The Application Of Computerised Modelling Techniques In Manufacturing System Design

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Summary

The absence of a definitive approach to the design of manufacturing systems signifies the importance of a control mechanism to ensure the timely application of relevant design techniques. To provide effective control, design development needs to be continually assessed in relation to the required system performance, which can only be achieved analytically through computer simulation. The technique providing the only method of accurately replicating the highly complex and dynamic interrelationships inherent within manufacturing facilities and realistically predicting system behaviour.

Owing to the unique capabilities of computer simulation, its application should support and encourage a thorough investigation of all alternative designs. Allowing attention to focus specifically on critical design areas and enabling continuous assessment of system evolution. To achieve this system analysis needs to efficient, in terms of data requirements and both speed and accuracy of evaluation.

To provide an effective control mechanism a hierarchical or multi-level modelling procedure has therefore been developed, specifying the appropriate degree of evaluation support necessary at each phase of design. An underlying assumption of the proposal being that evaluation is quick, easy and allows models to expand in line with design developments. However, current approaches to computer simulation are totally inappropriate to support the hierarchical evaluation.

Implementation of computer simulation through traditional approaches is typically characterized by a requirement for very specialist expertise, a lengthy model development phase, and a correspondingly high expenditure. Resulting in very little and rather inappropriate use of the technique. Simulation, when used, is generally only applied to check or verify a final design proposal. Rarely is the full potential of computer simulation utilized to aid, support or complement the manufacturing system design procedure.

To implement the proposed modelling procedure therefore the concept of a generic simulator was adopted, as such systems require no specialist expertise, instead facilitating quick and easy model creation, execution and modification, through simple data inputs. Previously generic simulators have tended to be too restricted, lacking the necessary flexibility to be generally applicable to manufacturing systems. Development of the ATOMS manufacturing simulator, however, has proven that such systems can be relevant to a wide range of applications, besides verifying the benefits of multi-level modelling.

Keywords: Simulation, Manufacturing system design, Generic models, Manufacturing simulators, Hierarchical modelling.

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List Of Contents

List Of Figures

Volume 1

Volume 2

List Of Tables

Chapter 1 Introduction

1.1 Focus On Manufacturing Systems

The importance and impact of a manufacturing system on a company's success in the market-place is only now being realized [Martin, 1987a]. In the face of resent increasing world competition, in both domestic and international markets, companies have looked to survive through the coherent integration of manufacturing operations with product design, sales, marketing and other functional areas. Implementation of a manufacturing system has therefore concentrated on the development of an effective and efficient design with particular emphasis on resource requirements and capabilities.

Traditionally customer orders were won on the basis of product quality and cost, however, even though today they are still relevant, they are not sufficient. No longer do quality and cost alone represent "order winning" criteria, for in addition companies now aggressively compete on the basis of product variety and delivery times. The relative importance of delivery times being recently identified by both Mckinsey & Co. management consultancy and B. Dumaine [1989]. Dumaine suggests that the quick delivery of products and services does produce growth in a company's market share. Whilst Mckinsey identifies that the development of a new product which is on budget but six months late in delivery will earn 29% less profit over five years than a delivery on time but 50% over budget. Thus the realization of delivery dates is of key importance.

The rising expectations of customers, fuelled by the increasing market competition, has created a greater demand for product variety, resulting in shorter product life cycles and clearly identifying the importance of flexibility and productivity in manufacturing systems [Iwata et al, 1984]. In the design of manufacturing systems therefore the most efficient structure, in terms of financial measures, has to be developed, which effectively satisfies all objectives and requirements relating to operational performance.

The approach to manufacturing has not been simply to add new technology hardware to the problem. As automation alone is seen as further weighing down the system with unnecessary technology, in addition to its present restrictions. Instead attention has focused on the important and substantial benefits to be gained through simply reorganizing existing facilities. The potential benefits being quickly and significantly realised by four British manufacturing sites [Caulkin, 1988]. These have all experienced improvements in manufacturing flexibility, productivity, product quality and delivery through the redeployment of existing resources.

In order to fully achieve the benefits from a system reorganization, attention has focused on the specification of manufacturing system design methodologies to provide a frame work for successfully completing the re-design process. The necessity for a structured approach being due to the lack of any overall manufacturing system design panacea and an abundance of locally oriented optimizing methods. The aim of the methodology being to recognize the principal issues involved and then simplify the design complexity, so as Dales et al [1986] says:

> " .... an effective arrangement can be established for the design and manufacturing of a range of products in a competitive manner."

As the design complexity increases so the decision-making processes are further complicated, capital investment, maintenance and operating costs increase and ultimately greater is the risk of failure. To support and implement an appropriate design methodology therefore requires the use of practical tools which focus on the overall optimal design of manufacturing systems and the effective training of engineers for their ideal utilization.

1.2 Role of Simulation

Simulation is one of the most important and valuable techniques available for the design and development of manufacturing systems. All other techniques focus on a particular aspect and subsection of a system, whereas simulation provides the only means of comprehensively and accurately predicting the overall performance and behaviour of a design. The technique utilizes a combination of logical and mathematical processes to represent both the individual member elements of a system and their highly complex and simultaneous interactions. This system representation is then evaluated over a period of time in order to predict its likely behaviour and performance characteristics. Simulation therefore is able to consider the complex and time based dynamic interactions of a manufacturing system and predict likely system behaviour in similar terms to those in which the original design requirements or objectives were specified, that is desired overall performance (e.g. component lead-times, WIP, resource utilization, etc.).

The industrial application of simulation, with respect to manufacturing systems, can be operational [Bollinger, 1981]:

- identifying potential design benefits,
- reducing possible design and operational risks,
- maximizing system performance,
- training personnel in operational procedures;

and educational:

- teaching engineers the principles of manufacturing system design and operation,
- identify the elements of a manufacturing system,
- providing experience of both design and operational decision making in a "save" environment.

1.3 The Project

Originally the principal objective of the project was to investigate the role of computer simulation in the teaching of manufacturing system design techniques. The work primarily focusing on the training requirements of personnel for future system design projects.

One of the initial conceptual ideas was to develop simulation techniques to fulfil two separate roles. It was hoped that the technique would be so developed that it could provide the basis for training manufacturing system engineers whilst also being a suitable and highly practical tool in the actual design process. However, an initial survey (chapter 4) of the application of simulation techniques in system design projects within Lucas Industries Plc., highlighted a significant misconception. Although the necessity for and potential benefits of using computer simulation in the design of manufacturing systems was clearly understood and promoted, in reality, however, very little, if any use was actually made of it. The survey only identifying a couple of instances in which computer simulation was utilized in the design process and then only to verify the final design proposal. The reason for this being due to the combination of excessive training and development time involved in the current methods of applying the technique.

Consequently a fundamental investigation of the role and application of computer modelling techniques in the design of manufacturing systems was undertaken. The objectives were:

- to identify the requirements for computer modelling in manufacturing system design;
- to establish were in the design process computer modelling would be most effectively applied and the respective functions it would fulfil; and
- to develop coherent computer modelling procedures which would satisfy the varying requirements of a manufacturing system design process.

The intention was to derive a computer modelling procedure that would promote the effective design of manufacturing systems by supporting and complementing existing design processes. As way of data inputs and reference material, the project therefore took full advantage of the extensive work and experience gained within Lucas Industries Plc., during the reorganisation of its manufacturing facilities. Inevitably the examples presented in this thesis are bias towards the Lucas cellular manufacturing organisation and Just-in-time manufacturing philosophy. However, any bias in the examples does not detract or invalidate the findings presented here in, the work having been undertaken from first principles.

Chapter 2 The Manufacturing System Design Problem

2.1 The Reasons For Design

Manufacturing system design is the translation of both business objectives and operational requirements into a system specification and implementation plan for either a new facility or for alterations to an existing one. Having been implemented all manufacturing systems are continually updated or re-designed until they have no further use.

Regardless of whether it is the design or re-design of a facility, the necessity to undertake such processes can arise from:

- the introduction of a new product;
- change in a product's life cycle;
- introduction of new production technology;
- growth/decline of a company's market share;
- change in market requirements;
- introduction of new control methods;
- excess stock, high raw material, WIP and finished goods inventory;
- poor product quality;
- previously poor system innovation;
- introduction of manufacturing cells;
- introduction of autonomous working;
- expansion/contraction of the number of manufacturing sites;
- government regulations.

However, what exactly are the objectives and requirements that have to be translated? Furthermore what precisely is being specified? To answer these questions the role of a manufacturing system and its composition has to be reviewed.

2.2 Role Of A Manufacturing System

The prime objective of any company is to make money [Goldratt, 1984] in an efficient manner so as to be profitable. This process of money making is generally achieved through a manufacturing system whose principal function is to produce products that meet specific market requirements. To this end the system utilizes limited resources, such as machines, labour and material in an integrated way so as to turn raw material into saleable products. To ensure the proper integration of the resources business strategies, organisational structures, data flows and control systems [Parnaby, 1988a] are all employed to plan, initiate and monitor the activities within a manufacturing system.

A manufacturing system must be managed efficiently in terms of return on capital employed for a company to survive. However, with the current growth in world competition in nearly all markets efficiency alone is simply not enough. A successful company has also to be effective. For long term survival depends on a company's ability to respond to the continually changing demands of customers. This is even more pertinent when future market requirements are considered as more and more customers are demanding higher variety, lower volume, better quality and shorter delivery times whilst also expecting lower product cost.

Thus all successful companies simultaneously strive for economic product manufacture and market competitiveness [Knight et al, 1987]. This directly relates to their responsiveness, flexibility and quality of service and can be encapsulated by such system features as:

- short lead times;
- improved customer service and reliable deliveries;
- low operating costs;
- low inventory investment;
- high quality;
- advanced product and process technology;
- high resource utilization.

These features therefore exemplify the type of objectives which must be translated into a manufacturing system specification. Furthermore they clearly illustrate the potential conflict between various design requirements which a final system specification must resolve. For high resource utilization generally goes against improvements in both customer service and inventory management. Whereas better customer service tends to oppose low inventory investment and high resource utilization. Design therefore involves having to compromise and make trade-offs between conflicting requirements.

2.3 The Composition Of Manufacturing Systems

2.3.1 Manufacturing System Elements

For any given set of objectives there is no ideal manufacturing facility, each alternative simple offers a different combination of system performance and behaviour characteristics. No one system is flawless or perfect, each has potential benefits along with specific drawbacks. This lack of any form of manufacturing system panacea and the necessity to make trade-offs between conflicting objectives, (each weighted according to a given set of circumstances) has generally resulted in vastly varying production facilities. No two systems being exactly alike. For each company, even those in the same markets, have their own unique requirements or anomalies in such things as the mode of working or method of production employed.

A manufacturing system therefore is a collection of individual elements [Iwata et al, 1984] each designed so that the overall system satisfies a company's specific business, market and operational requirements. However, it must be appreciated that these individual elements do not exist in isolation from each other. In fact complex interrelationships simultaneously exist between many, if not all system elements. Consequently the individual elements and associated dynamic interrelationships, which constitute a manufacturing system, collectively determine its overall behaviour and operational performance.

Each manufacturing system is unique largely due to its sheer complexity and the vast range of possible alternative element configurations. Therefore as no two systems have the identical product ranges and manufacturing objectives then each has its own unique combination of system elements. Further differences are created by the way in which a company interacts with its social and business environment. Within manufacturing systems the selection of the production process and therefore technology is both a very difficult and yet critical activity. Critical in that it determines a system's basic operational and organisational characteristics and requires a high level of investment. Whilst difficult because manufacturing systems are highly complex and future production requirements must be taken into consideration. Furthermore the specification of a manufacturing system through the design of individual elements is difficult to control. For each separate element cannot be considered in isolation. However, the evaluation of element interactions and overall system integration is generally beyond the capabilities of any analytical techniques.

2.3.2 The Nature Of Systems

The various subsystems or elements that constitute a manufacturing system can be classified [Iwata et al, 1984] into one of three groups, either physical, control or job (section 2.3.3). The actual type and number of elements in a specific system depends on a number of factors. However, the relationship between the demand for a product and the investment in the system determines the basic manufacturing process [Hill, 1985] and indicates therefore the general nature of the elements required. High demand for a product justifies a dedicated process whilst low volume demand points to a flexible process able to meet the manufacturing requirements for a number of products.

There are two important decisions which must be taken prior to adopting, for a given set of circumstances, a particular manufacturing approach. The two decisions relate to what and how much to buy-out therefore determining the size of the production task and secondly identifies the appropriate technology to undertake the required tasks. The choice of an appropriate manufacturing process therefore is based upon these decisions whilst also understanding the implications of any constraints that they may impose. However, although constraints can alter and effect a specific process, they do not change its overall nature. Fundamentally the selection of the appropriate manufacturing process for a company directly relates to the markets and associated volumes involved.

There are five principal approaches to manufacturing [Hill, 1985] and these are project, jobbing, batch, line and continuous processes. Each process and therefore relevant technology has different implications for a company relating to its market responsiveness, manufacturing scope and manufacturing characteristics such as level of investment, type of control, organisational structure and types of staff employed. The scope of each type of manufacturing process is illustrated in figure 2.1 and their individual characteristics are summarised in table 2.1. For a detailed discussion of the five approaches reference should be made to Hill [1985].

Recent developments in production technology, however, has lead to the introduction of hybrid processes, which have the combined advantages of two or more of the principal approaches (figure 2.1). The most significant hybrid at present is the flexible manufacturing system (FMS) which combines automated material handling with computer controlled machines. This hybrid fits in with the batch approach but has the advantage of reduced work in progress, greater flexibility and lower costs. However, all hybrids have the same disadvantages in that the technology is generally new to a company, the initial investment in the process is very high and the resulting system incorporates greater complexity in both its operation and control [Musselman, 1984; Yong et al, 1983]. Therefore although these systems offer substantially

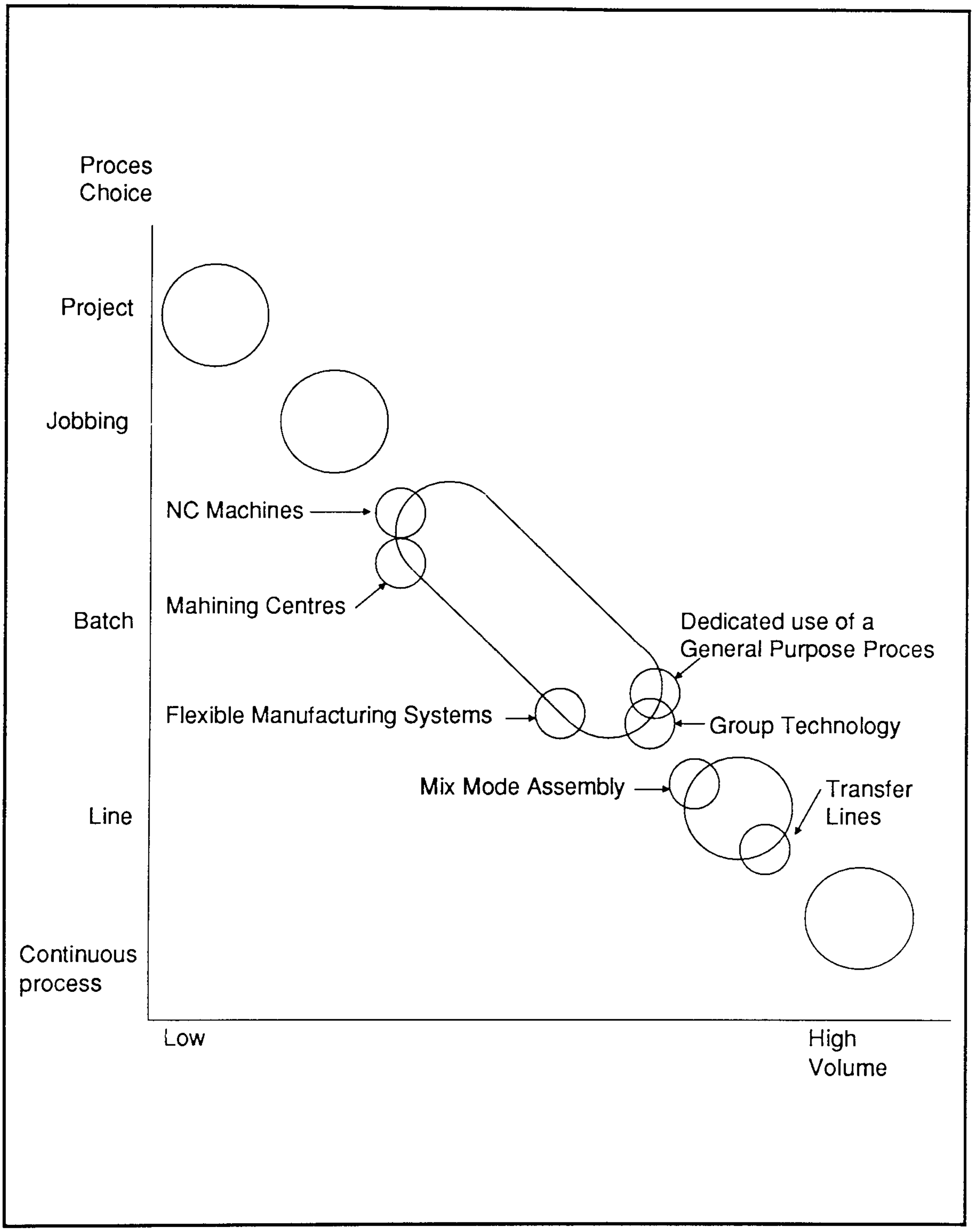


Figure 2.1 Manufacturing Scope (After Hill 1985)

Comparisons	Process Choice				
	Project	Jobbing	Batch	Line	Continuous
Product Variety	Very High Unique Products	High	Medium	Low Std Products	Very Low
Order Size	One Off	Low	Medium	High	Very High
Number Of New Product Introductions	Very High	High	Medium	Low	Very Low
Company Sells	Capability	Capability	Capability/ Products	Products	Products
Order Winning Criteria	Delivery/Quality/ Design	Delivery/Quality/ Design	→	Price	Price
Unit Costs	Very High	High	Medium	Low	Low
Initial System Costs	Low/High	Low	Medium	High	Very High
Equipment Technology	General Purpose	General Purpose	→	Dedicated	Highly Dedicated
Flexibility	Very High	Very High	High	Low	Inflexible
Capacity Changes	Incremental	Incremental	Step Change	Step Change	New Facility
Utilization	Labour/Plant	Labour	Labour/Plant	Plant	Plant
Manufacuring Task	Meet Deliveries/ Specification	Meet Deliveries/ Specification	→	Minimum Costs	Minimum Costs
Breakdowns	Not Critical	Not Critical	Semi Critical	Critical	Very Critical
Labour	Highly Skilled	Highly Skilled	Skilled	Semi Skilled	Unskilled
Work-In-Progress	High	High	Very High	Low	Low
Finished Goods	Very Low	Very Low	High	High	High
Production Control	Decentralised Entrepreneurial	Decentralised Entrepreneurial	→	Centralised Bureaucratic	Centralised Bureaucratic
% Of Total Costs Direct Labour Direct Material	 Low High	 High Low	 Medium Medium	 Low High	 Very Low Very High
Product Specification	Customer	Custome/Supplier	Supplier	Supplier	Supplier
Management Role	Technical Support	Technical Support	Administratiive/ Coordination	Administratiive/ Coordination	Technical Support
Production Planning	Operator	Operator	→	Specified	Not Necessary

Table 2.1 Manufacturing Process Characteristics

greater rewards, the cost of failure is far more expensive, with possible long term repercussions.

The specification of a new manufacturing system generally implies the development of new production techniques within a company which may have very little or no previous experience of such methods. The inherent complexity of the resulting manufacturing system creates difficulties in understanding its behavioural and performance characteristics and therefore in evaluating alternative design solutions. This lack of system knowledge and behaviour can only be redressed through studying the dynamic interactions inherent within a particular system.

2.3.3 System Differences

It is clear that most manufacturing systems are unique, having been developed explicitly to satisfy a company's specific requirements. Even so the systems can generally be classified into one of five broad manufacturing approaches, as identified above. However, in relation to their principal function, it appears that all manufacturing systems are identical. Each processes raw material in a prescribed sequence utilizing appropriate machines, labour and tools to produce a saleable product. Therefore the differences between various manufacturing systems can be classified into four categories, system characteristics, physical system, control system and job descriptions (figure 2.2). Each of these factors have a rather limited number of variables and are merely modifiers to the basic production process.

I. System characteristics

These are the performance measures of a system (e.g. lead-times, product costs, resource utilization, etc.), which

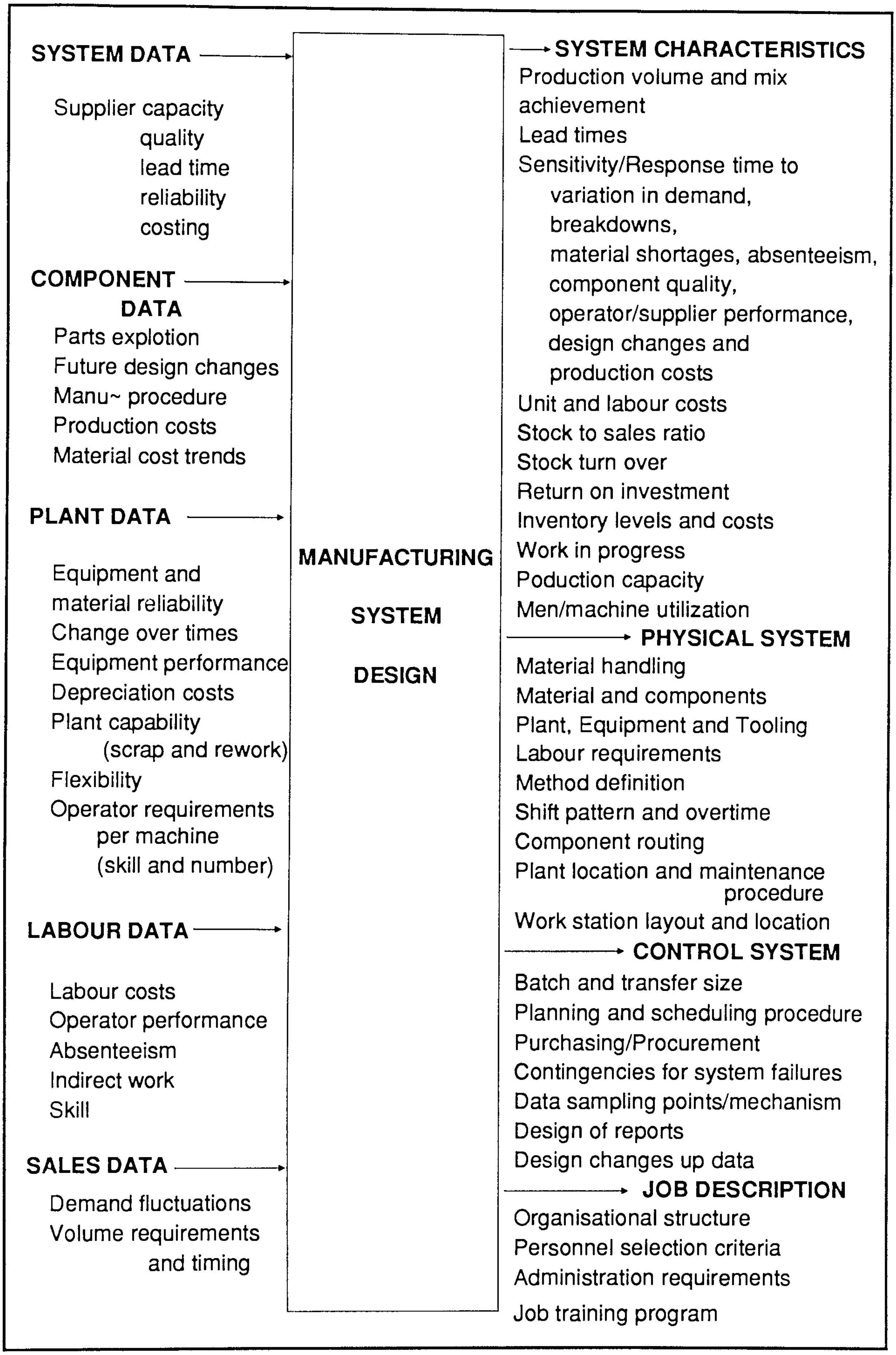


Figure 2.2 Manufacturing System Element Classification

form the basis for deciding whether to accept or reject a design. However, no design decisions are taken which directly relate to system characteristics. Instead decisions are taken regarding the various system elements which in turn determine the overall manufacturing performance measures.

II. Physical system

This classification represents the resources or hardware of the system, which includes anything that is directly involved in the transformation process whereby raw material is converted into a finished product.

III. Control system

The control system or software elements include those procedures which plan, monitor and control the activities within the manufacturing process. Such elements determine what to do next after an operation has either been started or completed or when some unusual conditions occur. Here also an employee hierarchy and reporting structure are defined.

IV Job Description

This is the identification of all jobs within a system. They are specified in the form of job specification and responsibilities, with specific training programs developed where necessary.

The above classification of system elements represents the overall spectrum of questions that a design should answer as well as identifying the data requirements to perform the process (figure 2.2). Furthermore this rationalization provides a structured and simplified approach to the problem of designing manufacturing systems, identifying precisely those aspects of a system that must be both elucidated and quantified in its design.

2.4 The Design Of Manufacturing Systems

In designing a manufacturing system the appropriate physical, control and job elements have to be identified. However, there are no simple answers, for the range of design possibilities and combination of system elements, especially at the initial stages of design is immense. In an ideal world a designer would thoroughly and systematically consider and evaluate every possible alternative combination of system elements, before any firm decisions or conclusions are made.

In the real world though a designer is constrained by available resources, i.e. time and money. Thus he relies heavily upon previous experience, intuition, ingenuity and personal judgement. However, increased competition within world markets together with the substantial costs associated in implementing new manufacturing systems technology has created a need to ensure that any design proposal is correct before being installed. For the true cost to a company of a poor design not only comprises the expense of system installation but also a reduction in market share and therefore future profitability. Consequently, manufacturing system design processes must ensure the development of appropriate and complete proposals. Unfortunately though relying totally on previous experience, personal judgement and so forth does not guarantee design excellence, as these subjective approaches can be misleading, invalid and inappropriate. Hence the use of mathematical algorithms.

Algorithms are generally employed in order to produce an objective and qualitative approach to manufacturing system design. However, the sheer size and complexity of the design problem makes it difficult to define mathematical procedures which are both appropriate and optimizing. For manufacturing systems are normally too large, ill-defined and ill-behaved to allow any kind of design optimizing algorithms to be developed. Furthermore, it is very rare for a problem such as design to be wholly expressed in terms of mathematical equations which can be solved. As Solberg [1979] says in order that mathematical equations are tractable, simplifying approximations have to be made regarding a manufacturing system. However, the vast number of manufacturing variables and the fact that many of the interrelationships between elements are either unknown or the behaviour so complicated means that mathematical models provide an over simplified and unrealistic representation and are often therefore inappropriate. Consequently, there is no one technique which can solve the manufacturing system design problem. Instead design is an iterative process, utilizing a variety of design techniques to make specific decisions regarding the various elements of a manufacturing system.

The existence of interrelationships between individual system elements indicates that in specifying a constituent part of a design, the effect that it will have upon other areas and the influences other areas place upon it, have to be taken into account. Each design decision cannot be evaluated independently and often there is the need to make compromises between a number of conflicting decisions in order to achieve a better or the best overall system performance. Furthermore as each design decision directly relates to either individual elements or their interactions, all decisions therefore effect the overall system behaviour and performance. Thus throughout the design process the overall system has to be continually evaluated to fully assess the consequences of all decisions. The decision making process is further complicated by the fact that it is difficult to quantify improvements in terms of quality, flexibility, system response and dependability.

