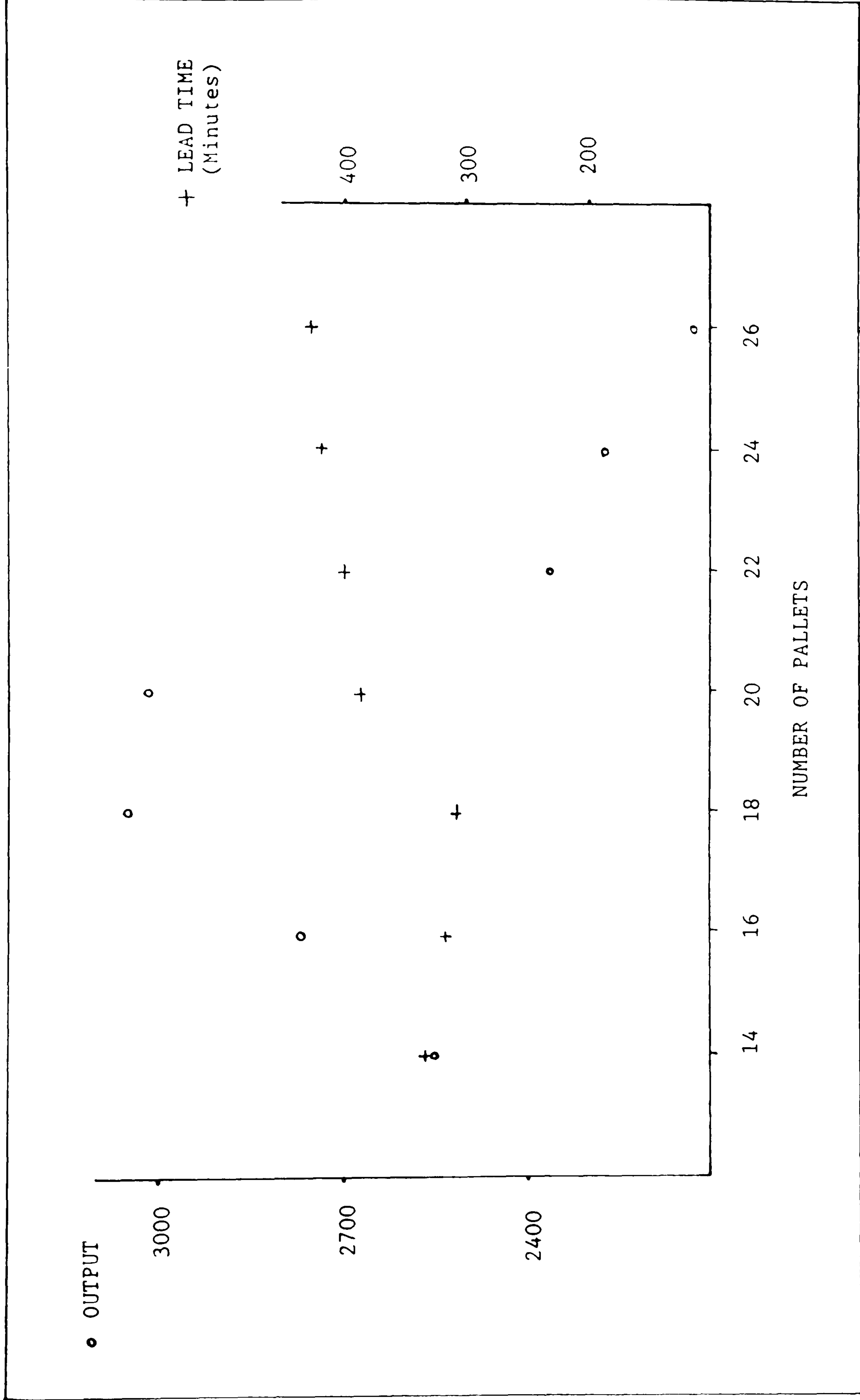


FIGURE 9.4 DIE FMS MODEL RESULTS - NUMBER OF PALLETS.