A designer has to simultaneously cope with detailed information about system elements in an integrated manner whilst not losing sight of the design requirements. As design is iterative, highly complex and of a time dependent nature there is a need for guidelines or a procedure to both reduce and optimise the search time for the most appropriate solution. This need for a design procedure or methodology is even more pertinent as a recent report indicating that new technology alone simply adds additional cost burdens to a systems existing confusion. Whereas in contrast the reorganisation of current facilities can produce outstanding results [Caulkin, 1988]. For when comparing American and Japanese industries, Harbour [White, 1983] has suggested that the performance differences are not due to technology but rather the way they are both designed and managed. To ensure the competitiveness of a company therefore effort has to be focused on the effective implementation of currently available resources rather than the development of new technology. Furthermore the incorporation of new technology generally brings with it complexity, which can easily render a manufacturing system inflexible and unable to respond to market changes. Consequently for a number of reasons there is a need for a general approach to the design of manufacturing systems.

The next chapter therefore discusses the actual process of design in order to then identify the specific requirements of a manufacturing system design methodology.

Chapter 3 The Function Of Design Methodologies

3.1 The Process Of Design

The design process is not a scientific activity as has been suggested [Siman, 1969; Popper, 1963]. Science is concerned with the investigation into the nature of things that exist, whereas design focuses on how things, that generally do not already exist, should be formed and operated. As Gregory [1966] says:

> "Science is analytic; Design is constructive"

In science a hypothesis is developed so that it can be shown to be incorrect. Whilst as March [1976] states:

> "a good design hypothesis is chosen in the expectation that it will succeed, not fail".

Furthermore Dr. Genichi Taguchi [Dunn, 1988] presents a view that in science there is only one true law, whilst in design there are a number of alternatively correct solutions. The question is simply which is the most appropriate for any given situation.

Why therefore has there been a tendency towards matching design with science if they are so diverse? In answer to this Cross [1981] suggests that the attraction is not,

> "in the method of science, but in the values of science.. rationality, neutrality and universalism".

He further states that design is a technological activity defined as:

> "the application of scientific and other organized knowledge to practical tasks by social systems including people and machines".

The implications of this definition are that there are various types of knowledge utilized in the process of design.

3.1.1 Knowledge In Design

It has been identified [Ryle, 1949; Russell, 1910] that there are two types of knowledge "know-how" and "know-that". "Know-that" is knowledge which can be explicitly passed on through procedures, rules, reference manuals or advice. It ensures that no errors are made and therefore determines competence. Whilst "Know-how" cannot be explicitly explained, it can only be gained via experience and relates to quality. This latter type of knowledge goes beyond "knowing-that" and sets standards of performance or ability.

In general the most commonly used method of designing a factory is a manual, rule-of-thumb [Fisher, 1986] or "Know-how" approach. It seems that formal, "Know-that" techniques are not that often utilized because:

- of the effort in learning how and when to use them;
- the inaccessibility of the techniques;
- their inability to solve a range of design problems.

As has been previously stated, manufacturing system design cannot rely on a designer's "know-how" or previous experience there must be "Know-that". However, it seems that formal design techniques have not been very popular. This implies the need for a design procedure or methodology that indicates when and how to use appropriately available techniques.

3.1.2 The Role Of A Design Methodology

Having identified the need for "Know-that" and before developing a specific manufacturing system design methodology, the general objectives of such a procedures must be reviewed.

The purpose of a design methodology is to guide a designer through the design of large and complex systems in an incremental fashion. Popper [1966] states that the design process follows a given pattern, specifically:

$$P1 \longrightarrow TS \longrightarrow EE \longrightarrow P2$$

where

P1 is the current problem;

TS is a tentative solution to the problem;

EE is error elimination of the proposed solution TS;

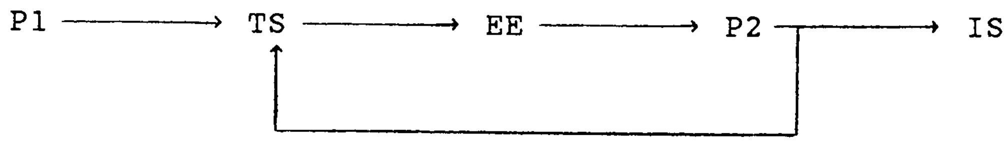
P2 is the solution to the problem P1, which represents a new problem, in which new relationships exist.

This representation of design introduces a number of important aspects regarding the process.

- Design is an investigative process. Identifying the requirements and expectations of the design, evaluating the current situation and available resources and studying any previous design solutions.
- Design is a creative process. There is no mathematical procedure or simple equation based answers to solving the problem. Also there is no one technique that can produce an ideal solution. A solution is developed through a combination of "Know-how", brain storming, random searching, ingenuity, good memory, etc. The process is such that it cannot be automated.

- Design is a rational process. The analysis and testing of possible solutions entails scientific, mathematical and logical analysis which can be automated.
- Design is a decision making process.

Thus design is a trial an error or iterative process and therefore Popper's pattern needs to be modified to clearly show this.



where

IS is the ideal solution, which will represent future design problems.

As Rzevski [1981] writes, a design methodology is a means of:

> "controlling the complexity of both the design process and the system which is being designed."

It therefore provides a systematic and structured approach to the identification and quantification of those elements required in a particular system. It orders the sequence of design decisions. So allowing a designer the opportunity to investigate the near infinite range of solutions before selecting the most appropriate one. Also the methodology ensures that appropriate techniques are used in a logical manner at the relevant stages of the design process. Thus design methodologies are specified to help ensure that design aims and objectives are realised whilst coping with the detail and complexity of the task itself.

3.2 Scope Of A Manufacturing System Design Methodology

3.2.1 Manufacturing System Design Objectives

Having discussed the purpose and aims of design methodologies in general, the detailed objectives of manufacturing system design tasks must firstly be understood before the specific requirements for a structured procedure can be identified.

The objectives for a design project provide a focal point for the development of an effective and efficient manufacturing system. Before considering any project specific design objectives it must be realised that there are a number of prerequisites that any manufacturing system design task must achieve. These arise due to a number of factors. Firstly there is no one technique which can produce a complete system design solution because of the sheer scope and complexity of manufacturing facilities. Furthermore there is no "ideal" solution as design is a compromise between conflicting objectives which dictates the necessity for an iterative process. Also although these objectives are currently correct and appropriate, they are likely to change in the future, with an additional shift in emphasis, thus making the original system invalid. The combination of these factors therefore creates the need for a structured, systematic approach to using the available design techniques and evaluating the alternative solutions, which a design methodology provides. However, it further establishes the necessity to produce system designs which are modular, adaptable, expandable and documented [Martin, 1987b]. These being the four basic prerequisites of any manufacturing system design. The objectives can be defined as:

Modularity: The development of designs in small individual modules. The interrelationships between modules must be determined. With a design done in small modules it is easier to modify and will cause less disruption to the rest of the system.

Adaptability: Tailoring the design to a specific implementation, thus ensuring that it is appropriate.

Expandability: Designing in the ability of a system to change and evolve in the future, in accordance with varying or new operating objectives. This will increase the life of a system. However, it is often difficult to identify all the prospective users let alone their precise needs and expectations that would be valid over the years.

Documentation: Ensuring that in the future it is clearly understood how the system was constructed and works.

An important requirement in the design of a manufacturing system is to produce the simplest possible structure that satisfies specific objectives. There is never simply one objective. In fact there is generally a wide range of objectives with some inevitably conflicting. These detailed objectives not only specify the expected system performance characteristics, such as:

- product lead-times;
- order delivery achievements;

- return on investment;
- inventory levels;
- operator/machine utilization;

but also establishes the requirements for the work performed by the designers. This includes [Bollinger et al, 1981]:

- specification of a system design and implementation plan within a time duration of, on average four to six months;
- presentation of monthly management reports;
- demonstration of proposed design feasibility;
- reduced risk of system design failure;
- identification of system design and cost implications;
- design of personal training programmes.

3.2.2 Requirements For Manufacturing System Design Methodology

The aims of a design methodology are well documented [Warnecke, 1982; Fisher, 1986; Parnaby, 1986], but simply it has just two main objectives [Dales et al, 1986]. Firstly to bring about a better understanding of the fundamental design issues and current situation and secondly to simplify the complexity of the problem by establishing effective design procedures.

Design should be a step by step development (as Fisher [1986] and Rzevski [1981] say), starting with highly aggregate and rough decisions and progressing at the end of the process to very detailed, micro design. This approach to design suggests a hierarchical representation of a system. Thus initially the design process starts by considering the overall system (e.g. factory). Progress is then made by designing the subsystems (e.g. departments) within the overall structure and then further subsystems within those, until the lowest level of design is reached (e.g. operators, machines and fixtures). Such an evolutionary approach allows the designers to learn and understand how the elements of a system work and interact with each other, as the complexity increases (figure 3.1). Furthermore such a strategy constrains the designer to making a relatively small number of decisions at a time. This is very important as it reduces the occurrence of system errors. If these decisions could be verified before passing onto the next stage, it would ensure that future decisions are taken on the basis of previously substantiated information. Otherwise decisions would be based upon assumptions and only verified, along with the final system design, at the end of a project.

If a manufacturing system design methodology is to be generally applicable it cannot be a rigid, uncompromising set of procedures. Ideally it should highlight the design action which is appropriate in specific circumstances.

A manufacturing system design methodology should:

- be applicable to any type of manufacturing system design problem;
- aid the designer's creativity;
- help designers to perform the appropriate design tasks, using the relevant techniques at the correct stage of design;
- help select the "best" design that satisfies all objectives by making value judgements;
- help create designs which are easy to modify;
- aid an incremental design development, starting with global decisions and ending with very detailed ones;

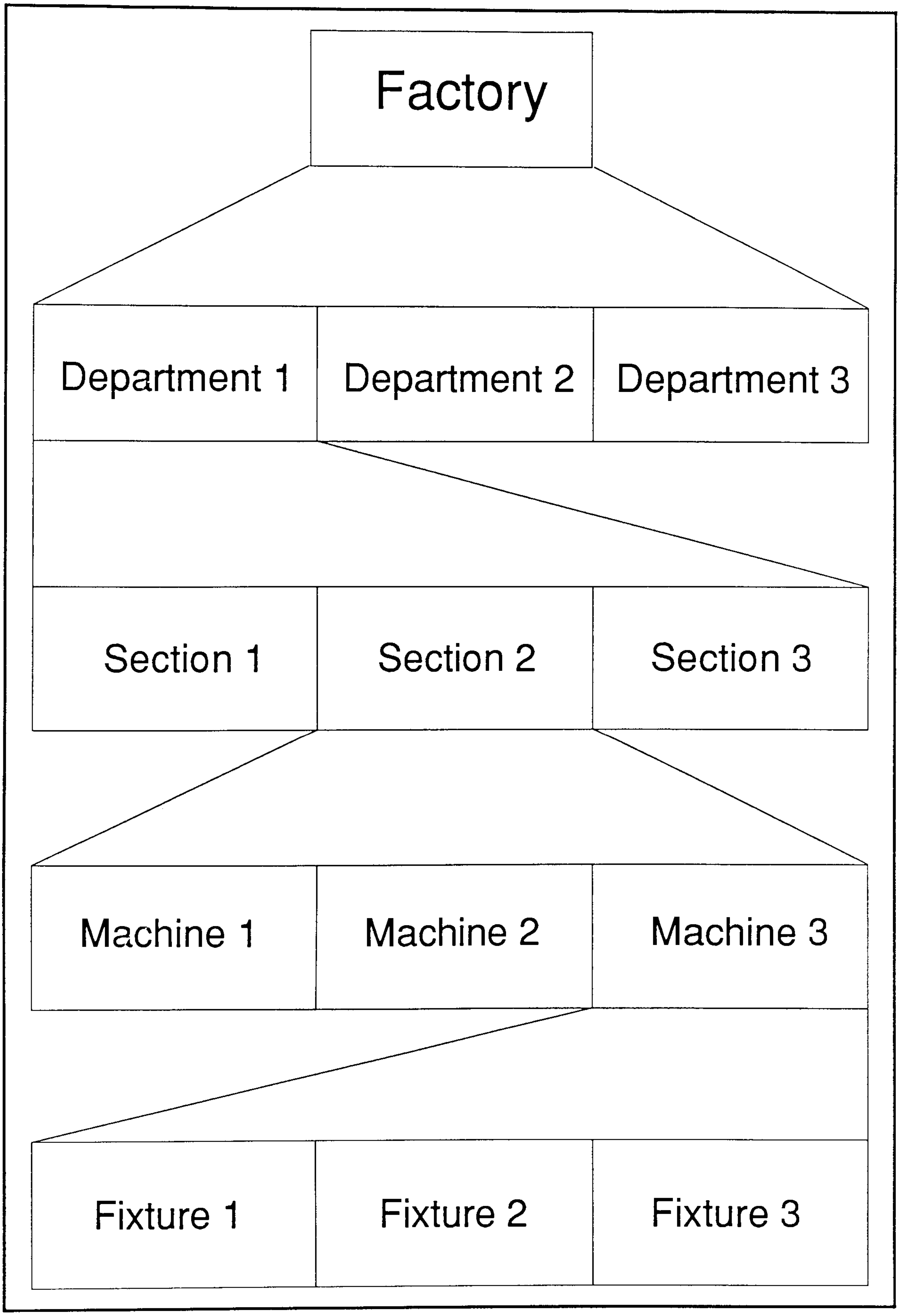


Figure 3.1 Manufacturing System Hierarchy

- ensure only a small number of decisions are made at a time.

A methodology must not [Rzevski, 1981]:

- de-skill the design work;
- restrain designer's creativity and value judgement;
- impede proper design considerations.

A suitable methodology therefore would include the following stages:

- establish a clear understanding of the requirements to be satisfied;
- establish an understanding of the current situation;
- consider new and existing technology;
- determine the relationships between system elements (e.g. operators, machines and transport);
- specify and select different types of manufacturing elements (e.g. for machines this includes lathes, mills, furnaces, CNC machines, etc.);
- analyse the overall design performances;
- select the "best" design.

Chapter 4 Manufacturing System Design Evaluation

Having examined the function and specification of a manufacturing system design methodology, attention can now focus on the procedures that have been adopted to facilitate the development of appropriate designs. However, any discussion on the process of controlling and evaluating the formulation of a system specification, requires a reference or focal point, in the form of an established and proven design methodology, against which it can be set. In order therefore to put into context a discussion on design approaches and problems to evaluation, a highly valued and currently prominent methodology is first presented.

4.1 A Manufacturing System Design Methodology

4.1.1 Introduction

This section presents a manufacturing system design methodology which has been developed from the work of Parnaby [Parnaby, 1986; Parnaby, 1988a], Dales and Johnson [1986] and a survey undertaken by the author. The survey was of five manufacturing system re-design projects in Lucas Industries Plc., which covered systems ranging from small batch to volume line or flow production. The relevance and importance of the re-design work undertaken in Lucas being exemplified by the transformation of the Lucas Diesel Systems plant at Sudbury. Through simple reorganization, the factory operating cost have been reduced by £10 million, lead times have been dramatically cut from 55 to 12 days, quality has improved by between 12-15% and productivity has risen by 50%. The success of the plant is further underlined by single-sourcing agreements from both

Ford and Cummins.

The aim of the survey (Appendix A) was to determine whether or not an effective design procedure could be identified and adopted to aid in the design of any type of manufacturing system. Furthermore the study reviewed the use of available techniques to support the various stages of the design process and identify their individual roles.

The design methodology discussed below is based on the five stages of designing a manufacturing system as stated by Parnaby [1986]. These are:

- market and product analysis;
- steady-state design assuming average system performance;
- dynamic design taking account of system variability on operating performance;
- design of data collection and information flow systems;
- control system design including the organisational structure;

From these five basic stages, a step by step design methodology can be developed (figure 4.1, a product of the aforementioned survey) to provide a framework for undertaking a re-design project. Each stage of the methodology is intended to provide answers which will themselves aid in resolving the overall questions regarding a final design proposal.

The following description of the stages involved in the design methodology is only intended to provide a basic understanding and reference point for discussions later in this chapter. However, for a more detailed explanation of each stage reference should be made to Dales and Johnson [1986].

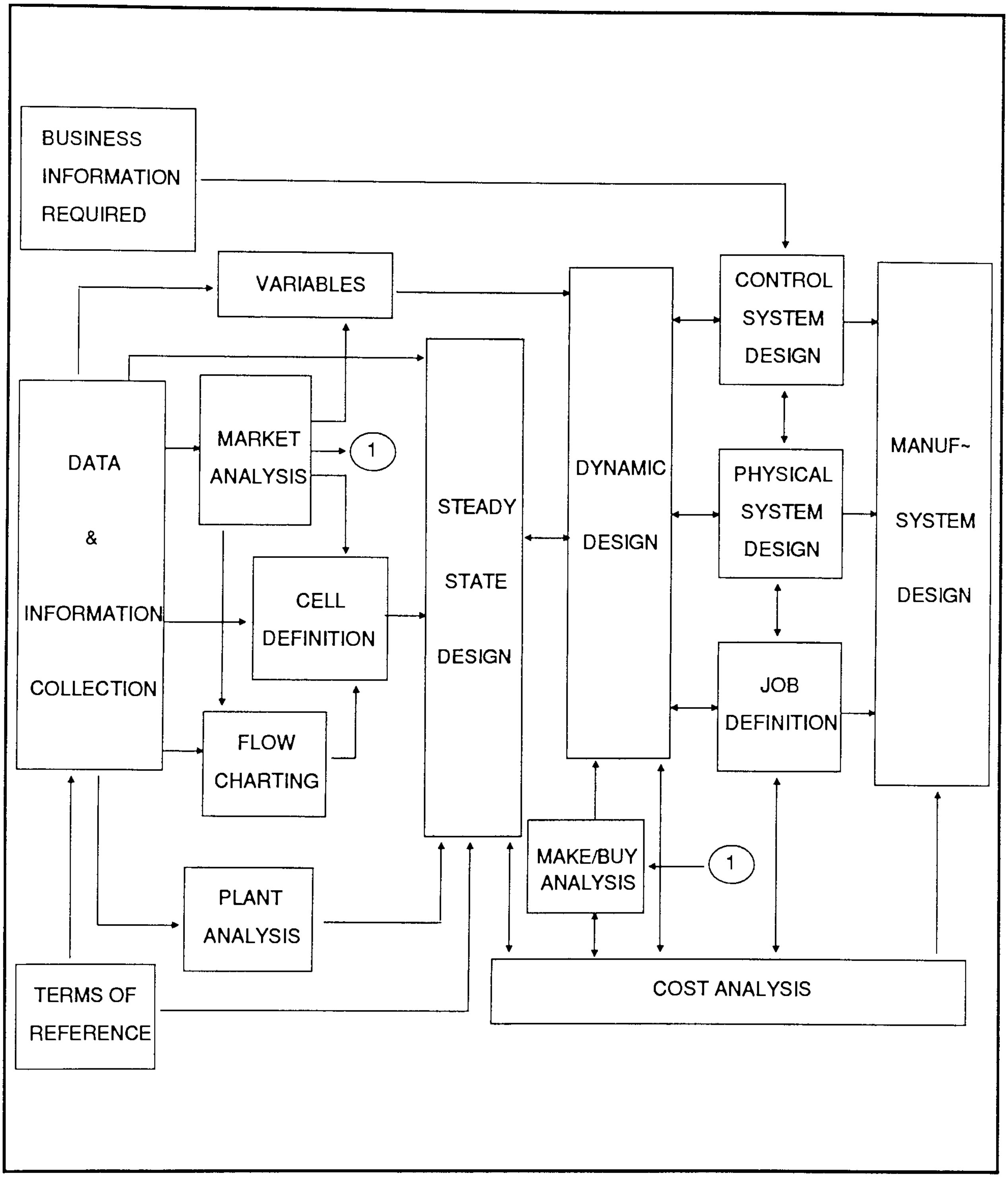


Figure 4.1 A Manufacturing System Re-design Process

4.1.2 The Stages of Design

Initial identification of the type of market a company competes in is important, helping in both defining and re-designing a manufacturing system. Identification is by product and important factors include:

Volume	- Ranging from Jobbing e.g. 30/month to mass production e.g. 500,000/month;
Product complexity	- From 1 to over 1000 parts in a bill of material;
Variety	- From 1 unique product to over 500 variations of a particular product;
Product age	- Relative to its particular market i.e. new, mature or old;

The stages of the design methodology (as identified from the results of the re-design survey and described by Dales and Johnson [1986]) include:

I. Objective Setting

The first stage in the design of any production facility is the setting of competitive manufacturing objectives, in order that it succeeds in the market place. Typically defined business targets include:

Stock turn ratio,
Lead times,
Product cost,
Selling price,
Stock levels and
Quality.

However, other objectives are also set depending upon the specific circumstances. These include:

(*) cellular manufacturing,

(*) job flexibility,

manpower reductions,

simpler product units,

product range rationalisation,

no-value-added activities reduced,

(*) supplier development,

(*) change over reductions,

(*) new control methods e.g. kanban, and

floor space reductions.

These latter requirements clearly indicate (*) that, from the outset, particular design solutions are often imposed upon a project. Such prescriptive goals as these infer prior knowledge of system characteristics and behaviour by senior management and illustrates how certain design decisions are made as early as the objective setting stage.

II. Data Collection And System Analysis

Before any problem analysis or system design can take place certain data has to be collected and it is important to identify the relevant data, understanding the use to which it will be put. Therefore data selection must come before collection. For example if some aspect of design is based upon component size then there may be no need to collect data regarding component weight. Further the use of standard units and specific dimension comparison can ease design. As well as collection, the storage of data is just as important [Dales et al, 1986] for traceability, retrievability and manipulation.

System analysis is the evaluation of the current situation and future trends in both the internal and external relationships of a business.

The external evaluation or market analysis identifies the company's market place and future trends, so providing an indication of current and future product volumes and varieties for which a manufacturing system has to be designed. The analysis identifies all customer requirements which a system must satisfy to ensure any chance of success.

The internal evaluation, comprising of machine capability studies, material flow charting and no-value-added activity analysis identifies the suitability of alternative production resources and methods which could be utilized in a proposed manufacturing system.

III. Cell Definition

Here the structure for the manufacturing system is identified that best satisfies market and customer requirements and which lends itself to simple methods of control. The development of a simple design solution is generally derived from the grouping of products and/or components into families. Family groupings are based on such things as:

- bill of material
- material used,
- physical attributes,
- production processes,
- batch size and production frequency.

Generally the groupings are produced using production flow analysis [Burbidge, 1971] or classification and coding [Love and Love, 1988].

The design should establish simple and minimum material and information flow patterns and provide a basis for relatively easy future development and growth.

IV. Steady State Design (figure 4.2, from the survey)

This involves determining the type and quantity of resources (e.g. men, machines, material and storage) required to achieve average production requirements, based upon average constant system performance. Furthermore the average level of service required from manufacturing support departments is established. Thus a design is developed which will, on average, achieve the required production volume and mix. However, life does not allow systems to operate at average levels of output and so from steady state, the process must proceed to dynamic design.

V. Dynamic Design (figure 4.3, from the survey)

Here the effects of potential variations from the average values (assumed at the steady state stage) are assessed on overall system performance. These changes can be due to uncertainty in the market analysis or variations in performance of certain elements. They include such things as:

- sales volume variation;
- product mix variation;
- product changes;
- machine breakdowns;
- operator performance variation and absenteeism;
- supplier delivery variations;
- scrap level fluctuations.

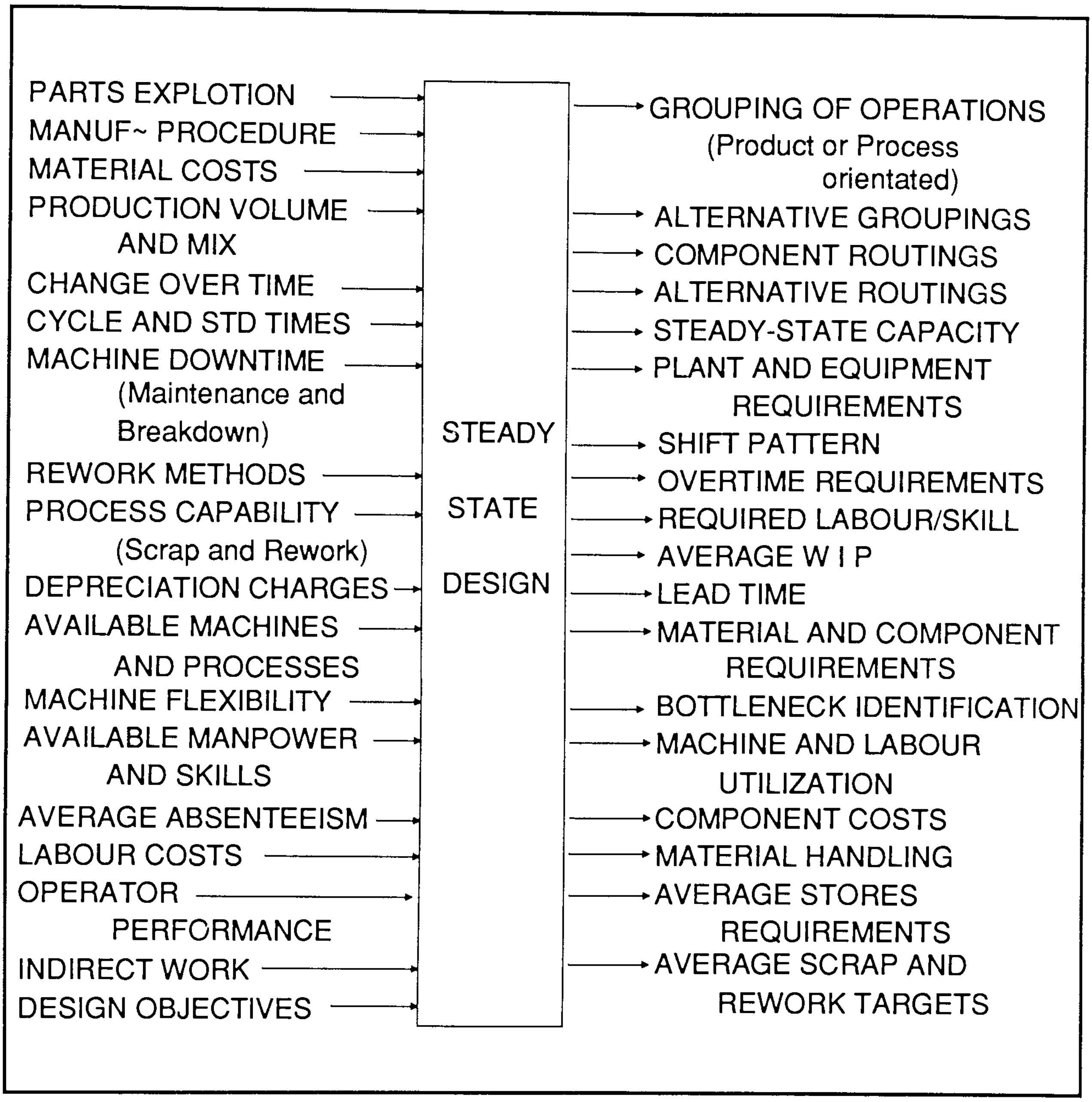


Figure 4.2 Steady State Design I/O Diagram

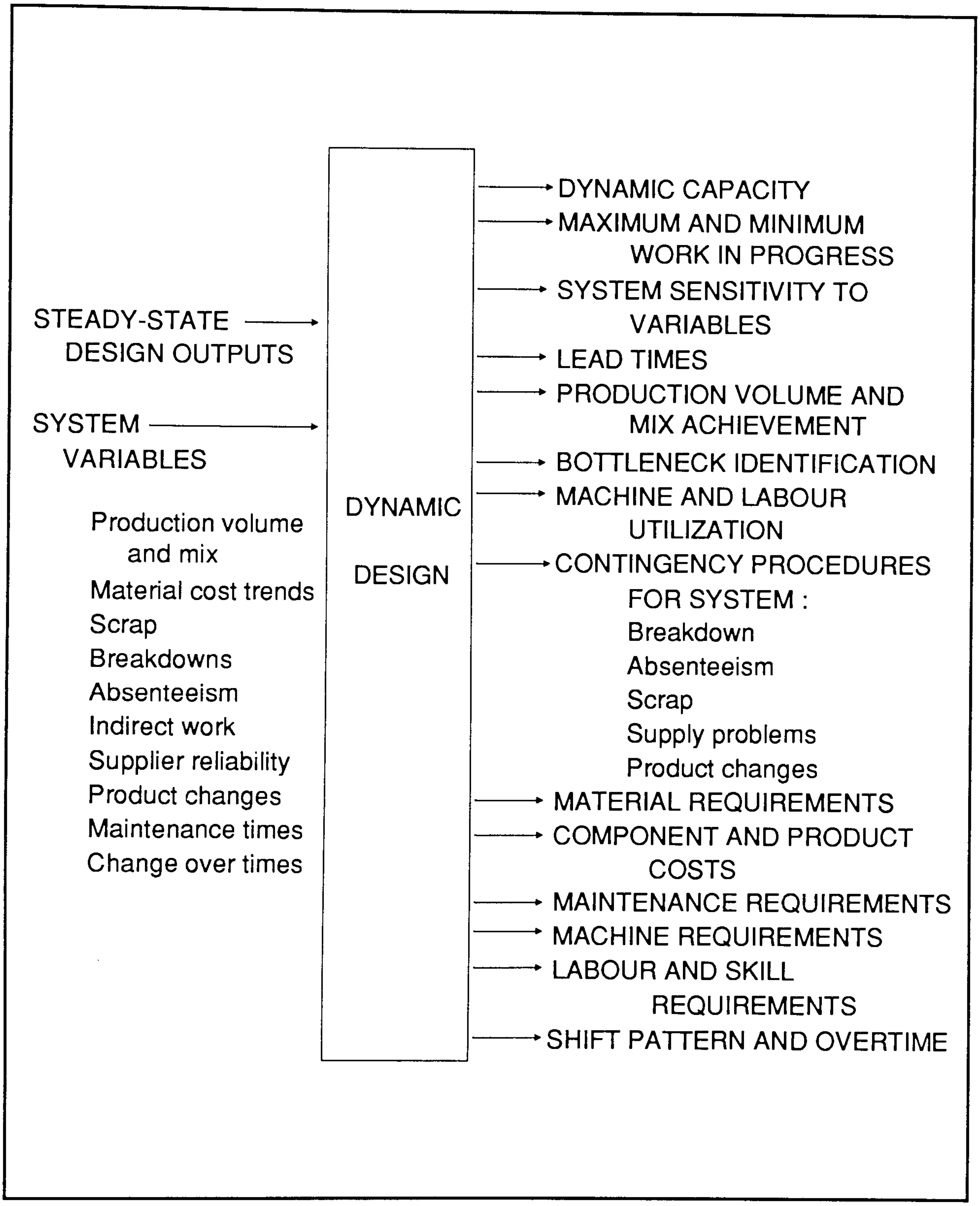


Figure 4.3 Dynamic Design I/O Diagram

A number of "What if ...?" questions are asked. What if a machine breaks down? What if an operator goes ill? What if scrap rises? As a result of this questioning it may mean going back to steady state and changing the design based on averages. Dynamic design caters for change.

VI. **Physical System Design** (figure 4.4, from the survey)

This is the design of work stations and assembly lines and their location within the appropriate work centre, cell, module, and department on the shop floor. It also involves the design of storage areas, (based on maximum and minimum stock levels) work containers, offices and material handling methods.

VII. **Job Definition**

This is the identification of all jobs that are necessary within the manufacturing system, specified in the form of job specifications and responsibilities. Having produced job specifications and thereby establishing the necessary skill requirements, the existing skills must be audited to determine and develop training programs.

VIII. **Control System Design** (figure 4.5, from the survey)

This entails identifying the various functions (e.g. production management, production control, stores control, sales control, etc.) within a manufacturing system and determining their individual data requirements. Then developing a distributed information and control system which will provide up to the minute data relevant to the various parts of a manufacturing system. Also by referring to set points or plans the system will draw attention to when planned events are not actually being met and therefore where

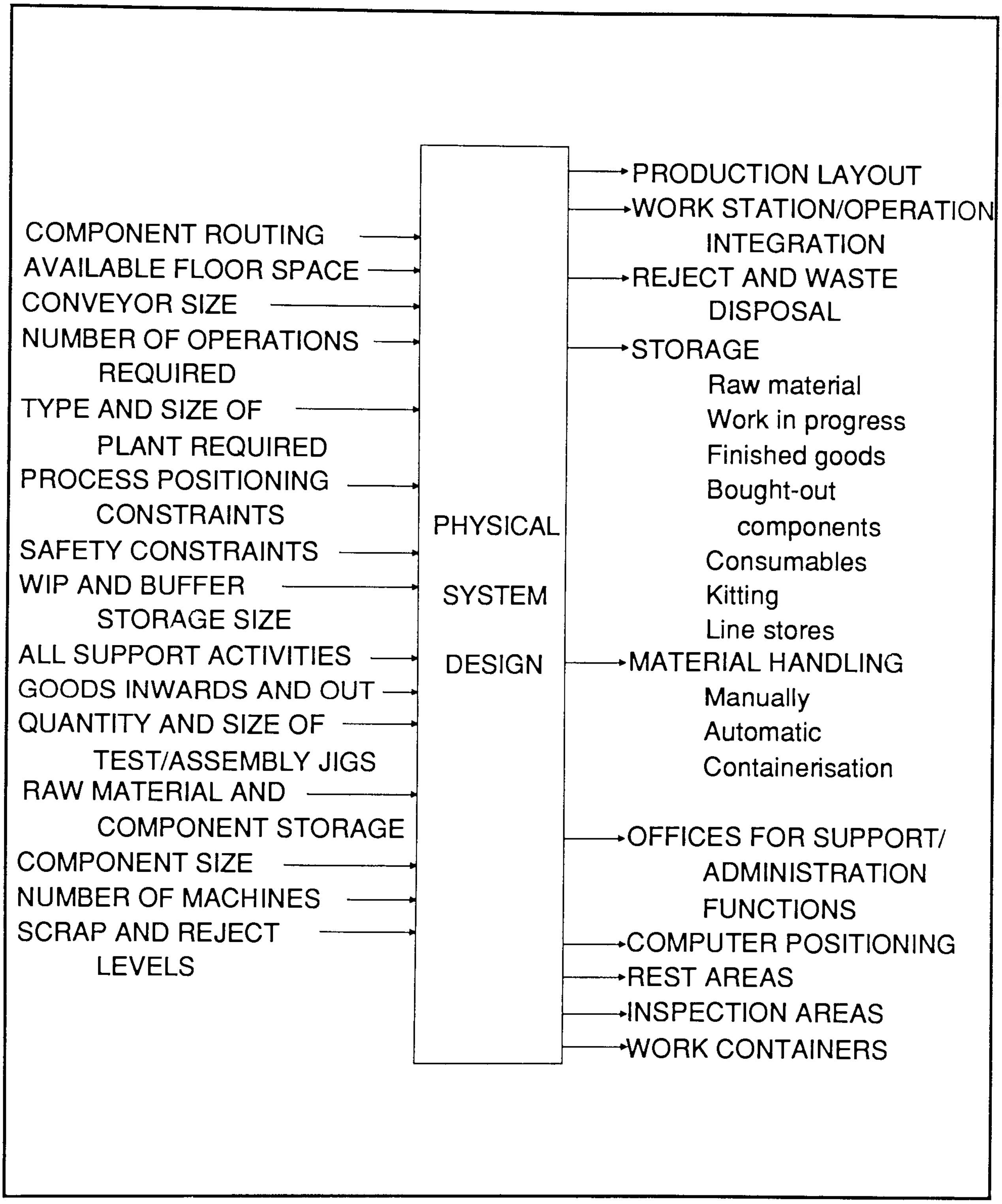


Figure 4.4 Physical System Design I/O Diagram

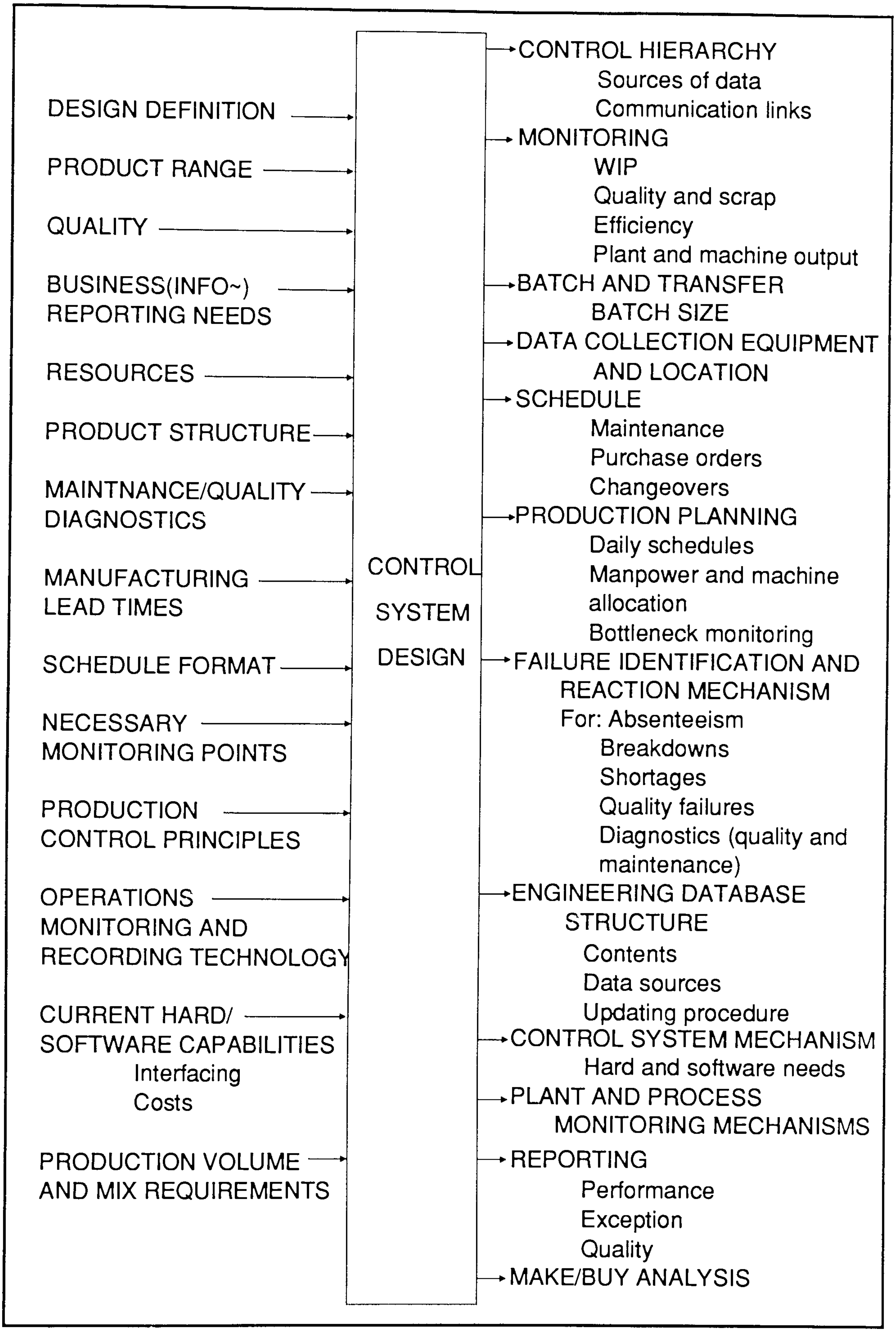


Figure 4.5 Control System Design I/O Diagram

immediate action is required. Furthermore the organisational structure is designed and should be simple, providing a very flexible arrangement. The aim must be to reduce information flows and develop accountability and ownership.

IX. Financial Assessment

This is an integral part in the design of a manufacturing system as it relates system performance to the business targets. A manufacturing solution can provide a number of performance benefits but unfortunately some of these are very intangible. However, the financial assessment of a design provides an effective basis for evaluating alternative design solutions. Financial assessment or costing is not performed at a specific stage in the design process but is a continuous activity which provides a mechanism for monitoring and guiding the development of a design.

4.2 System Requirements And Design Performance Correlation

4.2.1 General Design Techniques

The design of a manufacturing system commences with establishing the strategic business objectives. These targets determine the minimum system performance measures that any manufacturing facility, implemented in the future, must achieve. Due to the underlying urgency to correct or improve the performance of an established manufacturing system through its re-design, such projects are typically completed in four to six months. On completion a final design proposal is put forward which, on evaluation, best satisfies the initial system performance criteria. As each decision affects overall system performance, it is important to evaluate each one bearing in mind the simultaneous existence of highly complex interrelationships between many system elements. This enables the consequences of all decisions on the general behaviour and performance of a coherent design to be assessed.

During design, while a lot is known about the behaviour of individual system elements under different circumstances, very little information is available with regard to the manner in which they interact with each other. This is borne out by the fact that there is no one stage in the design process that considers all aspects of a system's overall performance. Instead each stage concentrates on certain subsections and specific aspects of a system. Furthermore the majority of design techniques only apply to system elements in isolation from their neighbours, thereby discounting interactions. This is bewildering in a process where objectives are specified in terms of the required overall system performance. Consequently because of the inherent limitations of most design techniques [Wemmerlov et al, 1987] a phase of overall system design integration and evaluation is essential. The objective being to assess overall system behaviour and performance in order to compare with the desired performance criteria.

A number of techniques used to aid the design of manufacturing systems do not have explicit design objectives associated with them, e.g. material flow charting or classification and coding. Therefore there has to be a separate evaluation of a decision to that of its formulation. However, even with techniques such as production flow analysis which do have explicit or implicit objectives (i.e. minimum material movement) they may conflict with the required overall objectives, therefore making the technique inappropriate.

Thirdly and in relation to the previous point, the optimum setting of specific elements of a system does not necessarily produce the best overall design configuration. The benefits gained from achieving local design optimization may be offset by interactions leading to poor performance elsewhere. Thus irrespective of the techniques all design decisions must be evaluated relative to the performance of the overall system. Furthermore it is inevitable that there will be a certain amount of conflict between design decisions which can only be resolved through appropriate compromise made on the basis of overall system performance evaluation.

The basic or informal way of progressing through a design project is to rely wholly on value judgement or experience and then revise the design once it has been implemented. A pilot scheme is generally developed whereby the performance can be observed and, with techniques such as Taguchi [Taguchi, 1986], experiments undertaken in order to optimize the system. However, the high costs associated with the design and implementation of a manufacturing facility, have placed significant emphasis on the minimisation and justification of design risks and cost, respectively. In addition the increase in market competitiveness has created a desire to achieve the manufacture of a product right first time. However, relying on a person's past experience and skill provides no reliable guarantee of obtaining an adequate design. Furthermore the introduction of new technology into a company generally implies the existence of little or no previous experience to rely on. Thus financial assessment is performed to aid in the design of a system.

4.2.2 Financial Assessment

The fundamental problem with financial assessment or cost analysis is its dependency on other methods or techniques of evaluation. For cost analysis does not directly evaluate system performance. Instead it merely provides a basis for comparison between alternative design solutions and/or against desired performance criteria. Though the process can identify design benefits or deficiencies, ultimately the assessment can only be as thorough and accurate as the evaluation techniques upon which it is based. As these techniques predict the expected system performance, such as WIP, resource utilization, scrap, etc. upon which cost analysis can be performed. Consequently having established the limitations of current design techniques, the deficiencies of cost analysis are all too apparent. If the underlying design techniques cannot assess overall operational behaviour or evaluate the highly dynamic interactions inherent within a system, then a financial assessment cannot compensate for their deficiencies. A financial assessment requires an integrated and coherent performance evaluation, to avoid diminishing the accuracy of the cost analysis and hence the justification of a design which, as Mackulak et al [1984] states, must be:

> "extensive, and must consider, as completely as possible, all aspects of facility performance."

An additional restriction of cost analysis is the necessity to establish and quantify performance measures in appropriate financial terms. This is obviously difficult as certain aspects of a systems performance (e.g. customer satisfaction) are hard to quantified in terms of cost.

In the design methodology presented in the previous section it is very apparent that each step of the process is only concerned with certain individual sections of a manufacturing system. The design process does not explicitly define one stage that considers the integration of individual sections into a coherent manufacturing organization, then subsequently assess the effects of interactions, between system elements, on the behaviour and performance of the specific system design. However, this is essential in order to establish a particular designs "correctness" against desired performance criteria, generally specified in terms of overall measures. Consequently it is important to identify methods which will eliminate some, if not all, of the above shortcomings. Computer modelling and in particular computer simulation therefore are very important and powerful design techniques [Wemmerlov et al, 1987; White, 1983], as they provide the only effective means of evaluating the dynamic integration of system elements.

4.2.3 Computer Simulation

Simulation allows a problem to be defined in a simplified form in order to understand and resolve it through a trial and error approach. Computer simulation provides the only means of thoroughly investigating the dynamic behaviour of a manufacturing facility, other than directly experimenting on the real system. Simulation can represent all individual elements and interactions that collectively constitute a manufacturing system [Solberg, 1978] and, with the resulting model, predict likely performance measures by emulating system behaviour as it evolves over time, through various state changes. The development of a model facilitates the investigation into the effects that resource availability and/or different operating procedures have on the overall behaviour and performance of either an existing or proposed system. This provides a means of thoroughly understanding how well a conceptual system design would operate if it were implemented and identifies possible areas of weakness. Furthermore by being able to quantify a system's performance, simulation enables a far more accurate financial design assessment to be performed.

It is possible to use mathematical models to evaluate designs, so long as the system is fairly simple and no complex interactions exist. Solberg [1978] states that, below a certain level of detail the mathematics of an analytical approach become intractable. Mathematical models are therefore unable to accurately represent all aspects of a manufacturing system's behaviour and so have a rather limited application in the evaluation of such systems. Consequently computer simulation is a very powerful technique, providing the only detailed and accurate method of evaluating all elements and interactions inherent within a manufacturing system.

During the early development of computer simulation its practical application was said [Bollinger et al, 1981] to be too costly or of little value (with models often unable to incorporate sufficient system detail to provide a realistic representation) or difficult because of the problems of gathering enough real data. However, with significantly cheaper computing power, improved techniques to develop computer models and a requirement to minimise design risks, simulation has become more widely accepted. The benefits of using the technique in support of manufacturing system design projects now being generally recognised [Norman, 1983; Brown, 1988].

Some of the benefits of computer simulation include the ability to study and evaluate a system's dynamic potential behaviour and overall performance characteristics even though it exists only as a paper design. The technique builds confidence in design decisions ensuring no unrealistic assumptions are made and that a design does not contain any major pitfalls. Also control systems and contingency plans can be formulated and assessed before implementation. Basically simulation provides a way of determining whether specific design objectives will be met.

The role of simulation in the design of manufacturing systems, as seen by the author includes:

- aid and support the creative design process by providing a better understanding of a design;
- provide a realistic representation;
- give dynamic insight;
- determine the feasibility and capability of a design;
- confirm or otherwise any assumptions about a design;
- verify resource requirements;
- ascertain the effects of changing system parameters.

The primary role of simulation should be that it both supports and guides the design evolution of a manufacturing system. The remaining points therefore define the mechanisms by which simulation achieves its first objective.

In the future it is envisaged [Shodhan et al, 1987 and Mellichamp et al, 1987] that as well as simulation, artificial intelligence techniques will be aiding manufacturing system design. Moreover it has been suggested [Mellichamp et al, 1987; Fisher, 1986] that expert systems could perform the whole design process. However, this goes against the idea that design is a creative process [Rzevski, 1981], and would stifle manufacturing system design innovation.

4.3 The Role Of Computer Simulation In Design

4.3.1 The Prescribed Use of Simulation

In the previously defined manufacturing system design methodology the specification of how and where to apply computer simulation results in a rather inefficient use of the full potential of the technique. There is a general temptation [Parnaby, 1986; Smith, 1985] to limit the application of simulation to only dynamic design, but this neglects certain fundamental decisions regarding strategic design parameters. Therefore such decisions taken both before and after dynamic design, are done so without any consideration being given to the consequences of such action on overall system performance.

In the design of a manufacturing system it must be shown that a final proposal achieves the original objectives. Therefore all relevant benefits, performance measures and cash flows have to be identified and quantified. This being the case, it is peculiar to note that the methodology suggests that one of the key strategic design decisions is taken without any reference to the likely resulting system behaviour.

The aim of the cell definition phase is to focus attention on one general design alternative which is subsequently developed throughout the remainder of the project. Ultimately therefore cell definition determines the eventual configuration, operation and behaviour of the final system design proposal. In effect this one stage tries to identify the best overall design specification from the vast number of alternative solutions. This is achieved through the use of either inexplicit or locally optimising design techniques, which necessitates an independent decision evaluation phase on the basis of overall system performance. However, in the absence of any specified application of computer modelling or simulation techniques at this stage, design proceeds from cell definition with limited consideration for the validity of the key strategic decisions that have been taken. Furthermore the lack of any evaluation into overall system behaviour implies only partial investigation of alternative design solutions. The selection of one particular design therefore can quite easily result in the most appropriate system being overlooked. Consequently if at this early stage the best or optimum solution is missed, then subsequently a lot of time and effort is unknowingly wasted on the development and evaluation of an inferior system design [Brown, 1988].

The application of simulation techniques only at dynamic design implies that decisions taken in subsequent stages will not be evaluated with regards to their effects on the overall system performance. This omission is rather startling when it is realised that at the dynamic design stage approximately only half of the manufacturing system design has been completed. One significant stage that remains outstanding is the design of the control system. This, by its very nature, is generally the most sophisticated part of a design as it controls the activities within a manufacturing system. The control system determines such things as what work a machine and/or operator should do next, what to do if a machine is busy or broken-down or an operator is absent. Thus decisions regarding the control system specifically relate to the interactions between system elements and have significant impact on the overall performance and behaviour of a design. Therefore to validate any decisions regarding the design of a control system requires the evaluation of the whole system design. The only technique able to do this is computer simulation, however, its use at this stage is not specified.

4.3.2 The Actual Application of Simulation

Having established the role and importance of computer simulation, it is peculiar to find that very limited and rather ineffective use is actually made of the technique within manufacturing system design.

The survey undertaken by the author of the actual practices adopted in the design of manufacturing systems highlighted that during most, if not all of the process, system elements are considered in isolation from each other. This was identified within the survey by the fact that none of the design teams interviewed undertook any form of dynamic system evaluation. Furthermore there are manufacturing system design methodologies [Shodhan et al, 1987] that suggest that individual element design should be undertaken without any consideration of a system's dynamic interactions. The combined artificial intelligence and simulation design methodology, presented by Shodhan and Talavage, suggests that the evaluation of a system, via computer simulation techniques does not commence until after the whole design has been specified, including the control system and operational rules.

It is accepted that the ability to evaluate the integration of individually designed system elements is a major benefit of simulation techniques. As White [White, 1983] says:

> ".. one of the most valuable contributions of simulation is the ability it gives us to model and study total systems."

In addition Dunham and Kochhar [Dunham et al, 1983], having reviewed the use of computer simulation in the manufacturing environment, concluded that there are three main areas of application: production scheduling, line balancing and in-process inventory. These processes are highly influenced by overall system structure and operation and therefore require complete system evaluation, as undertaken by Hollwey et al [1983], Bassett et al [1985], Buckley et al [1987] and Grant et al [1988].

However, there are some inherent problems with only evaluating overall system behaviour and performance once the total design specification has been completed. Inevitably the specification requires decisions regarding the type, quantity and operation of the individual elements from which it is comprised. The evaluation therefore of only completed system designs implies that the development of individual elements is based upon previously unsubstantiated decisions. The earlier individual decisions can be evaluated, in relation to overall system behaviour, the better future decisions will be, leading to more suitable final design specifications requiring less modifications.

Design, by its very nature is an iterative process, however, only evaluating complete system specifications does mean that the design loop is particularly large. This is due to the fact that the identification and quantification of system elements can take between two to four months, thus leaving the evaluation process to be performed relatively late in a project. If at that point a design does not satisfy the specific performance objectives several stages of design would have to be repeated. An alternative design is then developed which is again evaluated. All this occurs in the latter stages of the project, where due to the restricted opportunity for system changes and a lack of available time, no significant design amendments can be implemented. Since no significant part of the design process can be repeated, only minor design adjustments can be incorporated. Hence the development of a manufacturing system specification is inevitably founded on largely unverified design decisions.

In considering the actual application of computer simulation therefore, there is no indication that the technique is used to control and verify either the direction or progress of a design project. It is not fulfilling its major role (section 4.2.3). Instead where computer simulation is used it only checks and confirms the features and performance of a final design proposal, rather than supporting the evolution of the system.

4.3.3 Modelling Strategy Justification

The previous design methodology provides a very structured and appropriate approach to the design of manufacturing systems. However, it does fail to utilize the full potential of computer simulation techniques. Furthermore it seems to ignore the fact that the greatest opportunity to incorporate design changes is at the beginning of the process. By only considering overall system performance and therefore design validity at the dynamic design stage or latter, after a lot of time, money and effort has been invested, there is far less opportunity for change, especially strategic ones.

The accuracy and completeness of the investigation into alternative design solutions, adopted by the methodology, is questionable. The methodology focusing predominantly on the development and specification of just one possible solution, identified very early in the process, at which stage the available data and information, regarding alternative designs, is both limited and incomplete. In addition the subsequent investment of time, money and effort cannot be truly justified on the bases of strategic decisions which are not validated with respect to overall performance criteria.

The application of computer simulation in the design of manufacturing systems should fulfil a number of roles. Taking into account the inefficiencies of currently available design techniques, and the unique ability of simulation to evaluate the dynamic integration of individual system elements. Firstly simulation should encourage the continual evaluation of decisions, with respect to overall system requirements, as they are made. Future decisions would then be based upon previously substantiated ones, resulting in fewer design errors. So simulation would provide an effective mechanism to monitor and control the development and evolution of a design that was directly related to overall performance criteria and so aid the decision making process.

Secondly simulation should encourage a thorough investigation of all design alternatives in an efficient manner. Understanding that at the beginning of a study there is a near infinite range of design alternatives that should be evaluated but very little information available. Therefore modelling has to be quick but not particularly accurate. Whereas at the end of a project when there are only one or two alternatives left, design evaluation needs to be thorough. Consequently modelling has to be very detailed and extremely accurate, but not necessarily fast. The various design stages therefore require different levels of support from simulation.