N U M B E R O F T O O L K I T S O F E A C H T Y P E							
	1	2	3	4	5	6	INF
LOW MEAN OUTPUT	2592	2861	2826	2830	2835	2788	2800
HIGH MEAN OUTPUT	2673	2916	2868	2902	2905	2915	2898
LOW MEAN LEAD TIME	5.54	5.19	5.29	5.22	5.21	5.20	5.23
HIGH MEAN LEAD TIME	5.87	5.30	5.40	5.36	5.39	5.44	5.40

FIGURE 9.5 DIE FMS MODEL RESULTS SUMMARY - NUMBER OF TOOL KITS.

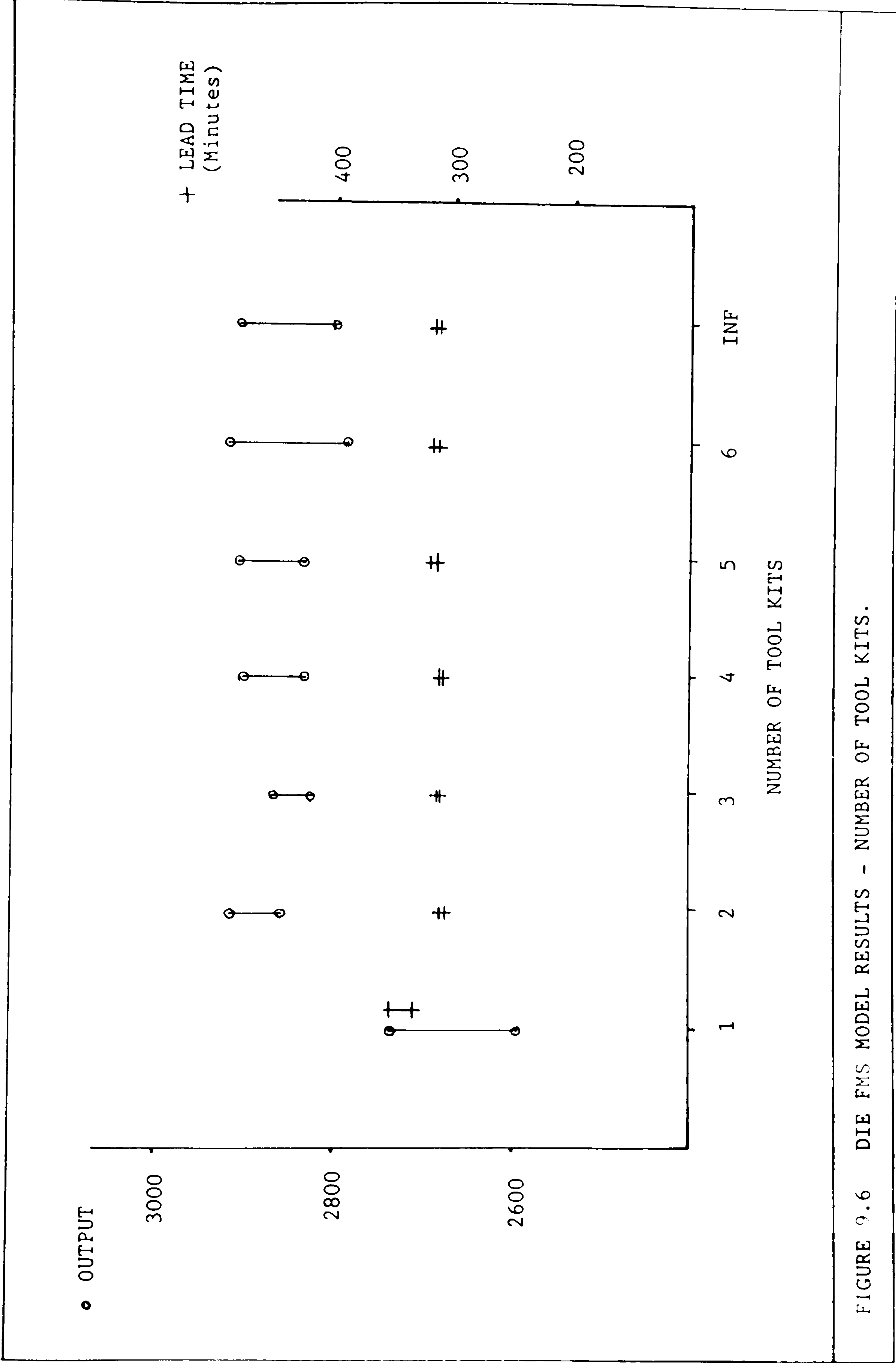
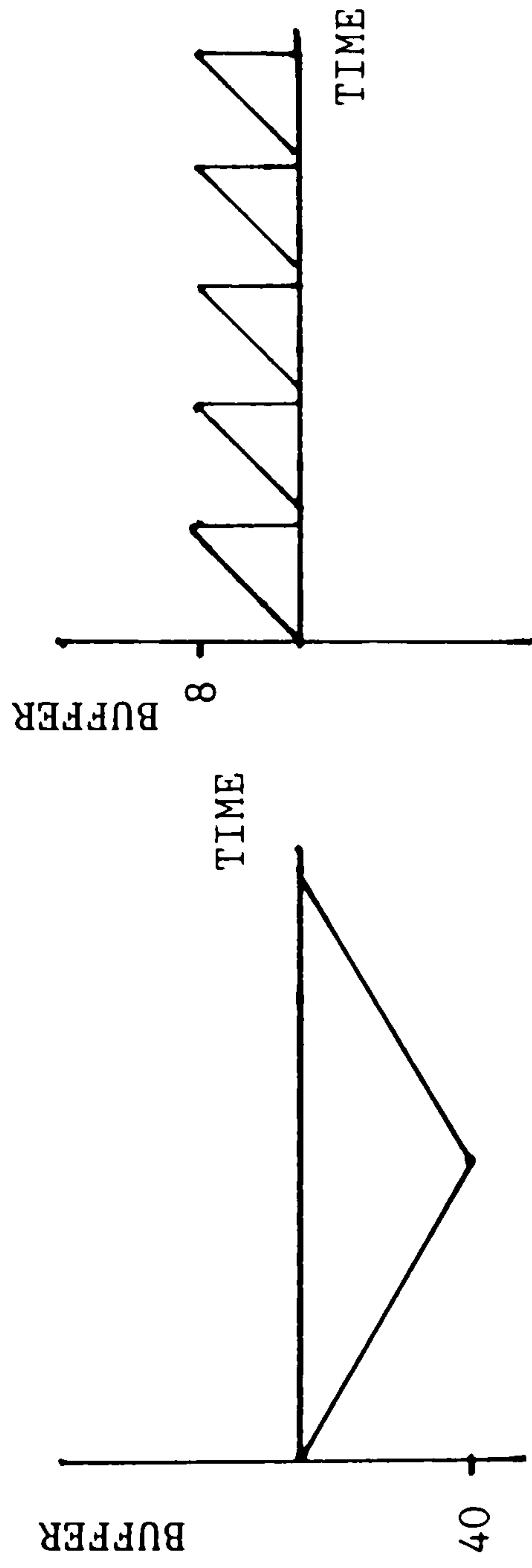
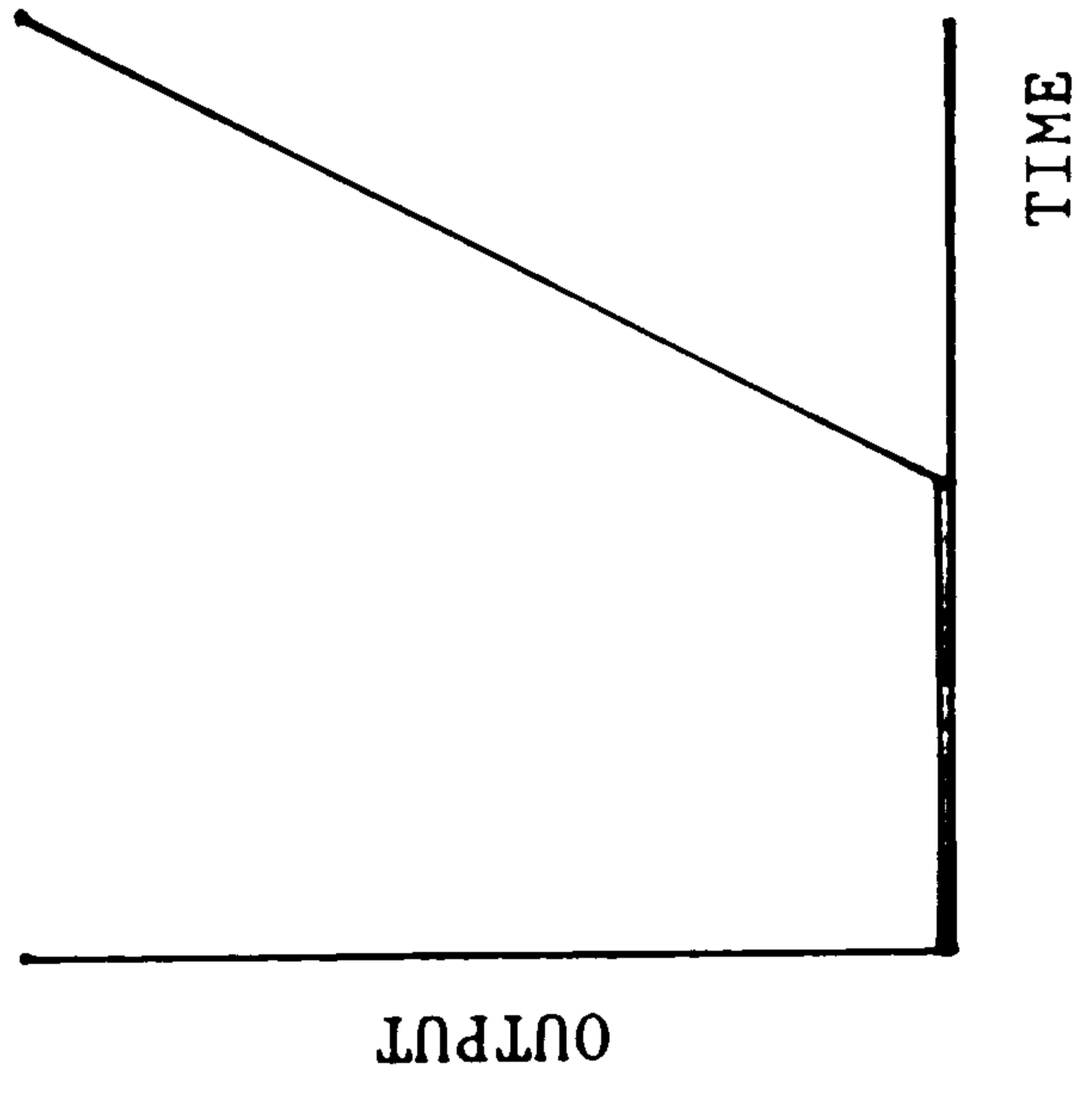
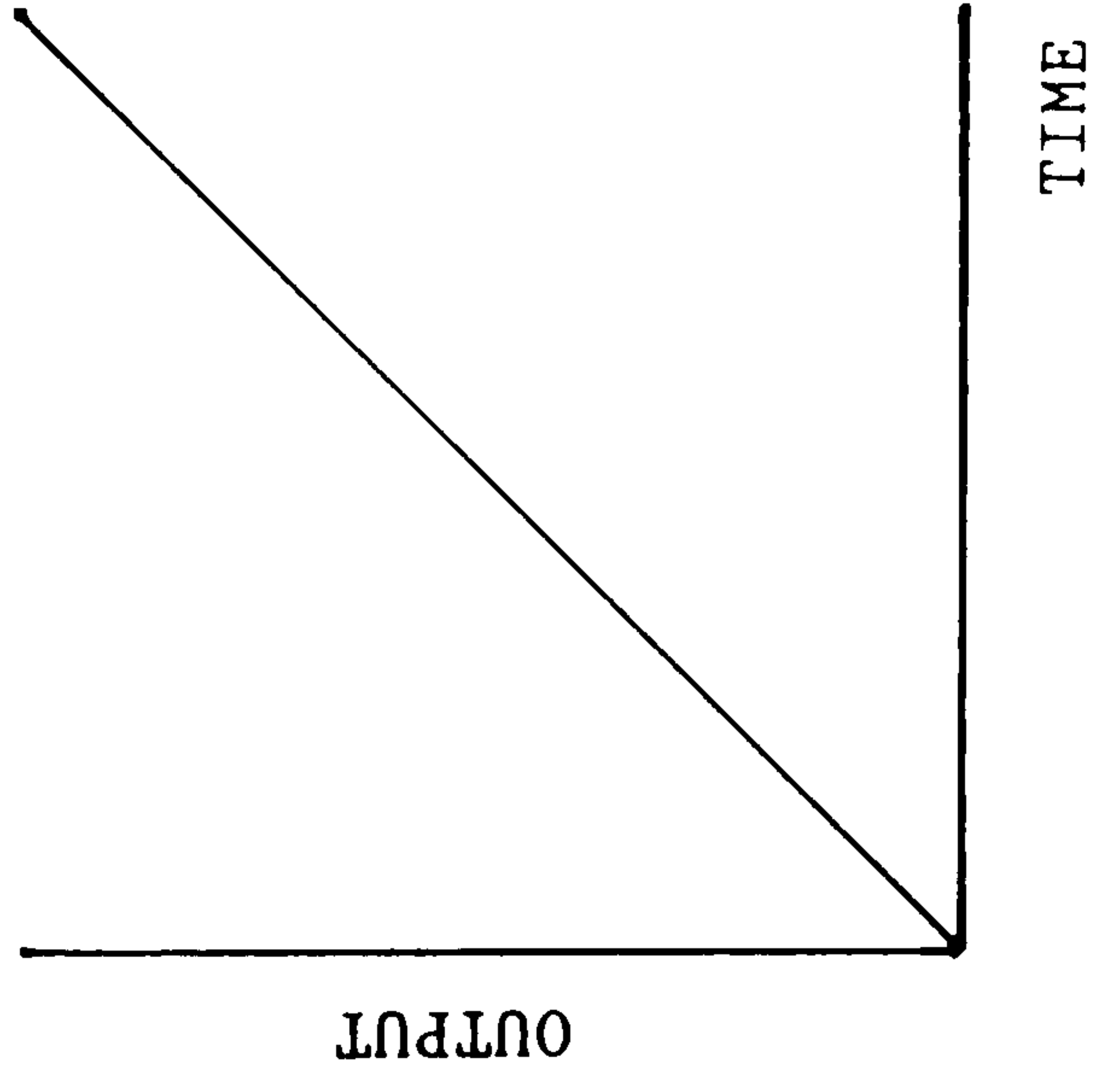
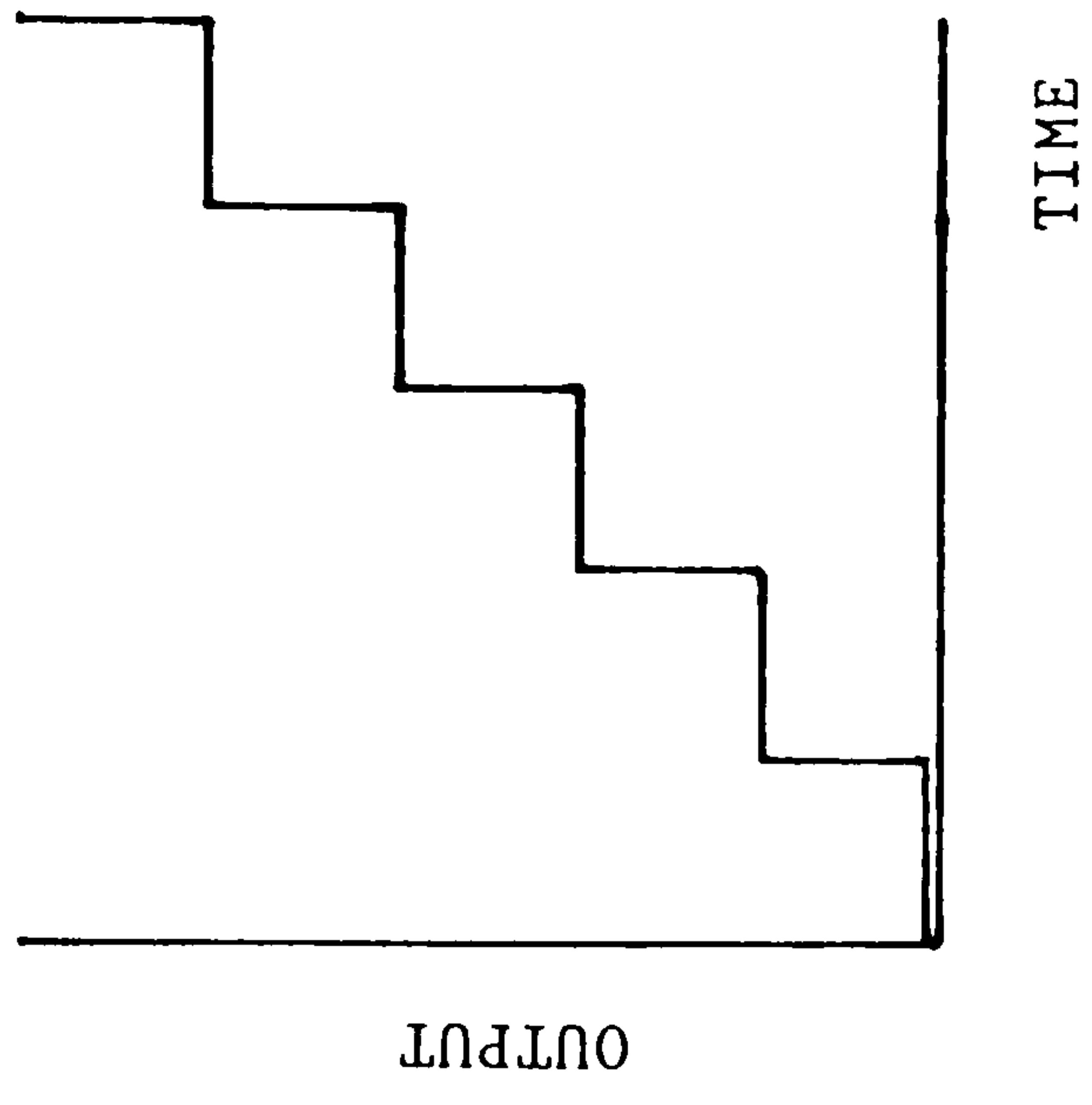


FIGURE 9.6 DIE FMS MODEL RESULTS - NUMBER OF TOOL KITS.



MAXIMUM BUFFER OF 40 UNITS

MAXIMUM BUFFER OF 8 UNITS