There is therefore a requirement for a modelling strategy which will complement the actual design process by integrating computer modelling techniques. Such a strategy would work in parallel with the previously developed design methodology, making the process far more efficient.

4.4 A Multi-level Modelling Strategy

4.4.1 Overall Modelling Philosophy

A new multi-level modelling strategy is therefore proposed which partitions the original design methodology into four sections (figure 4.6) producing a process which contains a number of small iterative loops, with each loop resolved before passing onto the next. Thus design development is continually checked against overall performance objectives and never more than a quarter of the design process has to be repeated at any one time. This resolves the problem of the original approach, where a design was only evaluated at the completion of a project, and which often resulted in having to reiterate the whole process and several months of work.

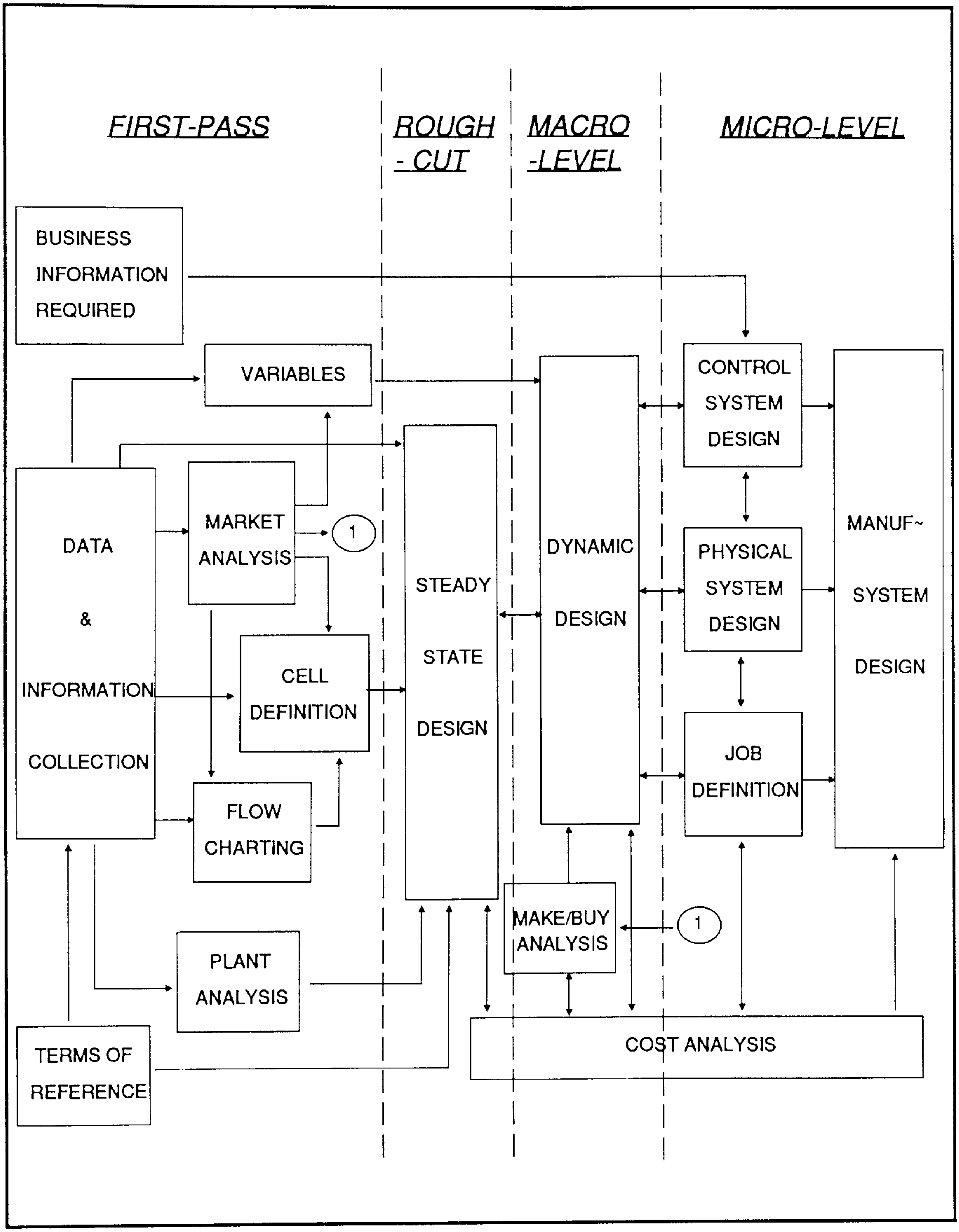


Figure 4.6 Multi-Level Manufacturing System Re-design

Therefore by sectioning the process into a number of discrete decision making stages, which are supported by efficient and appropriately detailed dynamic design evaluation techniques, then the whole approach to identifying and developing the best system configuration is changed.

The present methodology aims to identify the most suitable design configuration at the cell definition stage and then add the detail throughout the remainder of the process. The new approach, however, allows all feasible solutions to be considered until shown to be inappropriate. Therefore as design progresses and more detail is incorporated the worst alternatives can be rejected on the bases of the overall system evaluation until, at the end of the process only one solution remains i.e. the best. The strategy quite deliberately and methodically takes its time to identify the most appropriate design solution. Whereas the methodology quickly focuses on a particular alternative, which is not necessarily the most appropriate or whose selection is not thoroughly substantiated. Figure 4.7 clearly illustrates these differences in identifying the final design solution.

The modelling strategy initially considers the whole spectrum of design alternatives at the first-pass stage and on evaluation the worst are rejected. The remaining designs pass to the rough-cut stage, more detail is incorporated into them and again the worst are rejected. This is repeated at the macro-level, so that on reaching the micro-level only one or two designs, at the most, remain and from which, having considered each in detail, the best or optimum design is chosen. This approach allows a more thorough and structured investigation for the optimum design, given any objectives.

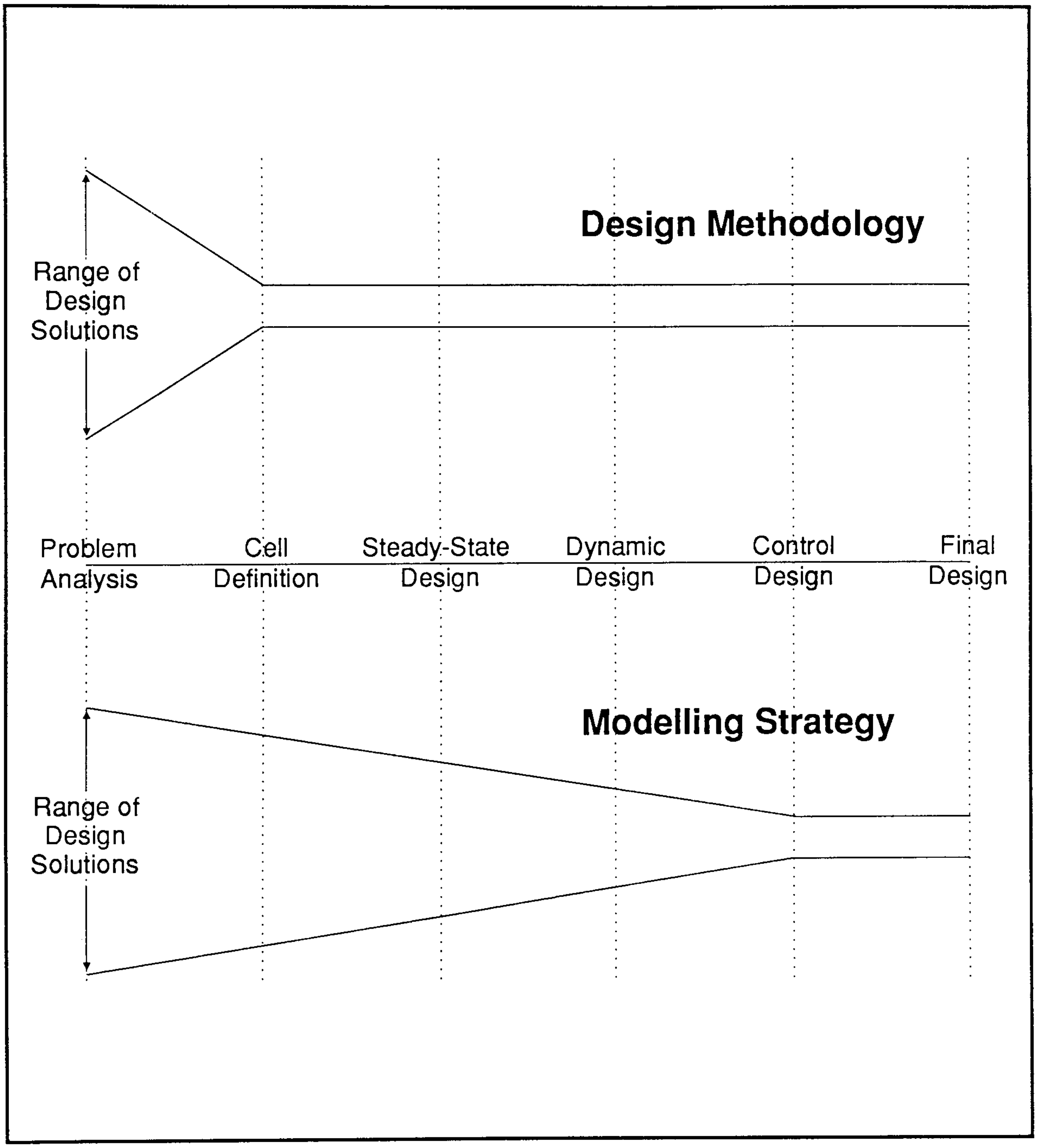


Figure 4.7 Design Solution Identification

In the multi-level modelling strategy as design progress from left to right the amount of available data significantly increases whilst at the same time the possible design alternatives decreases from near infinite to one. The strategy allows an approach whereby the overall factory or departments are designed at a highly aggregate level and attention can then focus on critical or bottleneck areas.

4.4.2 Modelling Strategy Definition

The full definition of the multi-level modelling strategy is:

1. modelling should match and support the design process (figure 4.6), i.e. first-pass, rough-cut, macro-level and micro-level.
2. modelling should encourage a single multi-level model approach, i.e. different levels of detail in one model.
3. modelling should support a progressive detailed design process, i.e. reject the worst alternatives at each stage.
4. modelling should encourage extensive design investigation by being efficient in terms of both:
   - evaluation at each stage of the design process i.e. appropriate modelling techniques; and
   - model development i.e. quick and reliable in appropriate time scale.

4.4.3 Multi-Level Modelling Definition

The contrast between the four alternative levels of detailed consideration and evaluation through which feasible design solutions pass, as defined in the above strategy, is primarily conceived to be due to data. Specifically the difference in the completeness of the data available at each stage and the necessary detail to which system elements need to be considered. That is at each level of design a manufacturing system is conceptualized in a completely different manner. These alternative views can either be represented diagrammatically (figure 4.8) or by input/output charts identifying the relative data requirements and performance measures considered in the evaluation processes at each level of design respectively (figure 4.9 to 4.12).

Perhaps a better appreciation of the differences between the various levels of design can be acquired by closely studying the separate approaches to system evaluation and highlighting the data inputs into the process and the performance measures that are examined.

I. First-Pass

At the first-pass stage (figure 4.9) of design there is a vast, if not near infinite range of possible alternative system configurations. Therefore evaluation here has to provide accurate and reliable results quickly (i.e. in minutes) to allow all possible alternatives to be evaluated. Also at this stage of the procedure very little detail of the alternative designs has been formulated. The various alternative design solutions are highly conceptual and therefore system evaluation need only provide long term, steady-state performance measures.

At first-pass a factory, department or any group of machines are simply viewed as a black box, with raw material, bought-in components and sub-assemblies feeding in and completed parts or products coming out the other end. The main focus here is on the average output of the box and the average

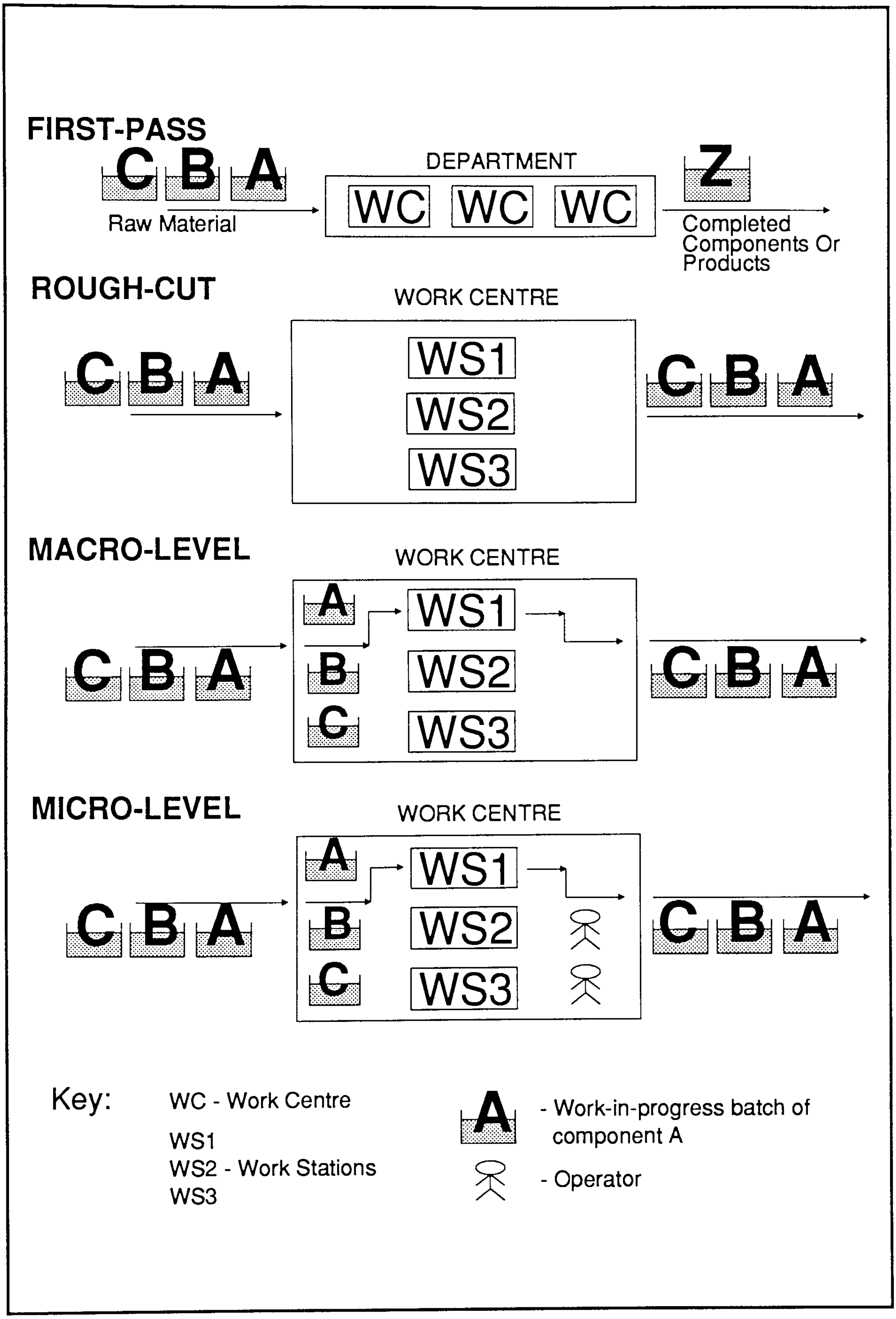


Figure 4.8 Multi-Level Modelling Description

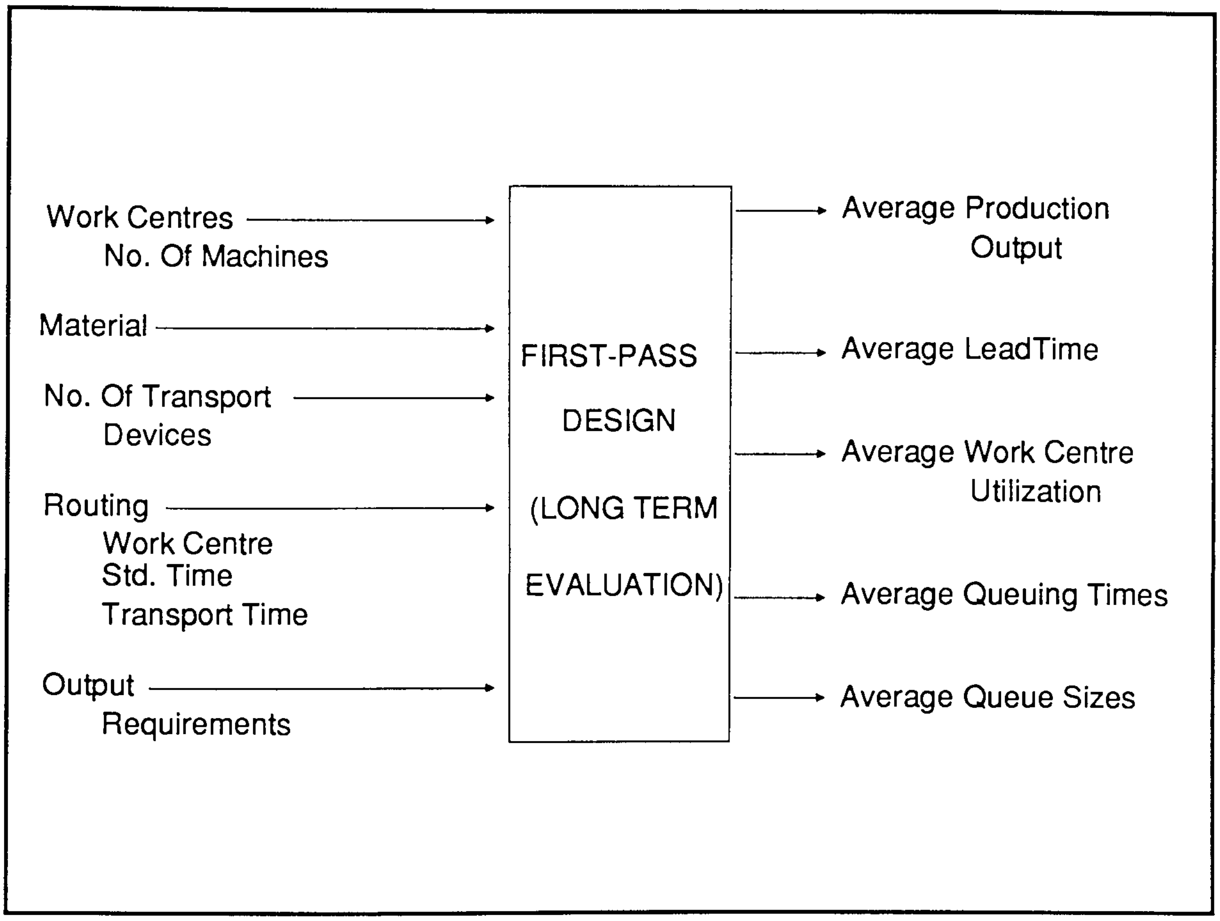


Figure 4.9 First-Pass Multi-Level Design I/O Diagram

duration for something passing through it. Whilst limited consideration is given to the individual operations which convert raw material into finished products or components.

II. **Rough-Cut**

The rough-cut level of design (figure 4.10) considers the dynamic behaviour of a system in fairly broad terms. The individual activities taking place at the work centres are depicted in a relatively simplistic manner, where a work centre is a group of similar machines that can do the same work. Furthermore discrete batches of work are modelled passing from one work centre operation to another through the system. Now a more accurate evaluation can be performed, indicating the volume and mix of parts that can be produced along with the total time to make them. Whereas before the calculated production output and lead-time were single values averaged over all manufactured parts. However, at this level of design no attention is given to the operation of individual machines within a particular work centre.

The step change from first-pass to rough-cut design is accompanied by a significant increase in the amount of data that is now considered. Whilst the range of design alternatives being developed has reduced through weeding out the inappropriate alternatives in the previous stage. Computer modelling at this stage is more detailed in terms of both the data and activities that are analysed. In order to evaluate the dynamic behaviour of a system at this level of detail, consideration is given to the individual operations occurring over time. The evaluation is therefore more accurate although the model data is still aggregated.

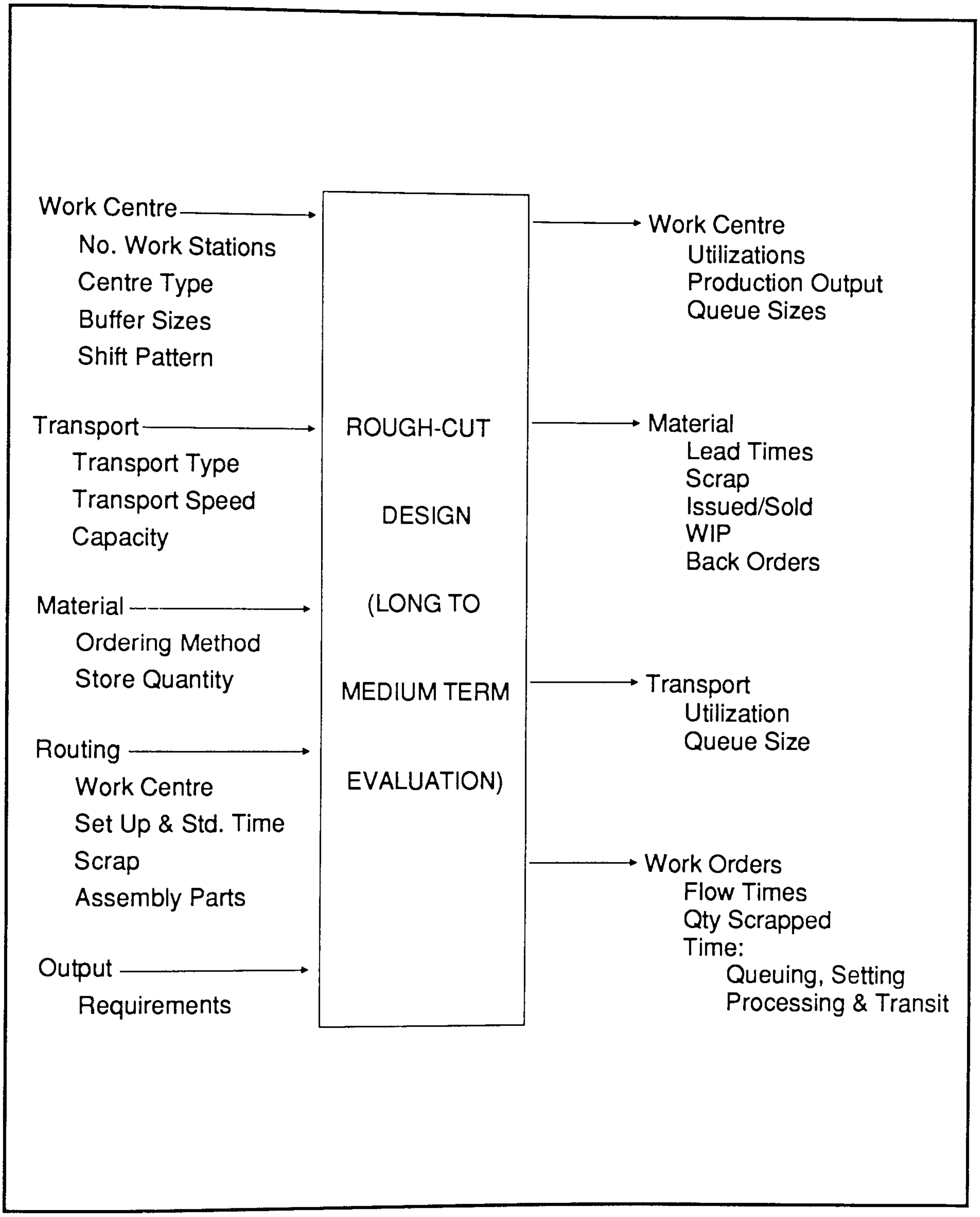


Figure 4.10 Rough-Cut Multi-Level Design I/O Diagram

III Macro-Level

At the macro-level (figure 4.11) individual machines are considered working at average levels of performance. As well as more accurate predictions of the total output and lead-times from the system, the behaviour and performance of the individual machines can be studied. Furthermore queue sizes, queuing time, component scrap, machine utilization and output can all be investigated under different working procedures and scheduling priorities.

In the macro design stage attention is focused on providing an adequate level of machine capacity, taking into account system variation in order that the design will achieve production output requirements. In addition work sequencing rules are established which provide the mechanism for selecting the "next job" at specific work centres. At this level of detail tool resources and limitation are considered. Fewer alternative design solutions now remain having been further whittled down by the previous stage. However, those that are left are considered in greater detail. Therefore a modelling technique to support this stage of design needs to allow a more detailed description of the proposed systems than in the rough-cut model, but still accommodate some level of aggregation (i.e. performance and scrap values and operator considerations). Again modelling at this level considers the individual operations occurring in the system.

IV. Micro-Level

The micro-level design stage (figure 4.12) is the most detailed and therefore most accurate study of a system. Here the operators are considered undertaking a range of activities along with discrete machine breakdowns, operator absenteeism

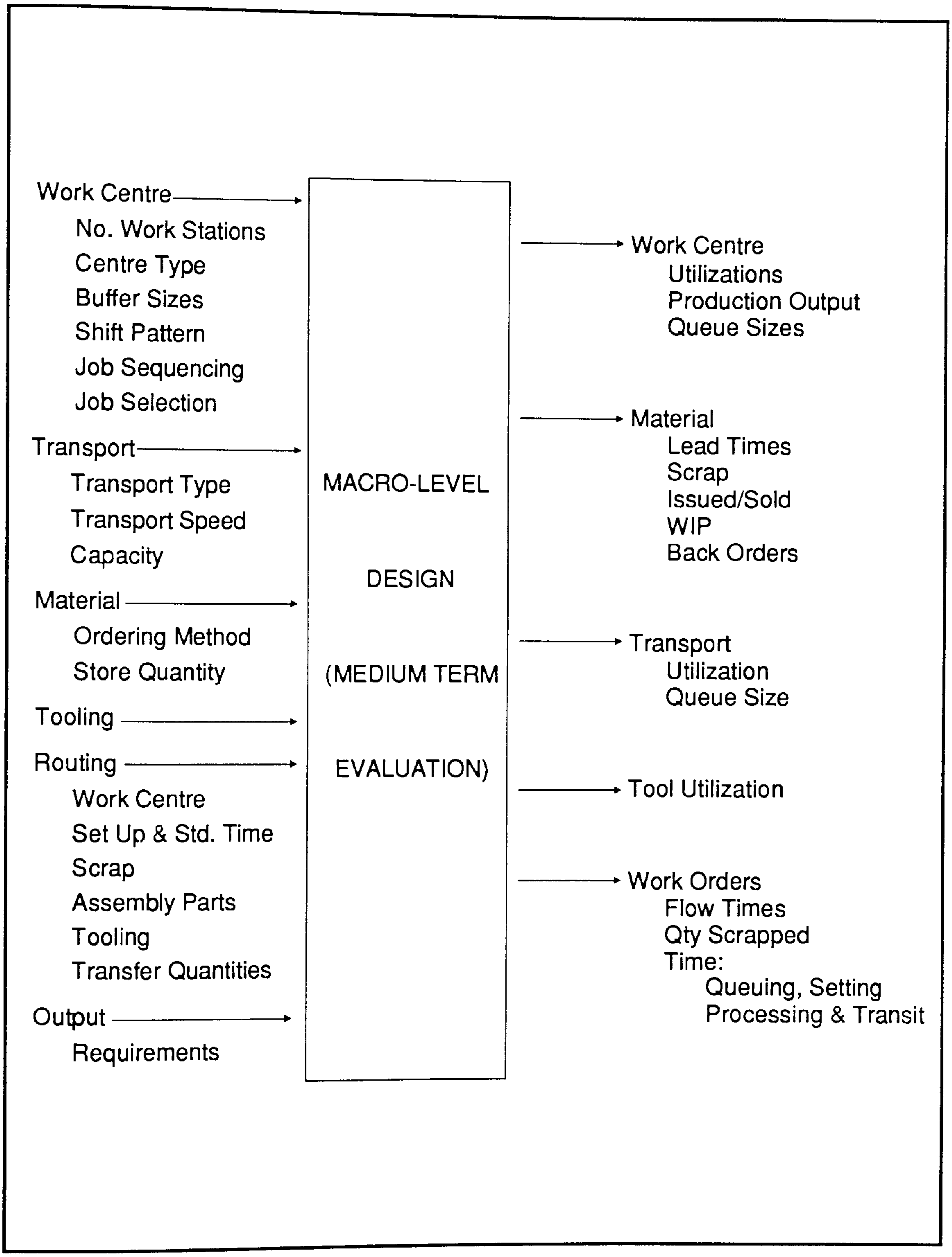


Figure 4.11 Macro Multi-Level Design I/O Diagram

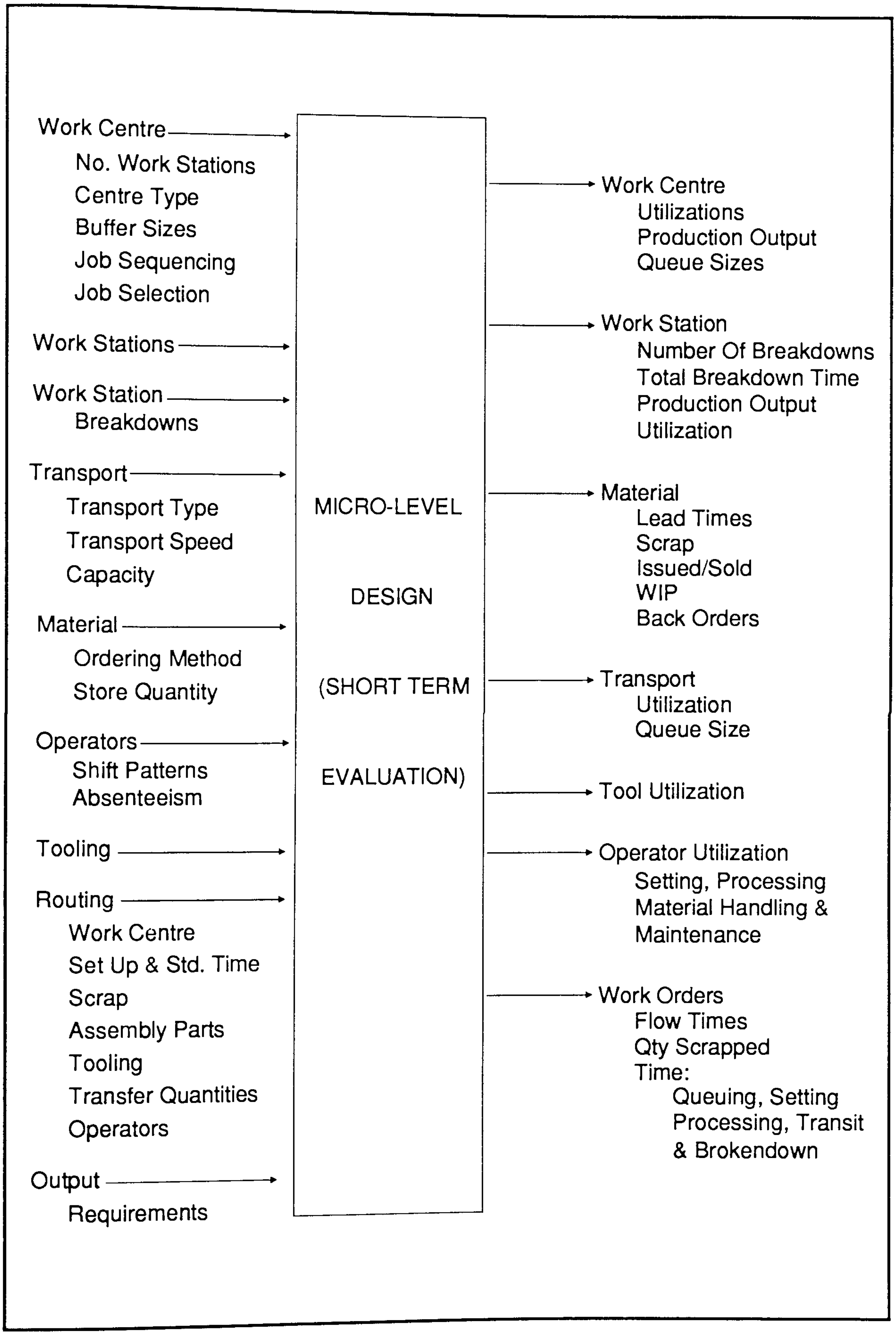


Figure 4.12 Micro Multi-Level Design I/O Diagram

and alternative material routes. Control rules for allocating operators to set up, process, maintenance and material handling jobs are also established.

Here only one or two design alternatives remain from which the appropriate system configuration and operation has to be decided upon. That is the system proposal that best satisfies the initial design objectives and company policies. This stage of design is different to the preceding ones in that here the best alternative is identified, whereas previous to this it was the worst proposals that were highlighted and then rejected. To support this stage of design modelling needs a microscopic representation of a manufacturing system design. At this level speed of evaluation is of little importance, instead it is the comprehensive study of highly detailed discrete operations and activities in order to accurately predict the precise dynamic behaviour and performance of a system.

This chapter has identified the need for a new multi-level modelling strategy to support and improve the efficiency of established manufacturing system design methodologies. The modelling strategy defines the requirements for a wide and varied range of appropriate computer modelling tools for the evaluation of system designs. Therefore the next chapter provides a general discussion on available modelling techniques. Whilst chapter six looks more specifically at the approaches available to develop computer models, with close attention being paid to the particular requirements of the modelling strategy.

Chapter 5 Computer Modelling

5.1 Introduction

Computer modelling has over the past 25 years been developed and established as one of the most effective and commonly used techniques to aid decision-making in business and industry. However, modelling itself is not new and has in fact been practised for centuries. The term modelling has been applied to some extremely diverse forms of model building ranging from pre-historic cave drawings to renaissance paintings and sculptures and from models of supersonic jet airliners to ball-and-stick models of molecules.

5.1.1 **Why Model ?**

The construction of "mental" models is inherent in the human thought process but such models have a number of significant defects which severely limits their usefulness. Therefore "real" models are constructed and utilized in order to compensate for the intrinsic deficiencies of mental ones.

Mental or descriptive models generally contain a high degree of contradiction, due to their contents being continually changed, without it even being realized. Also such models are impossible to review or challenge as it is unclear what information and experiences they are based upon. Furthermore, the obscure and vague nature of the mental process makes it difficult, if not impossible to coherently describe the model in words.

The unaided mind is simply incapable of relating all the complex factors in a system and mentally tracing their interactions through time. Therefore "real" models are utilized which specifically require us to describe the behaviour of a system in very precise terms.

The best definition of a model is provided by Shannon [1975], who say it is:

> "the representation of an object system or idea in some form other than that of the entity itself ...",

to help in explaining, understanding or improving it. A model differs from the real system in at least one characteristic. Rarely are all features of a system relevant and so in general a model is simply developed in terms of those characteristics of interest. As the irrelevant features of a system are ignored, a model is easier, cheaper and more convenient to study. However, a model cannot be expected to reproduce the exact behaviour of a system, as this is the price for the simplicity and accessibility. Therefore there is a compromise in modelling between the faithfulness of reproduction and the simplicity of construction and operation.

5.1.2 The Modelling Function

The range of computer modelling applications is fairly diverse, but there are several standard reasons for its use, which include:

- to aid thought: Provides a vehicle for discussion and evaluates the validity of ideas;
- to aid communication: Ideas and descriptions can be communicated without ambiguity in an efficient way. A model is comprehensive, revealing important internal system features;
- for prediction: The behaviour of a system can be

predicted with a model;

- aid experimentation: Modelling allows experimentation of systems where direct analysis would be impossible, impractical or prohibitive. Also it allows a more detailed evaluation of a system as it provides an ability to control and vary individual parameters.

5.1.3 Model Classification

This section provides a classification [Shannon, 1975] of models to help put into perspective computer modelling techniques (figure 5.1).

Physical models exactly replicate reality either directly or indirectly.

In iconic models the properties of the model itself represent the relevant properties of reality, e.g. scale models, photos and maps. They may be static to visualize space relationships e.g. plant layouts, or dynamic to evaluate variable stability e.g. wind tunnel testing.

In analog models the properties of a real system are represented by substituted features that behave in a similar manner. Problems are solved in the substituted state and translated to the original properties e.g. graphs and slide rules.

Symbolic models are always an abstract idealization of the real problem, in which simplified assumptions have to be made if a solution is to be found.

In analytical/mathematical models, mathematical symbols and processes are used. These models represent a deductive solution to a problem using calculus, differential equations, queuing theory, etc.

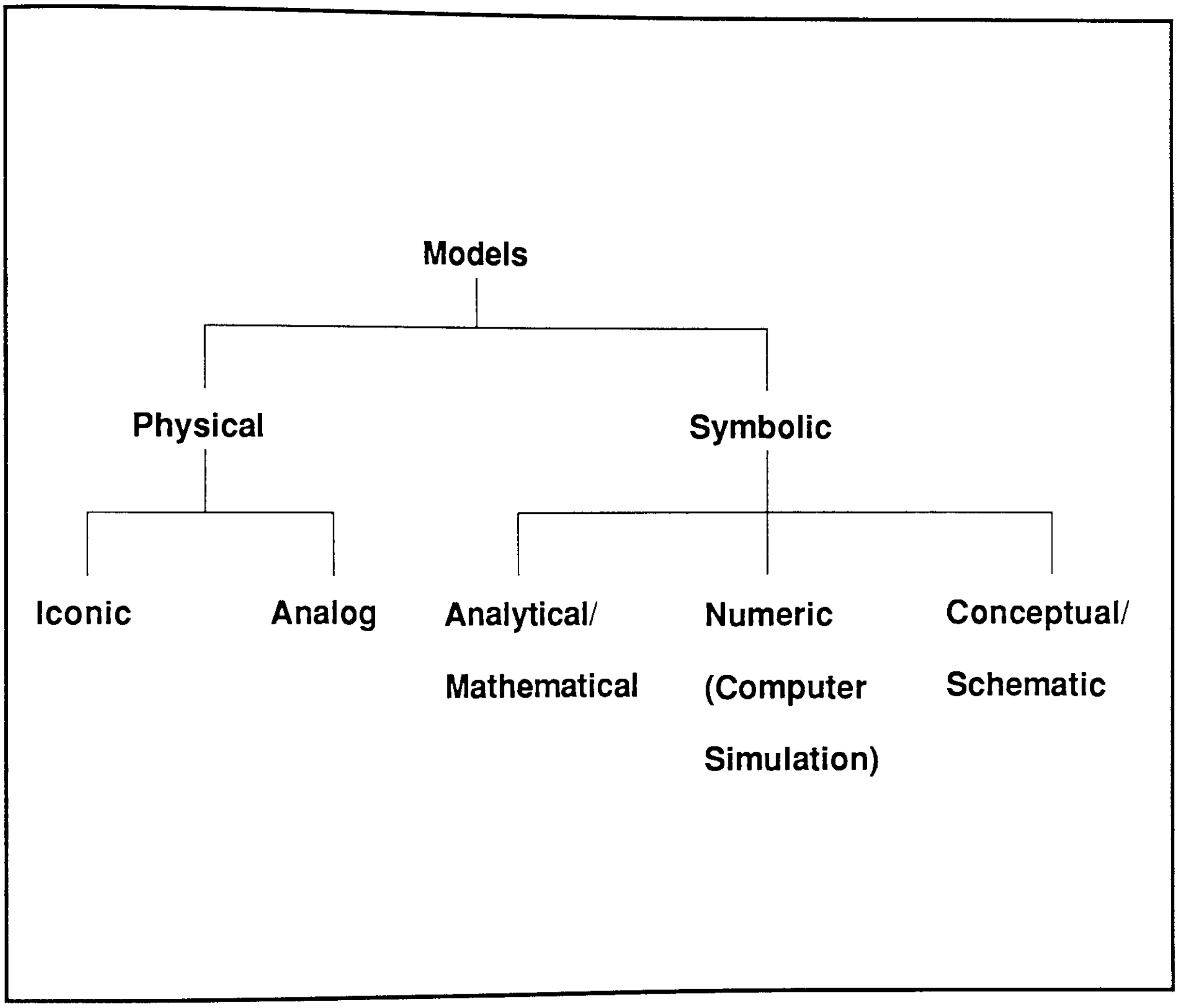


Figure 5.1 Types Of Models

In conceptual/schematic models reality is represented in the form of a diagram e.g. flow diagrams.

In numeric models, numbers, variables and logic are used, but not necessarily mathematically to imitate or replicate reality as far as the modeller chooses e.g. computer simulation.

Of all these types of models, mathematical and numeric modelling techniques are the most appropriate to aid in the design of a manufacturing system, as they can accommodate and emulate the complexity of such systems. They are further discussed in more detail in the following sections.

5.2 Mathematical Models

5.2.1 Introduction

Mathematical or analytical models provide a quick and easy solution to the evaluation of systems. Basically there are two types of analytical models, with static ones being by far the simpler in comparison to dynamic models.

Static models are equivalent to capacity balancing techniques used in manufacturing. Here the total work load allocated to each resource (i.e. machine or operator) is accumulated in terms of time and then compared to its actual available time. Unfortunately these models cannot incorporate any dynamic interactions or uncertainties of a system and so provide no realistic estimation of the total time for a "customer" or entity to pass through the system. They can, however, identify potential bottlenecks and effectively support a highly aggregated steady-state system evaluation. Such models being produced fairly quickly and easily through computerized electronic spreadsheets like Lotus 1-2-3 and Supercalc 5.

Dynamic models are far more comprehensive being founded on the theory of queuing networks. Such models predict steady-state performance by considering collectively a system's dynamic interactions and uncertainties. The performance measures that are derived from these models indicate the expected behaviour of the actual systems, whilst in a state of equilibrium. The results therefore predict the medium to long term performance characteristics of a system. However, dynamic models cannot predict the behaviour of a system as it changes from one state to another, caused by variations in system parameters. This means that transient behaviour cannot be modelled, which could be the result of the removal or addition of a resource or change in the level of scrap, absenteeism, standard times, etc. It is possible though to consider a system with or without a resource or at one level of performance or another and obtain a number of sets of results, based upon the system in different states of equilibrium. Recent work on queuing theory models has indicated that they do provide acceptable performance estimates, generally within 5% to 15% [Suri et al, 1985a] of those obtained from simulation techniques. As dynamic models are based on complex mathematical representation of systems, they require specialist expertize to develop them. Two examples of established dynamic mathematical models are CAN-Q [Solberg, 1976; Solberg, 1977] and Manuplan [Suri et al, 1985a].

5.2.2 Queuing Theory Models

Mathematical and more specifically queuing theory models cannot investigate any time dependent properties of a system. They do not provide a step-by-step investigation but, via mathematical theories and equations, do evaluate the long term average system performance. That is the system's steady state behaviour.

The theory behind queuing models assumes that a "customer" requires at least one "service" from a system. Inevitably the "customer" may have to queue at each service centre before it can be served and thus the system is viewed as a network of queues. Therefore many service facilities, (e.g. banks, garages, ticket offices, etc.) production systems, communication and computer systems and transport systems can be viewed as queuing systems.

In the CAN-Q mathematical model, "customers" move randomly from one service centre to another, in accordance with a range of routing probabilities reflecting the frequencies with which the specific centres are visited. Whilst service times are regarded as random variables, though only the average times are required. Although the specific "customer" routes are redundant within the actual evaluation process, they are still necessary to determine the routing probabilities and average service time for each centre.

5.2.3 Input Requirements and Output Results

Queuing models are unable to represent extremely detailed system features or behaviour. The specification of a very detailed or complex system model is generally impossible to be represented mathematically or any equations which are derived are simply intractable and unable to be solved. Whereas if too little detail is expressed then the model does not realistically represent a system. Thus a compromise between a model's representation and ease of solution has to be made. Generally a queuing model's data input requirements include:

- the number of service centres and servers at each centre;
- types of customers and their mix ratio;
- total number of customers in the system;
- frequency visit probabilities for each centre;
- the average service time at each centre.

The system performance measures provided by a model include:

- average production rates;
- average throughput times;
- average centre utilization;
- average number of customers at a centre;
- average number of queuing customers.

5.2.4 Queuing Model Advantages

The advantages of mathematical models include:

- very easy and quick to use, providing rapid evaluation;
- data driven, new models are created simply by changing input data;
- simple data requirements;
- includes certain dynamic interactions and uncertainties;
- predicts the medium to long term average performance of a system.

5.2.5 Queuing Model Disadvantages

The disadvantages of mathematical models include:

- unrealistic assumptions assumed;
  e.g. All service centres have an unlimited queue size, thus queue blocking cannot be studied.
- reduced user confidence in the model;
  e.g. The theory behind mathematical models is very complex and the calculations are difficult to comprehend.
- difficult to validate models, due to the highly aggregate assumptions that are made;
  e.g. Usually validation is done against simulation models incorporating the same assumptions.
- relatively low accuracy and limited output;
- cannot support short-term transient or dynamic investigation;
- care must be taken in interpreting the results due to averaging effects and neglecting certain important system interactions;
- time-dependent features cannot be studied.

5.3 Computer Simulation

Simulation provides a means to investigate and evaluate real systems, for which it would be unsuitable to directly experiment upon due to ethical, disruptive or economical reasons. Systems that are unavailable for investigation due to being only at the conceptual or design stage, or are simply too unwieldy to manipulate, can also be simulated.

5.3.1 Definition of Simulation

There is, unfortunately, by no means a consensus among modellers as to the exact meaning of the word simulation. Recently due to the exponential growth of computer power and increase in computer modelling, it has taken on a rather restricted meaning. Naylor et al [1966] and others have defined simulation as:

> "..... a numerical technique for conducting experiments on a digital computer."

It has also been defined by Mcleod [1986] as:

> ".. the use of the model to perform experiments..."

However, simulation is a process which incorporates the construction and manipulation of a model to study a problem. Furthermore, a definition of simulation should not be restricted to experiments performed on computers. Therefore a more appropriate and general definition is provided here, adapted from Emshoff and Sisson [1970].

> Simulation is the process of designing and developing a model which describes the behaviour of a system in terms of mathematical and logical processes and manipulating it to evaluate and predict the dynamic performance of a system over a period of time.

5.3.2 The Use of Simulation

Simulation is not the most effective way to solve a problem. It is said that the technique is a last resort or brute force approach to problem solving, because of its lack of any analytical procedure.

Simulation is an iterative process which does not directly solve a given problem. It merely provides information or insight into the performance of a system, which in turn contributes to solving the problem. By iterating a simulation experiment with parameters changes from one run to the next, an optimum or near optimum solution can be obtained for a particular problem.

It is certainly true that whenever a problem can be correctly represented by analytical or mathematical procedures then there is no need to simulate. However, whenever a problem contains the combined effects of uncertainty, dynamic interactions and the need to examine it over a period of time, then it is too intricate to be solved by explicit functions. Therefore analysis has to be done via controlled experimentation and observation thus as simulation allows the construction and evaluation of a model, then it is an ideal technique.

Execution can be done manually using pen, paper and a pocket calculator and provides a very clear and detailed understanding of how a system operates. However, this approach is very time consuming, prone to errors, (especially over long periods of time) difficult to obtain a series of reliable results and can be extremely costly in terms of resources. Whereas the computer implementation of a simulation model provides a very quick evaluation process, generating far more reliable and consistent results. Unfortunately the development of such a model is generally a very lengthy and time consuming process. However, a computer simulation model enables a number of experimental runs to be performed in a relatively short space of time, whilst a graphical representation helps to illustrate a models behaviour.

Simulation has become very popular. In trying to identify where it can be applied and which systems can be modelled it is apparent that almost any type of system can be analysed. Simulation is being applied to a very broad range of diverse systems in a number of different ways. Models have been developed using pen and paper, high level languages, spreadsheets or special purpose simulation packages in such areas as:

> Design of woven fabric patterns [Shyong, 1987], storage and retrieval systems [Perry et al, 1984], planning services for renal patients [Davies et al, 1987], and analysis of third world ports [Sheikh et al, 1987], traffic congestion [Jacobs, 1987], robotic movement [Yong et al, 1983], aerospace, brewing, food processing [Istel, 1988], air and water pollution, social and economical systems [Shannon, 1983] and many, many more.

5.3.3 The History of Simulation

I. Pre 1958

The origins of simulation go back to the work of Von Neumann and Ulam in the late 1940's, who termed the phrase "Monte Carlo analysis" for a mathematical technique they used to solve a nuclear shielding problem. However, it was only with the advent of the computer in the early 1950's that made simulation a viable technique. All the early models were written in specific machine code. Thus they were not transportable between computers and generally digital computers were relatively slow, had small storage capacity and the man/machine interface was extremely limited and difficult.

II. 1958 To 1979

The development of simulation languages began in the late 1950's through the pioneering work of K.D.Tocher who established the fundamental principles of simulation. It was recognized that all simulation models, regardless of their application, contain a range of similar standard features. The first special purpose simulation languages were GSP (General Simulation Program) written by Tocher, and GPSS (General Purpose Simulation System), both of which were developed almost simultaneously by two different research groups. It must be realised that these simulation systems appeared at a time when there were no high level languages (e.g. BASIC or FORTRAN) and so were restricted to specific computers.

The emergence of high level languages, and especially FORTRAN, in the early 1960's meant that subsequent simulation systems would be machine independent and therefore more readily available. Two such languages were CSL (Control and Simulation Language) and GASP (General Activity Simulation Program).

Also during this time system dynamics or continuous simulation was being established. System dynamics was originally called industrial dynamics by J.W.Forrester [Forrester, 1961]. Forrester provided a simple and systematic mechanism for modelling in terms of feedback control loops. Here a system would be described in terms of differential equations which were easily simulated on a digital computer by approximating them to first order difference equations.

During the early 1970's the idea of the interactive production of simulation programs appeared. The most prominent work in this area was that of Clementson [1973] in the development of CAPS for ECSL. This was the start of symbolic modellers which, given the model logic, will automatically produce an error free simulation program in a particular language. Generally the logic is specified either in a diagrammatical form or via a questionnaire. Other modellers appeared in the late 70's, early 80's and these included Express for See-Why [Istel, 1985], Forge for Foresight and Draft [Matthewson, 1982], which incorporated multiple target language capabilities.

During this time 1958-1979, when computers were expensive to run, simulation exercises required large amounts of both computing power and time. Therefore only large scale, capital intensive, high risk projects justified the expense of being aided by simulation.

III. 1979 To 1988

By 1979 micro computers were emerging and showing considerable potential for profitable application, including the running of simulation models. Of particular interest was the exploitation of colour graphics terminals which resulted in bringing the price down and capability and flexibility up. Such terminals offer, via shapes and colour together with alpha-numeric characters, clear easily understood diagrams of simulation models. Hurrion [1978] capitalized on this capability when he proposed a visual interactive simulation (VIS) system. VIS systems provide a graphical representation of the state of a simulation model over time and allows a user to suspend model execution at will, change any parameters and resume the run. VIS became generally available in 1979 when See-Why was introduced. With graphics, simulation results are more readily accepted as a user or customer can "see" both the problem and solution. Immediately understanding the significance of any changes to a system, by being able to see and therefore verify the validity of any system alterations.

As computers were becoming smaller, cheaper and more powerful more and more non-specialists were using them. Attention therefore focused on the development of far more "user-friendly" packages. Interactive symbolic modellers were now quite popular, with packages such as Hocus adopting the activity cycle diagram logic as a means for users to define and input a model. However, a practitioner still required a detailed knowledge of simulation techniques and experience in using the various interfaces and packages. Thus effort concentrated on reducing the simulation expertise necessary to produce a valid model. Known as a generic model or simulator, one such system is Witness, released by Istel in 1986, which can be used quickly and easily to model a range of different systems. Other simulators, like Mast and simfactory, have been developed specifically to model manufacturing systems.

5.3.4 The Arguments for Simulation

In resolving the question of when to use simulation it is important to consider the advantages that it offers. These include [Law et al, 1982]:

- simulation can evaluate complex, real world systems, incorporating randomly variable elements, which cannot be accurately described by analytical methods;
- new operating procedures or policies for an existing system can be evaluated without disrupting its current operation;

- new, non-existing systems can be evaluated before its implementation;
- simulation allows along period of time to be evaluated in a relatively short, compressed space of time, or a system can be investigated under expanded time;
- system features and phenomena can be studied by evaluating their performance and interactions;
- more detailed and controlled experiments can be performed than with the system itself, as it is possible to fix system variables during an experimentation;
- with simulation, the actual process of developing a model can provide valuable knowledge and understanding of how a system really operates.

However, simulation does have some significant drawbacks, including:

- the development of a model is generally very expensive and time consuming;
- the simulation of a randomly variable system can only predict likely behaviour, therefore several runs are required and all the results statistically analysed;
- a model must be validated. If a model does not correctly represent a system, the results will be of little relevance to the real system.

5.3.5 Classification of Simulation Models

Computer simulation models can be classified in a number of ways although none are completely satisfactory. Some of these classifications are:

I. Deterministic vs. Stochastic.

A model is deterministic if all the components in a system behave in a completely predictable way. This is rare as most system components behave in a randomly variable (stochastic) manner. However, the random behaviour of components can be ignored with expected values of behaviour being used, making a model deterministic. Better results are, however, obtained from stochastic models which more accurately reflect reality and incorporate effects of random system components. In stochastic models variables can, under identical conditions, take on various values allowing the resulting effects on the system's behaviour, to be assessed.

II. Static vs. Dynamic.

A static model is appropriate for those situations in which a derived solution remains valid until some basic structural change occurs. Simulation models are, however, generally concerned with systems that are dynamic. That is, system variables are frequently changing with time.

III. Equal vs. Non-equal time increments.

The simplest way of controlling the execution of a simulation model is to proceed in equal time increments. Thus up dating and examining the state of the system at regular time intervals. In other cases a model is only updated and examined when it is known that a state change is due. These changes are usually called events and as time progresses from one event to another it is called the "next event" technique.

IV. Continuous vs. Discrete vs. Combined.

This is the most common classification and is to do with the way system variables in a model change value.

1. In continuous models variables are continually changing with time and are often an explicit function of time and figure 5.2 illustrates this behaviour. Some variables are inherently continuous, like temperature or a car's speed, but discrete variables can be represented in a continuous fashion. For example, by considering the human population in aggregate terms it can be modelled as a continuous variable, although in fact it changes discretely via births and deaths. Continuous modelling, also known as industrial or system dynamics, describes and develops a system model in terms of differential equations which can be approximated to first order difference equations.