APPENDIX A.1 OUTPUT AND BUFFERING REQUIREMENTS.

STATION	COMPONENT AT MACHINE			COMPONENT EN ROUTE		
	NO.	TYPE	TIME	NO.	TYPE	TIME
LOAD	S(1)	S\$(1)	P(1)	TC(2)	TC\$(2)	K(2)
M1	S(2)	S\$(2)	P(2)	TS(2)	TS\$(2)	
				TC(3)	TC\$(3)	K(3)
M2	S(3)	S\$(3)	P(3)	TS(3)	TS\$(3)	
				TC(4)	TC\$(4)	K(4)
M3	S(4)	S\$(4)	P(4)	TS(4)	TS\$(4)	
				TC(5)	TC\$(5)	K(5)
M4	S(5)	S\$(5)	P(5)	TS(5)	TS\$(5)	
				TC(6)	TC\$(6)	K(6)
M5	S(6)	S\$(6)	P(6)	TS(6)	TS\$(6)	
				TC(7)	TC\$(7)	K(7)
M6	S(7)	S\$(7)	P(7)	TS(7)	TS\$(7)	
				TC(8)	TC\$(8)	K(8)
T/OVER	S(8)	S\$(8)	P(8)	TS(8)	TS\$(8)	
				TC(9)	TC\$(9)	K(9)
M7	S(9)	S\$(9)	P(9)	TS(9)	TS\$(9)	
				TC(10)	TC\$(10)	K(10)
M8	S(10)	S\$(10)	P(10)	TS(10)	TS\$(10)	
				TC(11)	TC\$(11)	K(11)
M9	S(11)	S\$(11)	P(11)	TS(11)	TS\$(11)	
				TC(12)	TC\$(12)	K(12)
M10	S(12)	S\$(12)	P(12)	TS(12)	TS\$(12)	
				TC(13)	TC\$(13)	K(13)
M11	S(13)	S\$(13)	P(13)	TS(13)	TS\$(13)	
				TC(14)	TC\$(14)	K(14)
				TC(15)	TC\$(15)	K(15)
UNLOAD	S(14)	S\$(14)	P(14)	TS(14)	TS\$(14)	

FIGURE B.1 TABULAR REPRESENTATION OF POOLING SIMULATION MODEL.