2. In discrete models variables change value discretely at specific points in time, which are called events and this behaviour is illustrated in figure 5.3. Consequently the application of discrete models does raise the question of how to ensure that events occur at the proper time, in the correct sequence and in the right relationship to other events. This can be achieved by formulating models in one of three principal ways (figure 5.4):

   - *Event* where a model's operation is defined in terms of unconditional events, with each event detailing a specific state change. Model execution is then the continuous, time sequenced processing of events until reaching the termination time, with each event generally triggering further events that will be actioned at some future time.

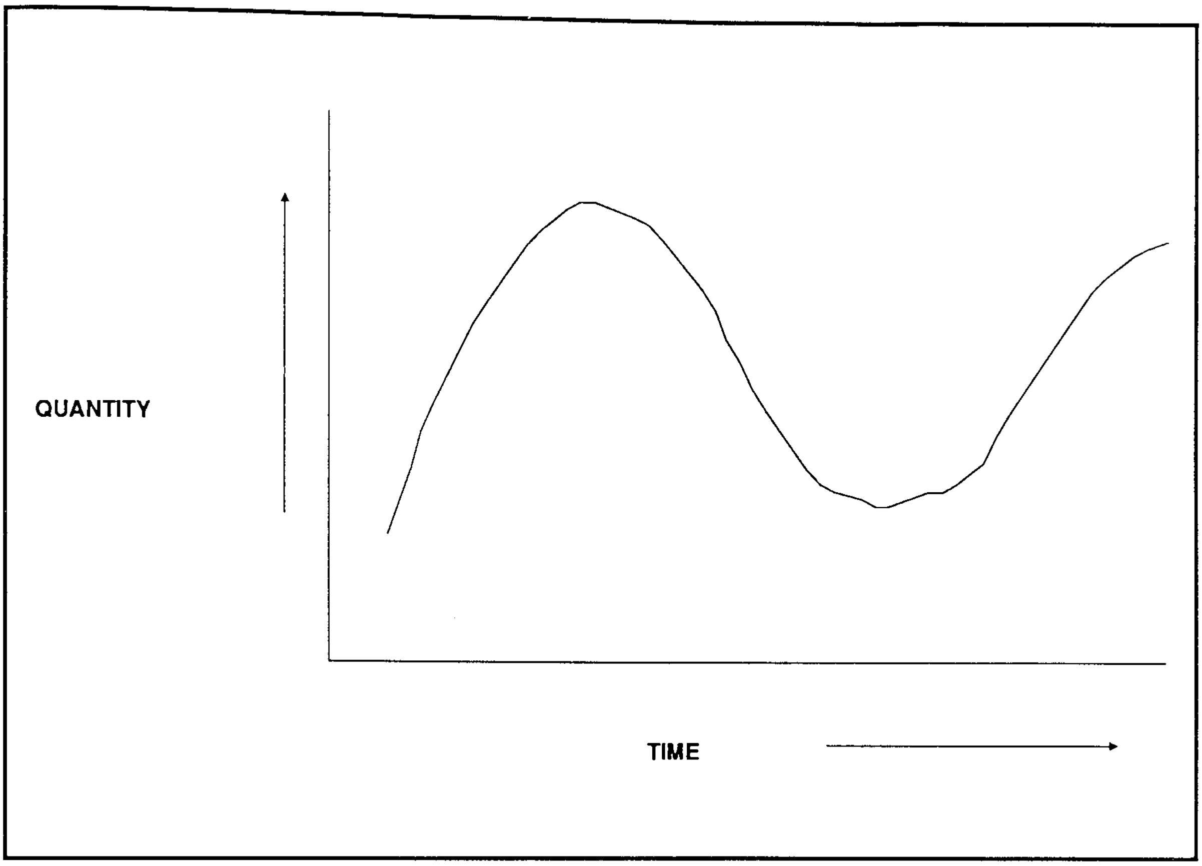


Figure 5.2 Continuous System Behaviour

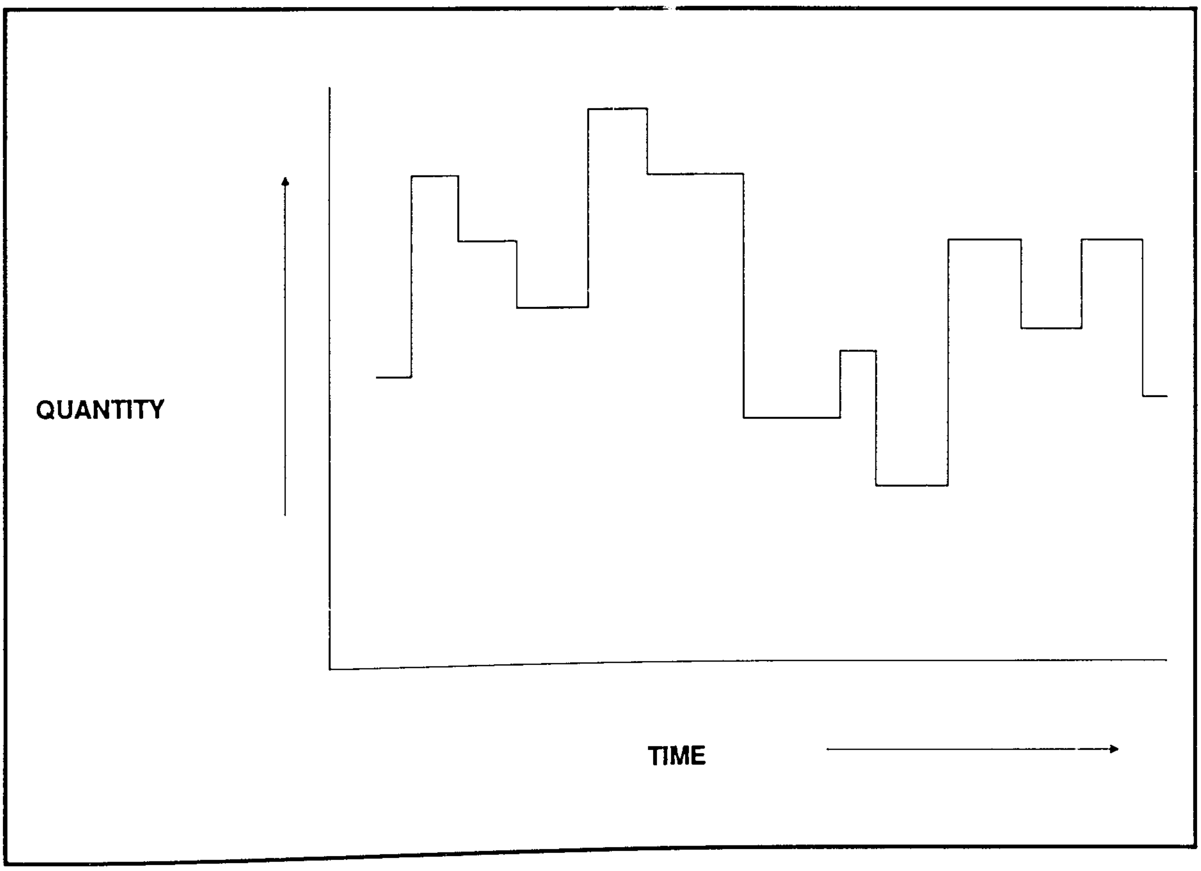


Figure 5.3 Discrete System Behaviour

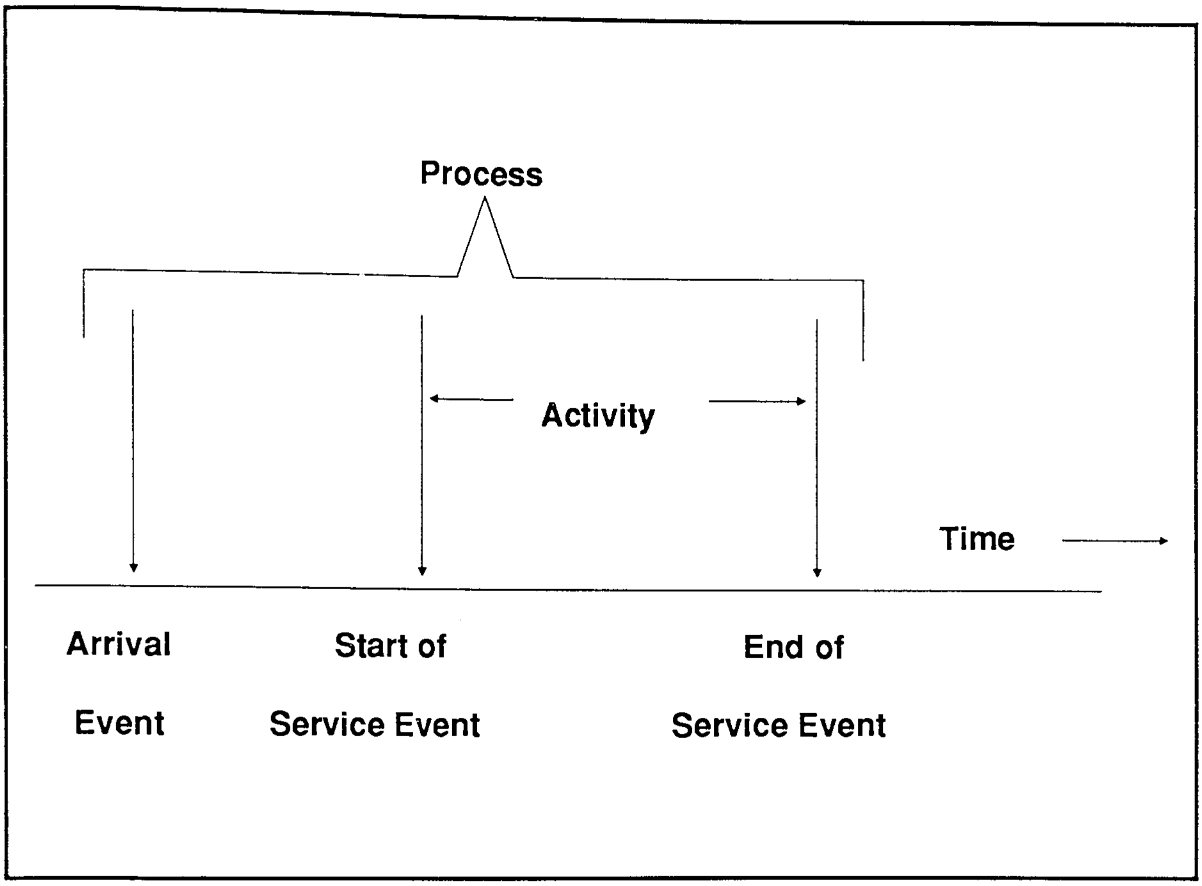


Figure 5.4 Approaches To Discrete Modelling

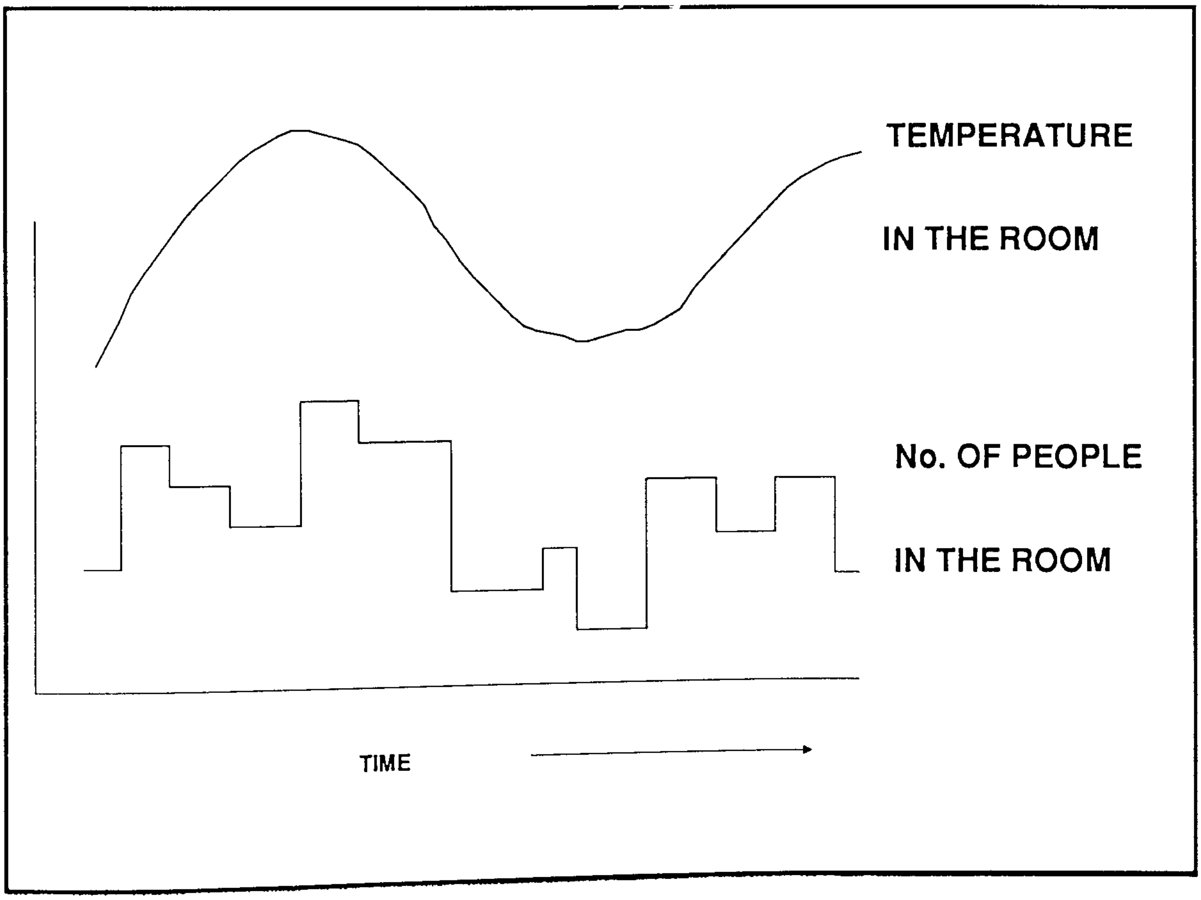


Figure 5.5 Combined System Behaviour

- *Activity* describing a model's operation in terms of individual elements or entities which engage in activities, subject to certain conditions. An activity being a state change, occurring over a period of time and in effect represents a pair of associated events which identify the start and finish of an activity. Models are first initiated by scanning the activities in priority order so as to activate those whose starting conditions are met. The clock is then updated to the earliest activity finish time (determined by scanning the activities) and the appropriate activity completed. All activities are then scanned to test if any starting conditions can now be met. This cycle is then repeated until reaching the termination time.

  Activity based models are rather inefficient in comparison to an event approach, although as models become "busier" this is not as apparent. However, an activity model is easier to write and modify. This compromise was achieved by Tocher in the GSP simulation language, which combined the simplicity of the activity model with the efficient running of the event approach by replacing the termination scan with an event list for recording the unconditional future completion of activities.
- *Process* defines the sequence of operations that a model element or entity passes through. Each entity has its own process which it follows as a simulation model executes. An entity progresses through its various operations until it is blocked or delayed.

3. A combined class of model has emerged due to the introduction of simulation languages such as SLAM II [Pritsker, 1984] and ECSL [Clementson, 1985]. Here both continuous and discrete models can be combined in one. Figure 5.5 shows both discrete and continuous behaviour in a model.

5.3.6 Development of a Simulation Model

The process of producing and implementing a computer simulation model is an iterative one, with a number of stages being undertaken in parallel, as illustrated in figure 5.6. Each stage is identified and discussed below.

I. Problem Definition.

To ensure that an appropriate model is developed for a given problem, the problem itself must be clearly identified and described in detail and understood by everyone. On occasions the existence of a problem can be identified but its exact nature is unknown. This therefore can lead to the re-evaluation and hence re-formulation of a problem as the exercise proceeds.

Here the objectives of the exercise are established along with the actual boundaries to the problem and therefore the factors, parameters and variables to be included in a solution. Now the modelling technique(s) that is most appropriate for this type of problem can be identified. Assuming simulation is selected an action plan can be formulated which will specify the costs and duration of the work. The plan further identifies all alternative systems and associated features, which are to be considered along with a method of evaluating each proposal relative to the others.

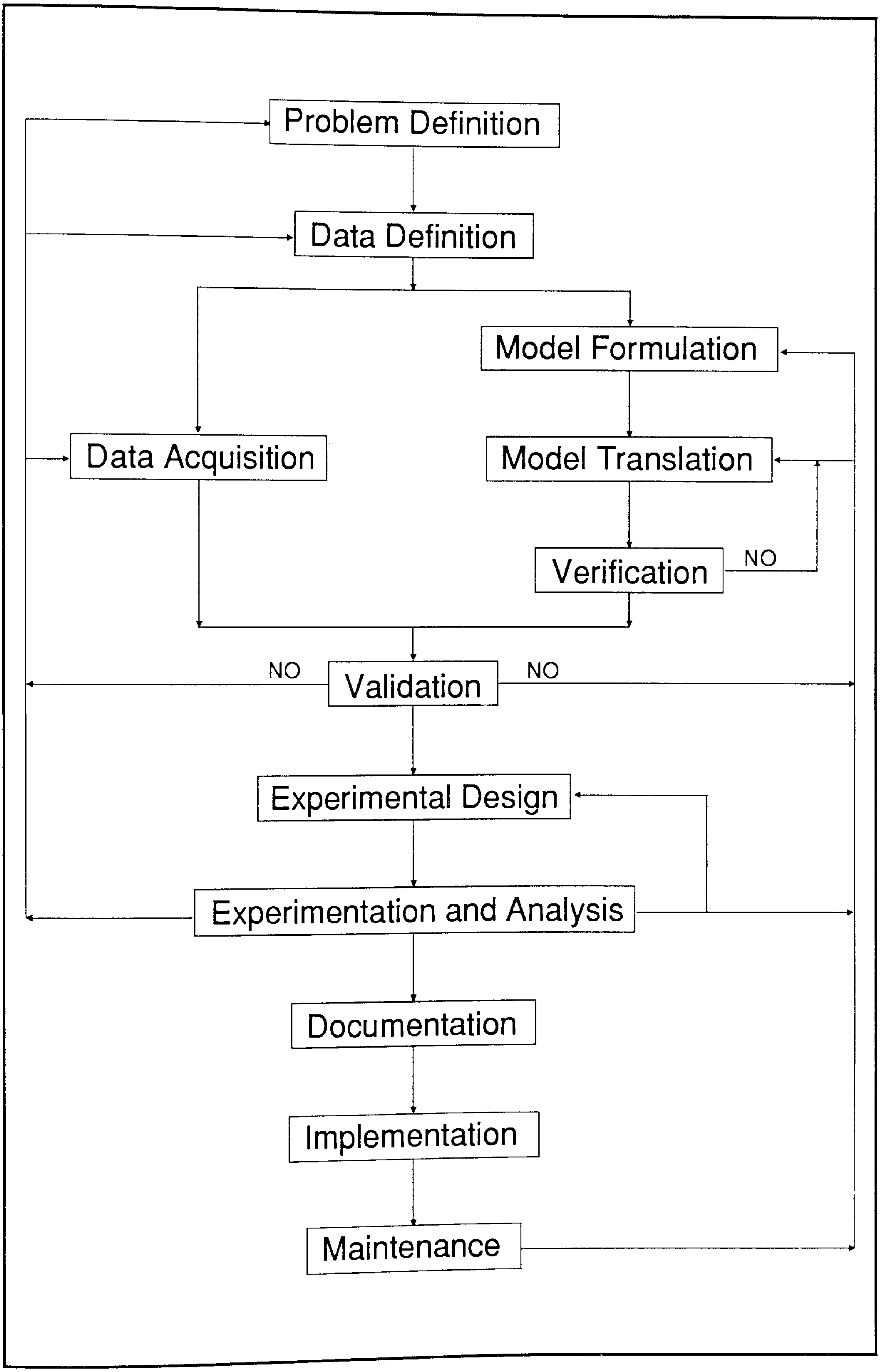


Figure 5.6 Stages In Simulation Modelling (After Love)

II. Data Definition.

This is the identification of the inputs and outputs of the system under investigation along with information regarding the various system components and their inter-relationships. Important factors which need to be resolved include establishing the sources, availability, accuracy and form of the necessary data. Normally data can be obtained from historical records, by taking samples or consulting experts, however, there are cases for creating it artificially from theoretical ideas or assumptions.

The requirement for data is so that variables and parameters can correctly represent system characteristics and that initial values can be set.

III. Model Formulation.

This stage involves the process of representing the relevant characteristics of a system in terms of mathematical and logical procedures suitable for manipulation and computerization. A model should be designed around the objectives and scope of the investigation rather than emulating the real system exactly. However, the model should contain sufficient and appropriate flexibility so that it could, if necessary accommodate additional features at a later date.

An effective approach [Carrie, 1988] to model formulation is through the use of activity cycle diagrams developed by K.D.Tocher and refined by P.R.Hills. The technique is to decompose a system into entities and produce a diagram for each, showing their "life" cycle or behaviour pattern in terms of alternating periods of activity and queuing. The diagrams are an excellent means of communication and ensures that correct and complete models are built.

IV. Data Acquisition.

This is the collection of the data required for the study and its manipulation into an appropriate form (i.e. statistical distributions). The use of sensitivity analysis techniques can be very valuable in determining how thoroughly this task should be undertaken.

V. Model Translation.

Since simulation models are of highly complex systems, they require a computer to accurately manipulate them. There is therefore a requirement to convert the logical representation of a real system into a computer program. The major prerequisites of a any computer program of a simulation model are that it be logically valid, complete and capable of sustaining experiments. The issue therefore is how best to proceed. There are four basic approaches to programming a simulation model, each with their own advantages and disadvantages (section 6.1), and include the use of:

- high level languages,
  e.g. Pascal, C, FORTRAN and BASIC;
- general purpose simulation packages,
  e.g. Simscript, Genetik and GPSS;
- symbolic modellers,
  e.g. Hocus and CAPS for ECSL;
- generic simulators,
  e.g. Witness, Mast and Simfactory.

VI. Verification.

Verification establishes that the program produced in the previous stage is a correct representation of the model formulated to replicate the system under investigation. That is ensuring that the program executes as intended. Verification methods include:

- good programming practice;
  e.g. modular construction, testing and documentation.
- manual program checking;
- monitoring the evaluation process by periodic program dumping and a manual check of events as they occur.

VII. Validation.

Validation is the most important and essential stage in a simulation exercise. This stage establishes a model's credibility, ensuring that it provides a sufficiently accurate representation of the real system. Thus any inferences drawn from the simulation results do correctly relate to the system under investigation. The process of validation is not an either-or decision (i.e. it is or isn't valid), but is the degree of confidence that there is in the reliability of the results for a particular purpose. There are two approaches to the validation of a model [Shannon, 1975]:

- the rationalist proves that a model is valid by accepting basic ideas as a foundation and then uses logic to derive different effects, and
- the empiricist does not accept any assumptions which cannot be verified separately by experimentation or the analysis of data (e.g. historical data).

Ideally validation needs to involve both the consideration of a model's structure and the comparison of its output statistics with historical data. Therefore validation should be established against a number of criteria, which are, as suggested by Hermann [1967]:

- internal validation
  i.e. low output variance from a constant model;
- face validation
  i.e. does the model look correct, this is achieved principally through the use of computer graphics which animate the evaluation process;
- Variable-parameter validity i.e. sensitivity testing;
- hypothesis validity
  i.e. justify and prove every change of state in a model;
- event or time-series validity
  i.e. compare model against historical data.

VIII. Experimental Design.

This is the specification of alternative model configurations to simulate and the design of experiments to perform on them, so that they produce the required information. The length of simulation runs, the duration of the initial run in period and the number of runs for each experiment have also to be determined.

IX. Experimentation and Analysis.

This involves the execution of simulation models and the analysis of subsequent results, to draw inferences and reach conclusions relating to the original purpose of the exercise. Based on the analysis it can be determined if more simulation runs are required and if so what form they will take.

X. **Documentation.**

Done clearly and concisely for future reference.

XI. **Implementation.**

Putting the model to an operational use, by making changes to the real system based upon the results obtained through simulation.

XII. **Maintenance.**

Improving and updating the model as new data becomes available. This is where documentation becomes important.

5.3.7 Future Simulation Developments

Currently the largest area of interest in the world of simulation is in the introduction of artificial intelligence techniques. An expert system with its built in "expertise" can construct simulation programs enabling non-specialists to directly obtain the benefits. Since such systems will be extremely user-friendly and targeted at the engineer instead of the simulation expert, they will significantly enhance symbolic modellers. Furthermore expert systems can analyse the results of simulation experiments, identifying and highlighting areas of further evaluation or even recommending appropriate action. This would be an important asset in promoting the use of simulation techniques by non-specialists.

Significant future improvements in the performance of simulation models has become possible through parallel processing techniques due to new multi-processor hardware [Wilson, 1987]. Parallel processing is even more relevant with the introduction of a new style of programs incorporating object-oriented programming [Zeigler, 1987]. Object-oriented programming potentially provides the ideal mechanism for producing complex models in a well structured manner. The approach revolves around objects. These are autonomous program modules containing relevant information pertaining to a specific item, along with those procedures that either retrieve or alter this information. Objects have very rigid boundaries and interfaces, the latter of which provides the mechanism for object execution through parameterized messages. The object related information can only be accessed by the internal procedures, therefore objects only perform those activities that constitute its instruction set. Thus this independent modular approach, with its standard interface lends itself to parallel processing.

Normally simulation techniques are used to decide upon the trade-offs between various system configurations and gain insight into the performance of a system. This can be effectively achieved by under-taking sensitivity analysis on system parameters. This is limited, with current approaches requiring a large number of detailed simulation experiments to be performed and results analysed. However, there are now techniques which reduce the required number of experiments and one is known as perturbation analysis (P/A), encompassed within Sense [Suri et al, 1985b]. P/A simply needs to observe a single simulation experiment or the actual working system, during which it considers what would have happened if certain parameters were different. Also there is Taguchi which, rather than performing all experiments, uses statistics to select only those experiments necessary for the appropriate conclusions to be drawn. Taguchi can and is generally used for experiments on the real system.

Chapter 6 Manufacturing System Design Modelling.

Previous chapters have considered the problems associated with the design of manufacturing systems and have established the requirement for a new modelling strategy to improve the performance and efficiency of current design methodologies. Specifically the modelling strategy has identified and defined four levels of design evaluation and decision making, within the process of manufacturing system design, which requires the support of appropriate dynamic system evaluation techniques. The last chapter therefore, provided a general discussion on available modelling techniques. This chapter aims to identify the most appropriate computer modelling approach (or approaches) that best supports the new modelling strategy. Hence all available modelling approaches are put in context and specific modelling requirements, necessary for the effective implementation of the strategy, are identified.

6.1 Methods of Developing Dynamic Computer Models

6.1.1 Introduction

The development of the multi-level modelling design strategy (section 4.2.4) to both support and complement the current approaches to the design of manufacturing systems, has identified the requirements for a highly versatile computer modelling system. This system must be applicable to all design stages, ranging from the initial conceptual first-pass phase through to the detailed micro-level design study. This section therefore provides a general discussion on the five different alternative methods of undertaking a computer modelling exercise and in particular focuses on the problems associated with their application. The range of possible modelling systems include high level languages, general purpose simulation packages, symbolic modellers, generic models or simulators and mathematical models, each with their own specific set of associated benefits and disadvantages. Table 6.1 identifies the typical characteristics of the various methods, but being a generalisation it must be realised that there are exceptions, individual systems within a category may vary from the group norm or average.

6.1.2 High Level Languages

High level languages are used for the development of simulation models simply because they are so readily available and are generally already known. Furthermore they provide the greatest flexibility in a simulation exercise with regard to what is undertaken and how it is achieved. There are no restrictions on the range of systems or specific features that can be replicated, the kind of experiments undertaken or the type and format of output reports and graphics. However, programming or model translation is a very lengthy and time consuming activity, with no helpful simulation debugging features readily available. Also every new model goes through a process of "re-inventing" the wheel, with regard to the production of standard simulation features, which is in addition to the development of the more specific model related procedures and functions. High level languages include such systems as FORTRAN and Pascal, along with spreadsheet packages like Lotus 123.

APPROACH	FEATURES											
	Variety Of Systems	Range Of Applications	Level Of Expertise	System Software Costs	Model Development Time	General System Awareness	Required Level Of Verification	Degree Of Model Validity	Execution Speed	Code/Model Readability	Ease of Model Structure Changes	Necessary Level Of System Learning
HIGH LEVEL LANGUAGE	VERY HIGH	VERY HIGH	VERY HIGH	VERY LOW	VERY HIGH	LOW	VERY HIGH	VERY HIGH	HIGH	VERY LOW	VERY LOW	MEDIUM
GENERAL PURPOSE SIMULATION PACKAGE	MEDIUM	VERY HIGH	HIGH	HIGH	HIGH	MEDIUM	MEDIUM	VERY HIGH	MEDIUM	HIGH/ MEDIUM	LOW	VERY HIGH
SYMBOLIC MODELLER	MEDIUM	HIGH/ MEDIUM	HIGH	HIGH	MEDIUM	HIGH	LOW	HIGH/ MEDIUM	MEDIUM	LOW	MEDIUM	VERY HIGH/ HIGH
MODEL SIMULATOR	LOW	LOW	VERY LOW	MEDIUM	LOW	N/A	N/A	LOW	LOW	VERY HIGH	VERY HIGH	LOW
MATHEMATIC MODEL	VERY LOW	VERY LOW	LOW	LOW	VERY LOW	N/A	N/A	VERY LOW	VERY HIGH	VERY HIGH	VERY HIGH	VERY LOW

Table 6.1 Approaches To Computer Simulation

6.1.3 General Purpose Simulation Packages

General purpose simulation packages (GPSP) take advantage of the existence of certain standard simulation features in all computer models, to provide an easier approach to the development of a particular model, than that offered by high level languages. GPSP simplify the task of writing the computer code for a given simulation model by providing pre-developed routines to perform all the standard simulation functions as well as error checking procedures, without losing the scope of the previous high level languages. The standard simulation functions include the time advance mechanism, random number and statistical distribution generators, recording of simulation statistics, defining initial model conditions and producing output reports. In addition to reducing the program development time, the main advantage of these systems is that they generally make several man-years of simulation experience available in the form of error-free computer code. Furthermore they provide a well defined programming structure within which to develop a model. Thus GPSP are developed for the specific purpose of performing simulation exercises and are therefore far more appropriate for the simulation expert or specialist.

The disadvantages of the GPSP approach are that often no previous experience of the packages exists, they are more expensive than high level languages, are not so readily available and still require the specific model logic routines to be written.

There are two types of systems that come under the classification of general purpose simulation packages. These are simulation libraries and languages. What separates them is a subtle difference in the way they provide standard simulation routines for developing computer models.

1. Simulation libraries simply provide a library of pre-programmed routines written in a high level language such as FORTRAN. The model logic code is then simply written in the same language with program calls to the library routines to perform standard simulation activities. No new computer languages or syntax rules have to be learnt, just additional procedures and functions. An example of such a package is GASP.
2. With simulation languages a completely new computer language is provided with is own vocabulary and syntax rules. Here the whole simulation model will be written in this language alone. A new computer vocabulary therefore has to be learned. These systems tend to present a far better modelling structure and allow more meaningful variable names and English-like statements to be included, thus making the code easier to read than say FORTRAN. Furthermore one line of simulation code can represent a number of FORTRAN procedures. Simulation languages include ECSL, Simscript and Genetik.

6.1.4 Symbolic Modellers

The principal problem with the application of any type of computer language is the necessity to have to develop, write and debug a computer program. Thus having to know and understand the appropriate language vocabulary, syntax and semantic rules. In other words whether using a high level language or general purpose simulation package the technical problems of model formulation, translation, verification and validation (section 5.6) have to be addressed before a computer model can be confidently utilized. Therefore in order to reduce both the time and programming expertise required to produce a computer simulation model, attention has focused on the development of symbolic modellers.

Symbolic modellers incorporate an interactive interface or "user-friendly" front end. This dispenses with the need to write any programming code by allowing a model to be defined in a diagrammatical or symbolic way, from which a symbolic modeller can produce and evaluate a computerized representation. Ideally the conversion of the symbolic description, produces a well structured and error free computer simulation model which reduces, if not completely alleviates the requirement to undertake any model translation or verification. The description of a model can be achieved through activity cycle diagrams, as in Hocus (figure 6.1) or by using linear block diagrams depicting the flow of entities, like Siman uses (figure 6.2). Thus such systems provide error-free models with the inclusion of diagnostic and validation features including the facilities to graphically display a model and allow user interaction during model execution. However, as each symbolic modeller adopts its own unique approach to the representation and description of simulation logic, they all entail a significant degree of specialist knowledge and expertise. These types of system include Hocus, Siman (with blocks) and CAPS for ECSL.

The major disadvantage of symbolic modellers though is the fact that they can rarely accommodate all the necessary features for a particular model [Crookes, 1987; Paul et al.

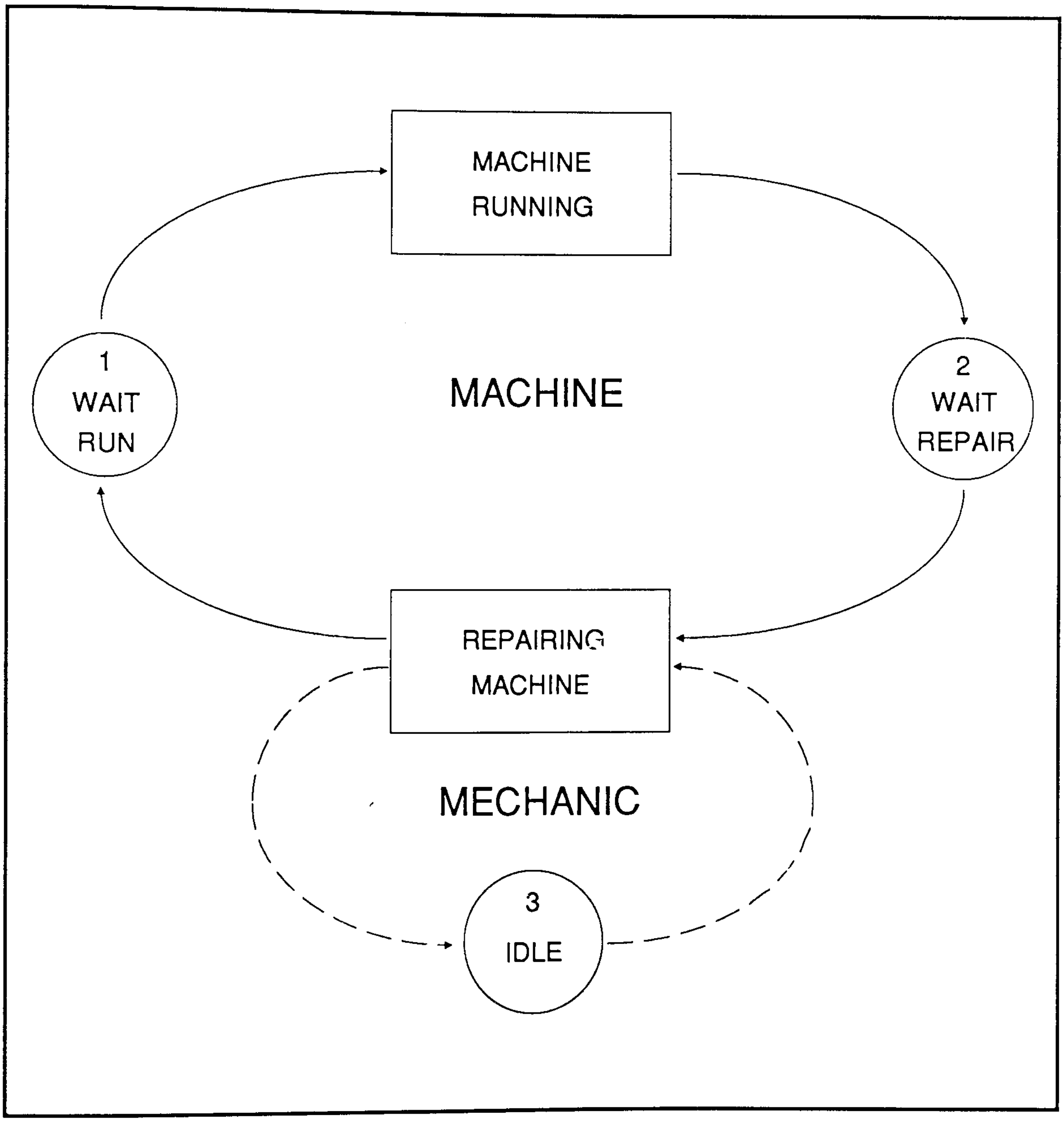


Figure 6.1 Activity Cycle Diagram

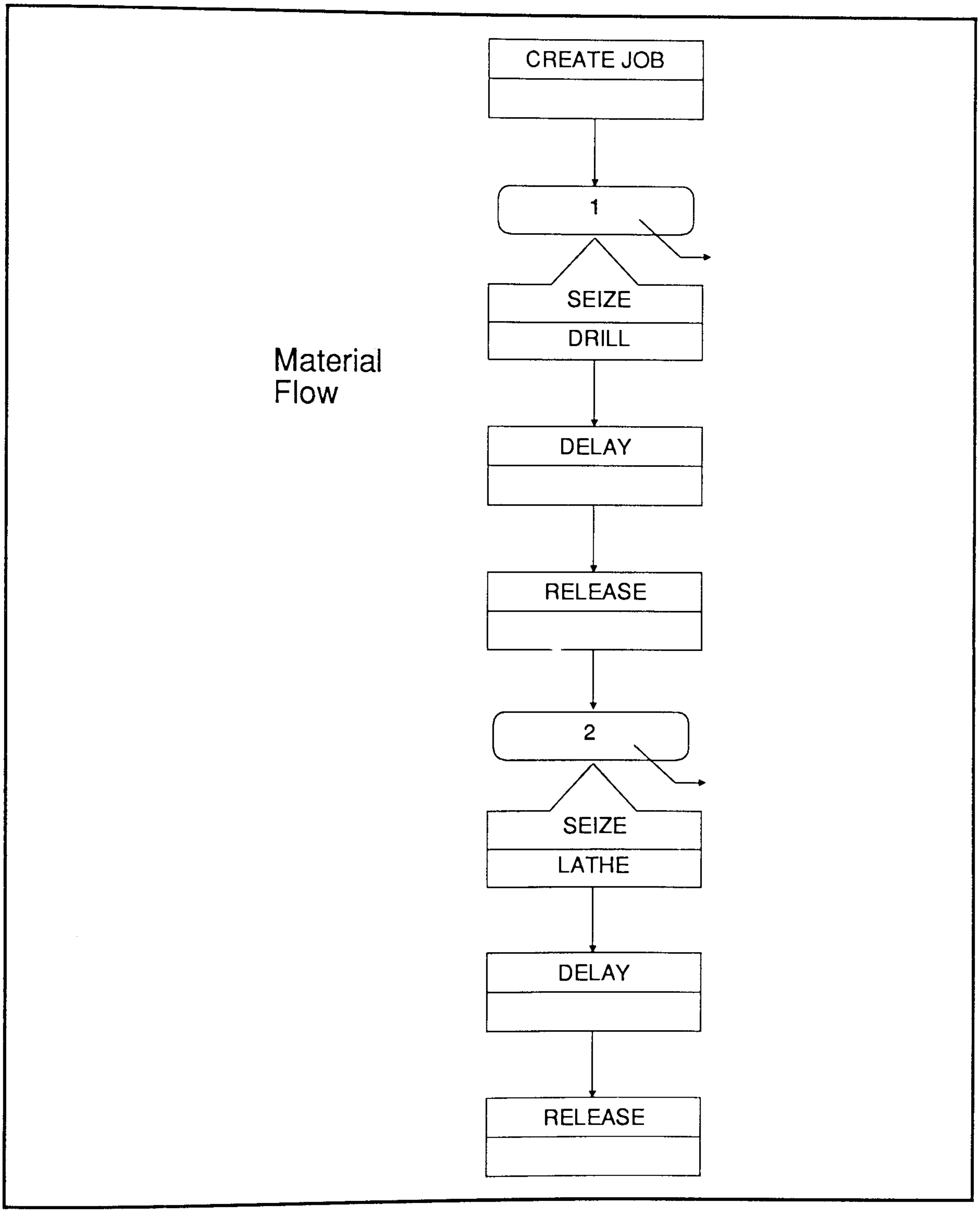


Figure 6.2 Linear Block Diagram

1987]. A good modeller, it is suggested can only represent between 70% [Crookes, 1987] to 95% [Paul et al, 1987] of features for any given model. Furthermore Uyeno et al [1980] states, that no symbolic modeller can ensure the development of a complete working model. Thus a modeller has to be able to add a certain amount of program code to accommodate complex system features into a model. Much therefore still depends upon the users expertise. Consequently, symbolic modellers are only appropriate for use by computer simulation specialist.

With symbolic modellers the relevant characteristics and behaviour of a system have to be defined in terms of mathematical and logical procedures before an appropriate computer model can be developed. This is exactly the same when using a high level language or simulation package. That is, the process of model formulation has to be performed even though model translation and verification may not. However, the problems associated with the phases of translation and verification are very insignificant when compared to those of model formulation and validation. The latter phases are the two most important, and therefore time consuming, stages in the development of a model. It can take nearly as long to get a model implemented using a modeller as it can using a simulation package, even though the latter requires both model translation and verification. As Smith [1986] states the process of model translation and verification accounts for no more then 10% of the total time to develop a model. The process of model validation is a very necessary activity regardless of what type of model is being considered. Be it a simulation, mathematical or any other type of symbolic or even physical model. Thus if the development time for a computer simulation model is to be significantly reduced and the technique therefore made available to a far greater range of non-experts, then the elimination of the model formulation phase has to be investigated.

6.1.5 Model Simulators

Over recent years people unfamiliar with the application computer simulation techniques have come to wrongly believe that an exercise can be undertaken and completed in a matter of hours, or days at the latest. This has largely occurred due to the marketing of simulation packages and symbolic modellers, such as See-Why and Hocus. However, contrary to what is implied both systems do take a considerable amount of time and experience to develop an appropriately valid simulation model. In more general terms, the excessive time and costs associated with the development of a model through any of the three previously discussed approaches, does not readily promote the regular use of computer simulation techniques. Currently simulation is only ordinarily applied in projects with high capital risks and/or long lead-times. Furthermore with the above approaches, it is the specialist who produces, manipulates and alters a computer model. However, there is an alternative: generic computer models or model simulators. These are far more comprehensive than specific application models, in which the odd parameter can be changed but are not as widely appropriate as symbolic modellers or simulation packages.

Model simulators are pre-written and verified computer models designed for the evaluation of a specific type and range of system, like FMS, automatic guided vehicle systems and automated warehouses. Then within the identified range of applications, the model provides sufficient features and parameters to accommodate any system specification, and which can be configured through relevant data inputs. Hence model simulators totally avoid any computer programming, only requiring the input of parameter defining data, which is generally controlled by the system through a dialogue or "conversation" with the user [Lucker, 1984]. Thus these packages are relatively simple to apply, requiring very little computer or simulation expertise and provide a very quick approach to the implementation of a computer simulation model. Furthermore along with eliminating the model translation and therefore verification phases of the development of a simulation model, simulators remove the requirement to undertake any model formulation activity. The mathematical and logical representation of the relevant characteristics, pertaining to the type of system under consideration, being established and checked, together with the program code, during the initial development of such a package. This further leads to an additional advantage of such packages, in that they can evaluate partially defined systems. To be effective, all other approaches require a coherent system to be defined before a corresponding model is produced, whilst simulators encourage system evaluation prior to the completion of any design or data collection activities [ISTEL, 1988]. Model simulators, being data driven, do not require either model formulation or programming and so redress the skills and expertise necessary to undertake a simulation exercise to those specifically relevant to the system under investigation. Thereby making the technique accessible to both specialists and non-specialists alike.

The major disadvantage of model simulators is the restricted range of systems to which they are applicable and therefore can evaluate [Crookes, 1987]. It is acknowledged that any type of computer language or symbolic modeller is far more flexible in what it can simulate. Hence before developing a simulator it is important that detailed and thorough consideration is given to exactly what the model should be able to represent. Otherwise the system could be so restricted as to be only valid for the representation of one or a nominal number of unique systems, and therefore have no obvious advantages over a specific model developed by one of the other approaches. This is important [Almodovar, 1988] as non-simulation experts will be able to produce their own models relatively easily. A simulator must ensure that modelling does not lead to an unrealistic representation of a system and totally invalid results, by supporting all possible system features. Furthermore the initial development of a special purpose simulator is far more expensive and time consuming than that required to produce a specific model in either a computer language or modeller. To develop, let alone incorporate additional features into an existing simulator, requires at least the same expertise, if not more than that necessary to produce a model in any computer language, because of the highly intricate nature of such packages. This therefore further highlights the importance of clearly and precisely identifying the appropriate features to include in a simulator very early on in its development.

To all intents and purposes model simulators are a compromise between the quick application of specific simulation models and the flexibility of symbolic modellers. Therefore model simulators encourage a far greater application of computer simulation techniques by providing the full benefits of the technique without the threat of wasting valuable resource time and money on an unsuccessful exercise. In other words, a simulator based modelling exercise is substantially easier to justify. However, containing sufficient flexibility to be applicable to all possible alternative system configurations, (for a given type of system) entails significant programming complexity and inherent intelligence in order to accommodate the necessary modelling adaptability. Far greater than that generally required for a given modelling exercise and therefore incorporated in a specific application model. Ultimately this could impede the actual evaluation process, resulting in a relatively slow model execution which may overshadow any potentially advantages of the approach.

6.1.6 Dynamic Mathematical Models

Dynamic mathematical modelling is not a very commonly applied technique in industry largely due to the theories and procedures upon which it is based. Generally such techniques utilize queuing theory and markov chain procedures. Significantly mathematical techniques are restricted to relatively small areas of application because of their limited ability to consider highly complex multi-server and multi-sequence queuing systems. Whilst those models which can accommodate the complexity are very detailed and highly mathematically orientated. To apply existing techniques generally requires specialist expertise to simply derive and prove the mathematical derivations on which they are based, irrespective of developing a new modelling procedure. Therefore due to the highly abstract and involved nature of mathematical models, it is often necessary to make the problem fit the available technique, by deciding how much detail to include in a model [Buzacott, 1985].

The application of mathematical models is complicated by the fact that they are difficult to validate. The internal mechanism of such models, being equation based, does not allow for any form of validation by comparison to the operation and changes in state of an existing system. Models have to be viewed as "black boxes" and validated on the basis of "face value" or output results. Though this is complicated by the format of the model input data (e.g. probabilistic component routes) and averaging of output results (e.g. average production output and average queue sizes). Therefore validation is performed at a highly aggregated level of detail by comparison to long term results taken from historical data, simulation models or experience.

The appropriate application of a mathematical modelling technique can, however, provide significant advantages. Models such as CAN-Q [Solberg, 1977] and Manuplan [Suri et al, 1985a] supply quick approximated average long term system performance results from fairly limited data requirements. In addition it has been demonstrated that CAN-Q can provide good "first-pass" evaluation results for a significant range of manufacturing systems [Co et al, 1986]. Furthermore the equations upon which these models are based are generic, and do not have to be re-formulated for each specific application. The models therefore are data driven with inputs specifically manufacturing orientated, hence CAN-Q and Manuplan can be viewed as model simulators, with the potential advantages of both speed and reduced data requirements.

6.2 Customer Requirements For A Simulation Design Tool

This section investigates specific customer prerequisites for the application of computer modelling techniques. The discussion will ultimately provide the basis for identifying the approach that best implements the defined modelling strategy for the dynamic evaluation of manufacturing systems. Furthermore the customer requirements will establish the broad system features necessary for a computer modelling package, as opposed to the functionality of the modelling system.

6.2.1 A "User-Friendly" Computer Modelling System

It is important to understand how prevalent computer modelling is in manufacturing industries, in order to highlight how acceptable and effective such techniques are, along with identifying the constraints which limit their more general adoption.

In recent years the general impression has been that a significant number of manufacturing industries do not apply operations research and specifically modelling techniques in production planning and control. In 1978 Kochhar [1978] undertook a survey into the application of computer and analytical techniques for the production planning and control of manufacturing activities in 173 companies. He concluded that the use of computer modelling techniques was less than 10% and this was totally confined to high technology industries. Such industries were associated as having a high research and development activity and/or care was taken over the production of their products. Since then there has been a steady increase in the general use and application of computers, due in particular to the development of personal computers. However, it is believed that the use of computer modelling techniques has not significantly increased. This is born out by two further surveys into the use of production management techniques in U.K. manufacturing industries.

The first survey [Lockyer et al] in 1980 investigated the use of management techniques made by the members of the Institution of Industrial Managers (IIM) (it should be noted, however, that this study is slightly biased due to the fact that IIM members have to study such techniques as a condition of entry). Then a study in 1986 [Oakland & Sohal] took a random sample of 131 companies from the 1983 Key British Enterprises (KBE) list comprising the 20,000 largest U.K. companies by annual turnover. The IIM report indicated that 87.5% and 80.8% of participants made no use of queuing theory and simulation techniques respectively, whilst the KBE survey found the proportion of no usage to be even higher, 93.9% and 90.9% respectively. Thus in the eight year gap between the Kochhar and KBE studies there is no indication that there has been any increase in the use of manufacturing modelling techniques. Furthermore all the studies indicated that the interest in and use of a technique diminishes as its level of sophistication rises. Finally the KBE study concluded by identifying the key factor affecting the use of all analysis techniques as being the,

> " lack of knowledge and scarcity of adequately trained personnel."

In contrast to these three surveys a recent report in The Engineer [Dunn, 1989] suggests that by the year 2000 production engineers will be proficient in three times as many new manufacturing processes and technologies as they are today. Specifically the report identifies a 240% growth in the use of simulation techniques, which corresponds to an estimated 40% usage level. If these figures are to be realised, the previous problems of insufficient knowledge and training have to be addressed. This is further supported by the fact that the role of the production engineer in the year 2000 will become increasingly varied. He will be expected to provide a greater contribution to corporate decision making, across a wider range of issues not currently associated with his job. It is anticipated that production engineers will have to provide input into business and market strategies, financial decisions, product design and software programming.

There can be no doubt that computer modelling techniques are fundamental in the design of manufacturing systems, especially now as such systems are becoming so technically sophisticated. The design process, as has previously been described requires two types of knowledge (section 3.2.1). The explicit rule based "know that" and "know how" that can only been gained through experience and which determines the quality of an activity. However, as manufacturing systems are becoming more and more complex, incorporating new production technology and methods, it is conceivable that the experience gained in the design of one system may not be relevant to the design of another. Consequently to extrapolate the performance and behaviour of a new manufacturing system design based upon previous experience can be potentially dangerous. Whereas computer modelling can provide valuable experience regarding the way in which a specific manufacturing system may behave as well as an insight into how it operates.

At present computer simulation exercises, with few exceptions [DTI 1990], involve two kinds of people. Those who own and understand the problem (e.g. manufacturing system engineers) and the model builder (e.g. a simulation consultant) who undertakes the study. The fundamental problem with such an arrangement is the isolation or separation of the problem owner from the actual evaluation process. The owner having a rather limited involvement in the generation of a computer model, generally providing only an initial problem definition and system specification. Consequently, the owner has to rely heavily on the expertise and judgement of the builder to correctly undertake the system evaluation. Although it is suggested [CACI, 1987a] that the two groups should work closely together, the owner is often prevented from doing so because of a lack of understanding in the concepts, vocabulary and implementation of the technique. Ultimately, due to insufficient participation in an exercise and an uncertain understanding of the implemented algorithms, the owner lacks any confidence in the results. He can then only gain confidence by watching it execute. However, a graphical representation cannot illustrate all aspects of a model's operation, and often it is the more subtle, concealed features that can invalidate a model. This owner/builder relationship therefore can significantly limit the experience and knowledge that a designer or non-expert could gain through the use of computer modelling techniques, regarding the behaviour and performance of a system. Furthermore it makes it difficult for the owner to retain control of the design process.

The current practises adopted in the application of computer modelling techniques therefore emphasize the need for an alternative approach which is simpler and far more accessible by both experts and non-experts alike. Thus the requirement is for an approach which involves no computer programming or modelling expertise to create, manipulate or analyse a model. The development and adoption of such an approach obviously making modelling easier to learn and apply, and as a result would greatly increases the general interest in the use of such techniques. Remembering that any modelling system must provide the end user with the ability and control to decide and select what features and assumptions are to be included in any particular model.

6.2.2 Appropriate Modelling Techniques

It has been suggested in Lucas [1987] that the approaches currently adopted in applying computer simulation techniques to manufacturing system design (i.e. simulation systems and symbolic modellers) are incompatible with the design process and specified methodology. Generally design projects only have a life span of between four to six months. Whilst, even with the necessary computer and simulation skills, in 1981 it would typically take six months to undertake a computer simulation exercise [Bollinger and Crookall, 1981], though more recent experiences have shown that, through the introduction of PCs, it currently takes only two to three months. However, even with such a significant reduction in lead-time, it is obvious that computer simulation is potentially a "bottleneck" activity, it still being possibly for the exercise to take at least half the total time available for completing a manufacturing system design project. However, the actual work involved in each modelling exercise is not necessarily unique. The stages of model formulation, translation, and verification are only concerned with developing an appropriate model of a specific system. Thus if only systems of similar type (e.g. FMS or automatic guided vehicle systems) are to be evaluated, then a significant proportion of the effort involved in the three stages will be duplicated in each exercise. Therefore there is an opportunity, in certain cases, to improve the efficiency of the simulation procedure.

The development of an efficient, coherent and maintainable simulation model using a high level language, general purpose simulation package or symbolic modeller requires the complete and integrated design of a model before any form of model translation is undertaken. The piecemeal or evolutionary development of a computer model makes it difficult to maintain a well structured and coherent model, due to the addition of new features and functions which may not readily conform to or fit within the original design. Ideally during the design of a manufacturing system the development of a computer simulation model should not commence until after all the elements of the corresponding system have been clearly identified and documented. Only after a complete system design specification has been prepared, can an appropriate, specific application computer model be defined and subsequently developed. However, because of the highly focused design of such a model, it is questionable whether it can, in the future, accommodate system design changes easily and effectively without the model structure being altered or the whole model rebuilt. Furthermore the generation of a full system design, in which all physical, control and job elements and functions are identified and quantified, takes between one to three months. The time generally accounts for over half that available to complete a project and represent the major phase in which design decisions are taken. Computer simulation therefore has to be applicable within these time scales.

Consequently there are a number of factors which effect the application of computer simulation and determine the effectiveness of the technique. In order for simulation to be a viable technique in the re-design of a manufacturing system, the time to develop and produce a computer model has to be dramatically reduced. Furthermore the necessity to fully identify all system features before developing a model, has to be alleviated and so allow the technique to be applied before a design has been completely specified. It is essential that future alterations to the operational logic and resources within a given simulation model can be accommodated relatively quickly and easily, without having to produce a new model.

6.2.3 The Justification of Computer Modelling.

Currently computer modelling has an image of being a very time consuming and costly technique requiring a great deal of expertise and to which there is a bit of an art! It is true to say that at present to undertake a computer simulation exercise generally requires expensive specialist software, a lot of time and significant amount of training. Thus the use of simulation has focused on costly, high risk projects inevitably in large companies. This is born out in the Kochhar [1978] survey (section 6.2.1) and by the fact that a major part, if not all, of the more recent literature on the subject of simulation refers to the modelling of automatic guided vehicles (AGV), flexible manufacturing systems (FMS) and computerized warehouses. Also consultancy groups indicate that a major proportion of their work is in one of these areas.

Emphasis on computer simulation for the evaluation of sophisticated, high technology manufacturing facilities, is substantiated by the development of commercial generic models, specifically for these types of systems. With particular attention being given to FMS generic models [Bevans, 1982; Carrie, 1988], as such systems involve a substantial investment, in terms of millions of pounds, and a complexity which makes it difficult to predict their performance. Hence justifying and absorbing the significant cost of undertaking a modelling exercise. However, all systems have some potential to improve upon their current performance and therefore create cost savings, regardless of the technology employed. Furthermore the less high technology there exists in a system, generally the greater the opportunities there are to make improvements. Such systems tend to be less formally designed and operated due to less sophistication and the lack of computer control techniques, which use for example performance optimizing algorithms. These low technology systems cannot justify up front the expense of a modelling exercise, because of the difficulties in identifying and estimating potential areas of cost savings in advance [DTI, 1990].

As previously identified (chapter 2) all manufacturing systems perform one main function, the conversion of raw material into saleable products, through the use of similar types of facilities and resources. Generally manufacturing systems, as Carrie [1988] says:

> "..exhibit much the same characteristics, although differing in detail."

The difference between individual systems arising from the detailed specification of facilities and the manner in which they are employed and integrated. However, current commercial simulators seem to infer that such models can only be developed to emulate a subsection of manufacturing systems, as all are concerned with specific areas of application. MAST [Lenz, 1985] and SAME [IFS] being specifically for FMS evaluation and GRASP [Yong et al, 1983] and SINDECS-R [Robinson et al, 1983] focusing on robotic manufacture. Systems such as FMS do contain sophisticated, high technology manufacturing facilities, but they account for only a small proportion of manufacturing systems world wide. The world FMS population being estimated at only 200 in 1986 [O'Grady, 1989]. The author believes therefore that only a limited number of standard features are necessary in order to model a substantial proportion of all manufacturing systems, containing more conventional facilities. In addition such standard features could possibly model certain aspects and behaviour of systems like FMS. The success of a simulator, orientated towards conventional manufacturing system, would depend upon its flexibility to represent system variations, which in turn will be a function of its design philosophy. An approach of this kind therefore would make the simulation of manufacturing systems cheaper and far easier to accomplish. Furthermore ensuring that the technique is a viable alternative in small and large companies alike and appropriate for short term, low risk manufacturing system design projects.

6.3 Quality Function Deployment Analysis

The two previous sections suggest that a pre-developed, model simulator, designed specifically to evaluate manufacturing systems, would best support the implementation of the proposed modelling strategy. To verify this assertion, the user requirements, as identified in the previous section together with more general desires, were used as the basis for a quality function deployment (QFD) analysis [Eureka et al, 1988; King, 1987]. The technique is a structured planning tool for product development, focusing on customer requirements for the specification of a product and also allows established products to be assessed against these requirements. QFD was used for the latter, to identify inherent problems associated with the application of each of the five modelling approaches, and specifically those relating to model simulators.

QFD provides a method of ranking different products or systems through a comparison of their features against importance rated customer requirements. A five point grading scale is used to assess a product's features against specific requirements and ranges from -9 for a strong negative correlation to 9 for strong positive correlation (table 6.2). The degree of correlation is determined by how well a feature satisfies the objective target value (which tends to be subjective) established for each requirement. The rankings are then calculated by summing, for each product, the individual feature grades multiplied by the relevant customer requirement importances rating, and comparing each product total.

In order to ascertain the most appropriate method of developing dynamic computer manufacturing system models, the five alternative approaches were evaluated. These being high

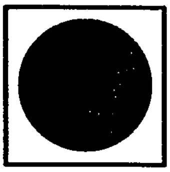
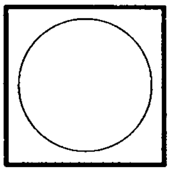
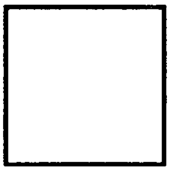
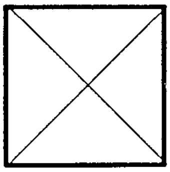
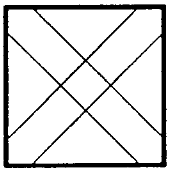
	Strong Positive Correlation	(9)
	Positive Correlation	(3)
		(0)
	Negative Correlation	(-3)
	Strong Negative Correlation	(-9)

Table 6.2 QFD Analysis Grading Scale

level languages, simulation packages, symbolic modellers, model simulators and dynamic mathematical models. The evaluation was achieved by performing a QFD analysis on eleven commercially available modelling systems. Each system representing one of the five alternative approaches and the analysis only considered their method and capability for modelling manufacturing systems. The customer requirements and importance ratings were established through a series of interviews with manufacturing systems and production engineers from various Lucas U.K. sites, ranging from batch to mass production. The requirements were concerned with computer hardware, simulation stages, graphics, training, model data, the modelling system and costs. The analysis, product scores and rankings are all illustrated in table 6.3.

The analysis not surprisingly split the eleven modelling systems quite convincingly into two groups, with the partitioning coming within the symbolic modeller classification. This is a fairly obvious result as the Siman, Witness, Simfactory, MAST and Manuplan systems are specifically designed to model manufacturing systems, this coinciding with the viewpoint of the analysis. This similarity is further indicated by the five graphs illustrated in figures 6.3 to 6.7, which depicts the distribution of grades over all customer requirements, for each of the alternative approaches. Figures 6.6 and 6.7 quite clearly highlight the substantial benefits to be gained through the specific design and application of a pre-developed manufacturing model, with each graph having a high upward curve in the region of positive correlation. Whilst figure 6.3 exhibits a "bath tub" curve, which illustrates how high level languages are either totally

Objective Target Values		MANUPLAN	MAST	SIMFACTORY	WITNESS	HOCUS	SIMAN	GENETIK	PC MODEL	SLAM II	SIMSCRIPT II.5	PASCAL	IMPORTANCE RATING		
·	◯	●	●	●	●		●	●	●	●	●	●	4	MS/PC Dos	Computer Hardware
256K	←				○	※		※				●	1	640K Ram	
None	◯	●	●						●	●		●	1	Maths Co-Processor	
None	←	●	●	●	○	※		※	※	※	※	※	5	Model Formulation	Simulation Stages
None	←	●	●	●	○			×	×	×	×	※	5	Model Translation	
None	←	●	●	●	○	×		×	×	×	×	※	5	Model Verification	
4 Days	←	●	●	●	●	※	○	※	×	※	※	※	5	Simulation Training	Training
1 Day	←	○	●	●	○	×	×	×	×	※	※	※	5	System Training	
3D	→	※	×		×	○	●	○	○	※	○	●	3	Graphics Display	Graphics
CGA	←	※	○			×				※	●	●	2	Standard Graphics	
1 Day	←	※					●	●	●	※	●	×	2	Ease of Use	
Automatic	→	●	○	※	×		○	×	※	×	×	×	4	Data Input	Model Data
Automatic	→	●		○			※						3	Data Output	
English Labels	→	※	●	●		×		○			○	○	4	Data Readability	
Everything	→	○	●	●	○	※		※	※	※	※	※	3	Engineering Terminology	
Std Feature	→	※	※	●	●	●	●	●	●				2	Interactive	Modelling System
1000 Operations	→	※	×	●		○		○			●	●	4	Model Size	
Any Manuf Sys.	→	※	×		○	●	●	●		●	●	●	5	System Modelling Scope	
None	←	※	×	×		○	○	○		○	○	●	5	Inherent Assumptions	
Events/Minute	→	●	※	×	×	×			×	×		○	3	Speed of Evaluation	
Resources/Rules	→	●	●	●	○	※		※	※	※	※	※	3	Standard Manufacturing Features	
Manuf. Perf.	→	○	●	●	×	×	×		×	※	※	※	3	Standard Manufacturing Reports	
System Logic	→	●	●	●	○				×	×		※	3	Self-Documentation	
Min Specificat~	←	●	●	●	●								4	Partial System Modelling	
£ 5,000	←	○			※	※	※	×	○	○		●	2	Purchase Cost	System Costs
£ 10,000	←	●	○	○		×	×	×		×	×	※	4	Model Development/Maintenance Cost	
		225	366	438	147	-168	87	-69	-120	-234	-81	-105		Product Scores	
		225		317		-40			-126			-105		Group Average Scores	
		3	2	1	4	10	5	6	9	11	7	8		Product Rankings	

Table 6.3 QFD Computer Simulation Product Analysis

High Level Language

	-9	-3	0	3	9
Pascal	10	2	3	2	9

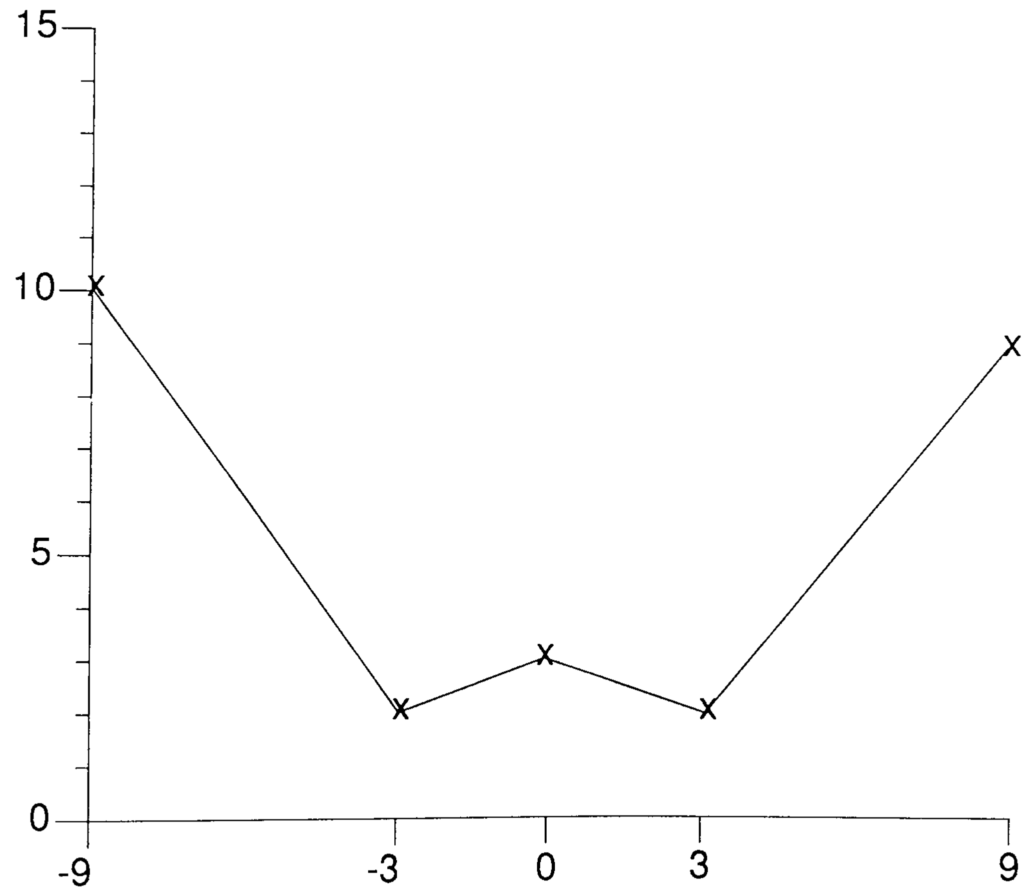


Figure 6.3 QFD Grading - High Level Language

General Purpose Simulation Packages

	-9	-3	0	3	9
Simscript	6	4	8	3	5
Slam II	9	6	6	2	3
PC Model	4	7	9	2	4
Genetik	5	6	7	4	4
Total	24	23	30	11	16
Average	6	5.75	7.5	2.75	4

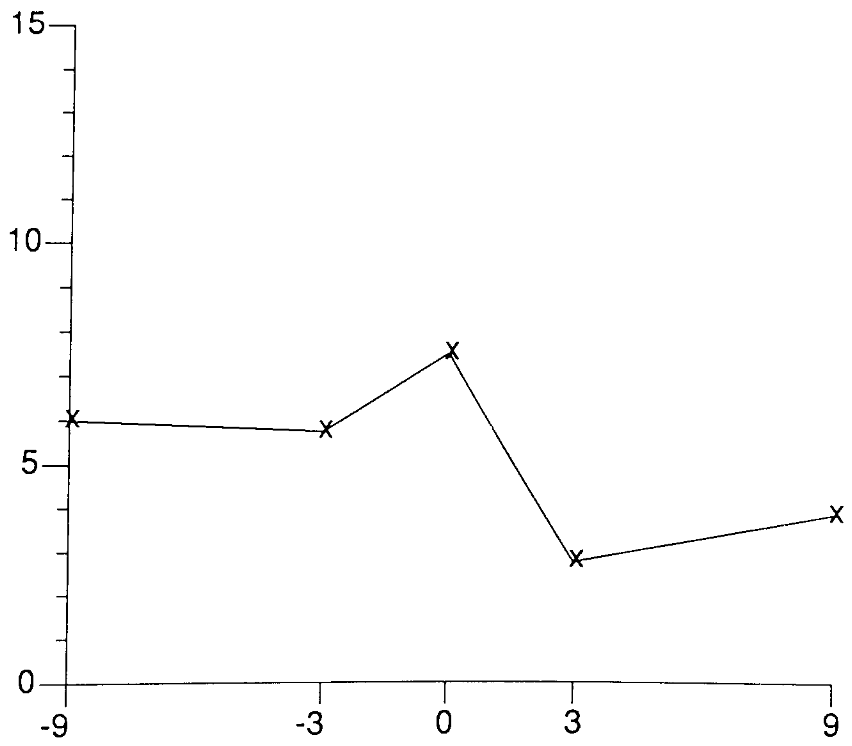


Figure 6.4 QFD Grading - Simulation Packages

Symbolic Modellers

	-9	-3	0	3	9
Simon (with Blocks)	2	3	13	3	5
Hocus	6	7	8	3	2
Total	8	10	21	6	7
Average	4	5	10.50	3	3.50

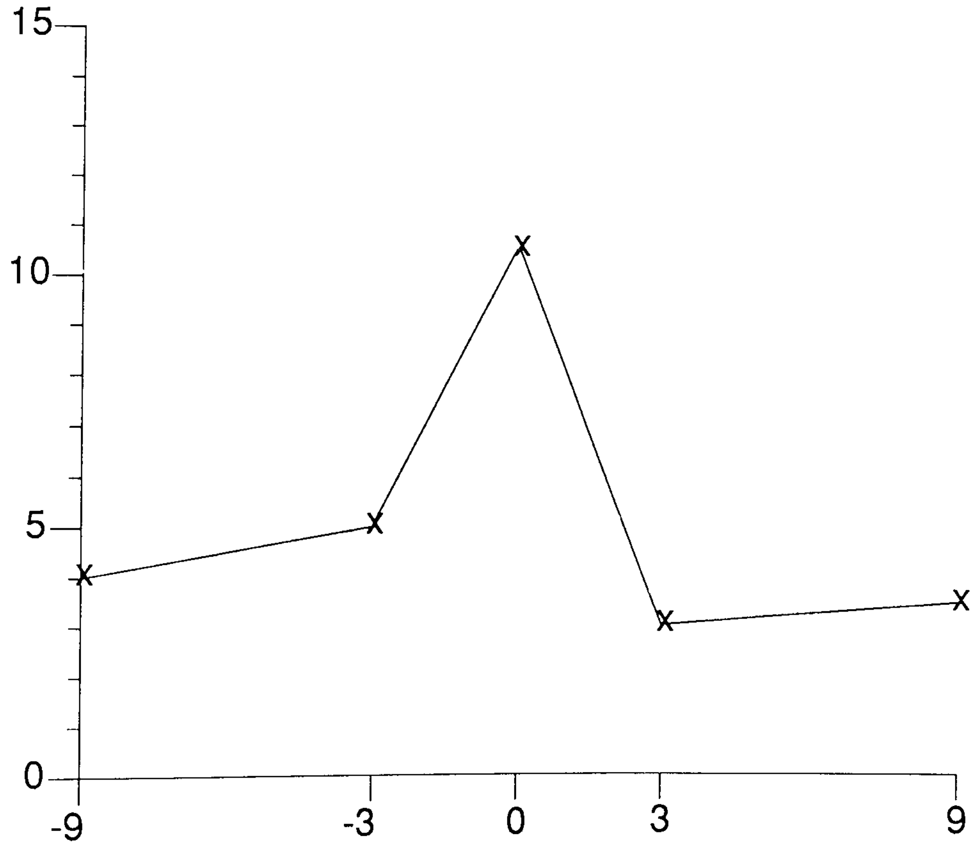


Figure 6.5 QFD Grading - Symbolic Modellers

Model Simulators

	-9	-3	0	3	9
Witness	1	4	8	9	4
Simfactory	1	2	7	2	14
Mast	2	4	4	3	13
Total	4	10	19	14	31
Average	1.33	3.33	6.33	4.67	10.33

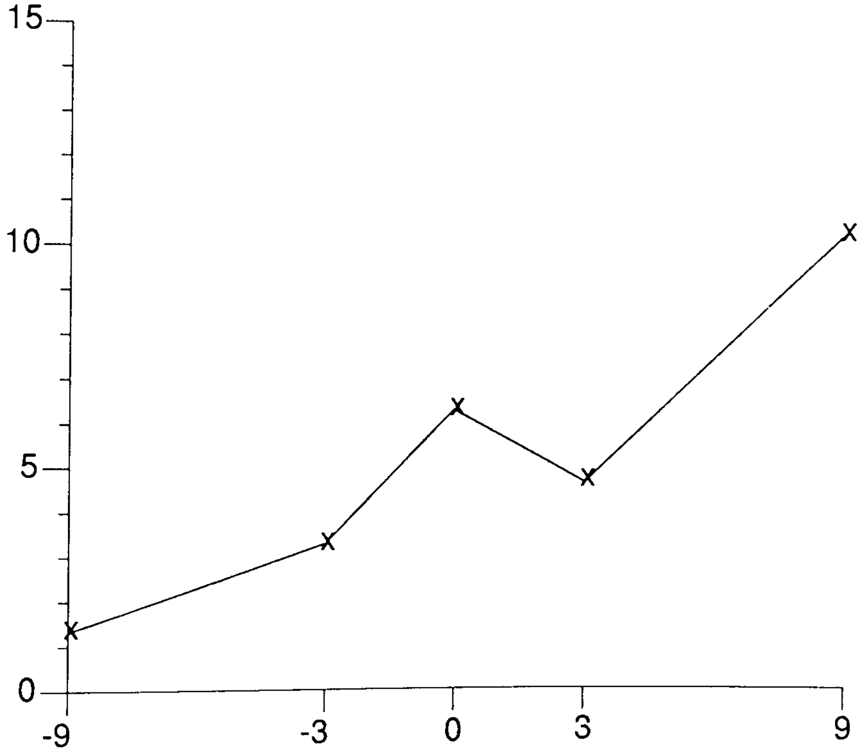


Figure 6.6 QFD Grading - Simulators

Mathematical Model

	-9	-3	0	3	9
Manuplan	8	0	1	4	13

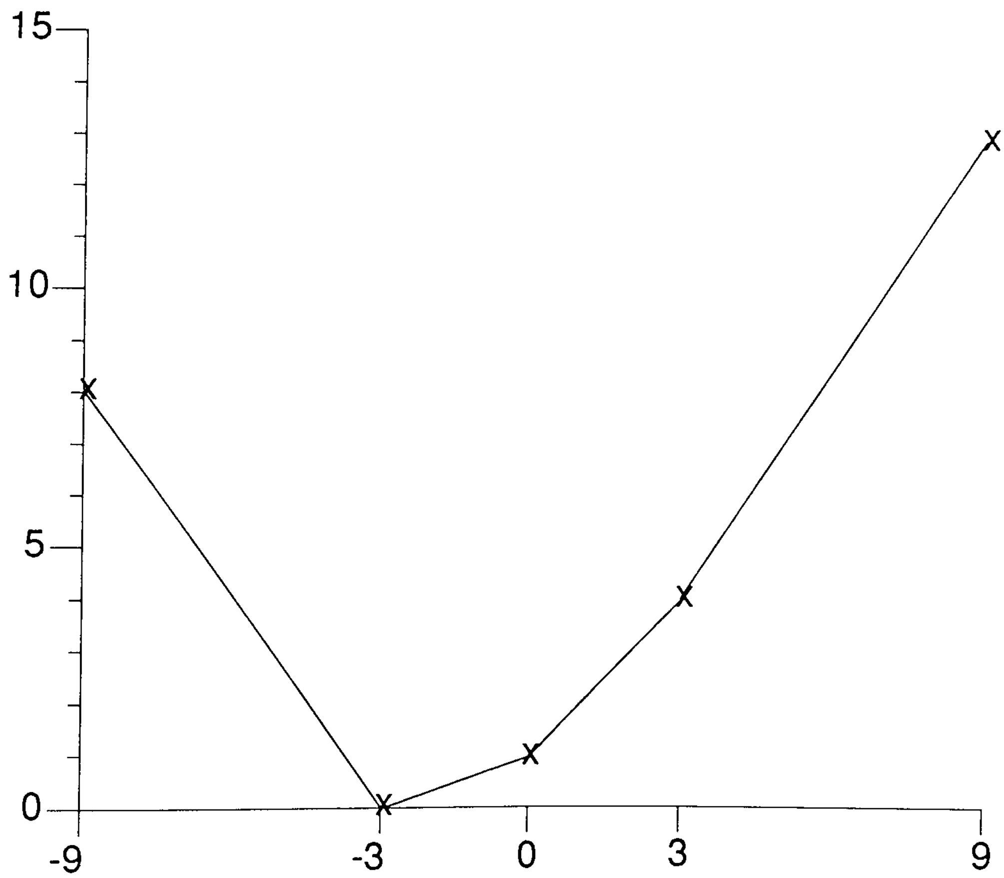


Figure 6.7 QFD Grading - Mathematical Model

satisfactory or inadequate with regard to any particular customer requirement, there being no half measures. As the dividing line between the systems occurs within the symbolic modeller group figure 6.5 was believed to be inappropriate. Therefore two further graphs were produced, one of the Siman (with blocks) and another of the Hocus symbolic modeller (figures 6.8 and 6.9). Figure 6.9 now quite distinctly indicates that there are no significant differences between the Hocus symbolic modeller and a simulation package, from the view of the user requirements. Whilst figure 6.8, which represents the Siman system (with blocks), does not highlight the substantial benefits of a simulator or mathematical model, even though Siman is manufacturing orientated.

On studying the QFD matrix the reasons why mathematical models and model simulators are ranked higher than other approaches becomes patently obvious. These approaches significantly reduce the effort and time involved in a simulation exercise, are easier to learn and operate, provide a clear representation of a model in engineering terminology, offer pre-developed manufacturing features and output reports, are self-documenting and overall have the minimum purchase and model development and maintenance costs. However, there are more important lessons to learn by considering where these approaches fail compared to the alternative ones. Basically there are four important areas that need to be addressed. These include ensuring that the modelling scope and application of a simulator is not so limited as to make it only relevant to a fairly restricted range of unique systems. This therefore implies an ability to emulate, within a specific range, all conceivable system configurations, without

Siman (with Blocks)

-9	-3	0	3	9
2	3	13	3	5

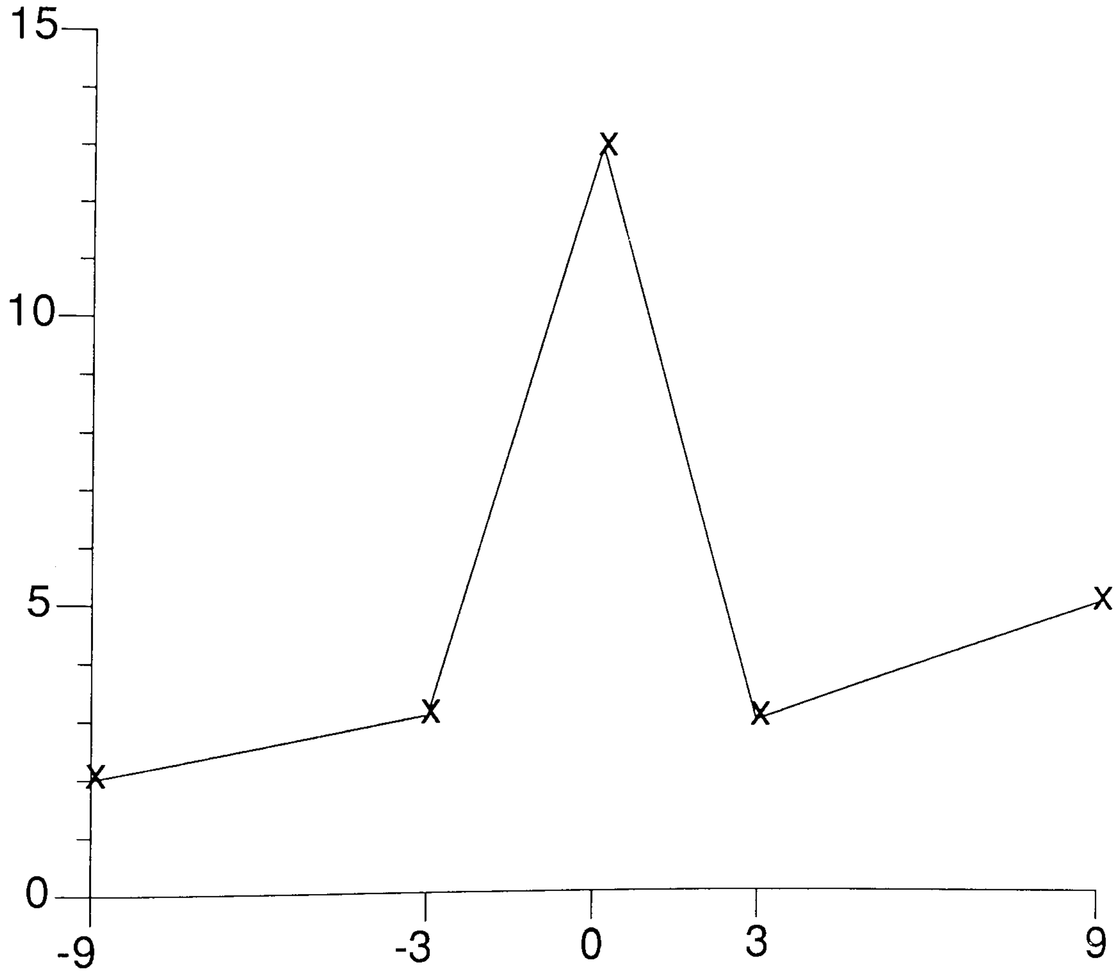


Figure 6.8 QFD Grading - Siman

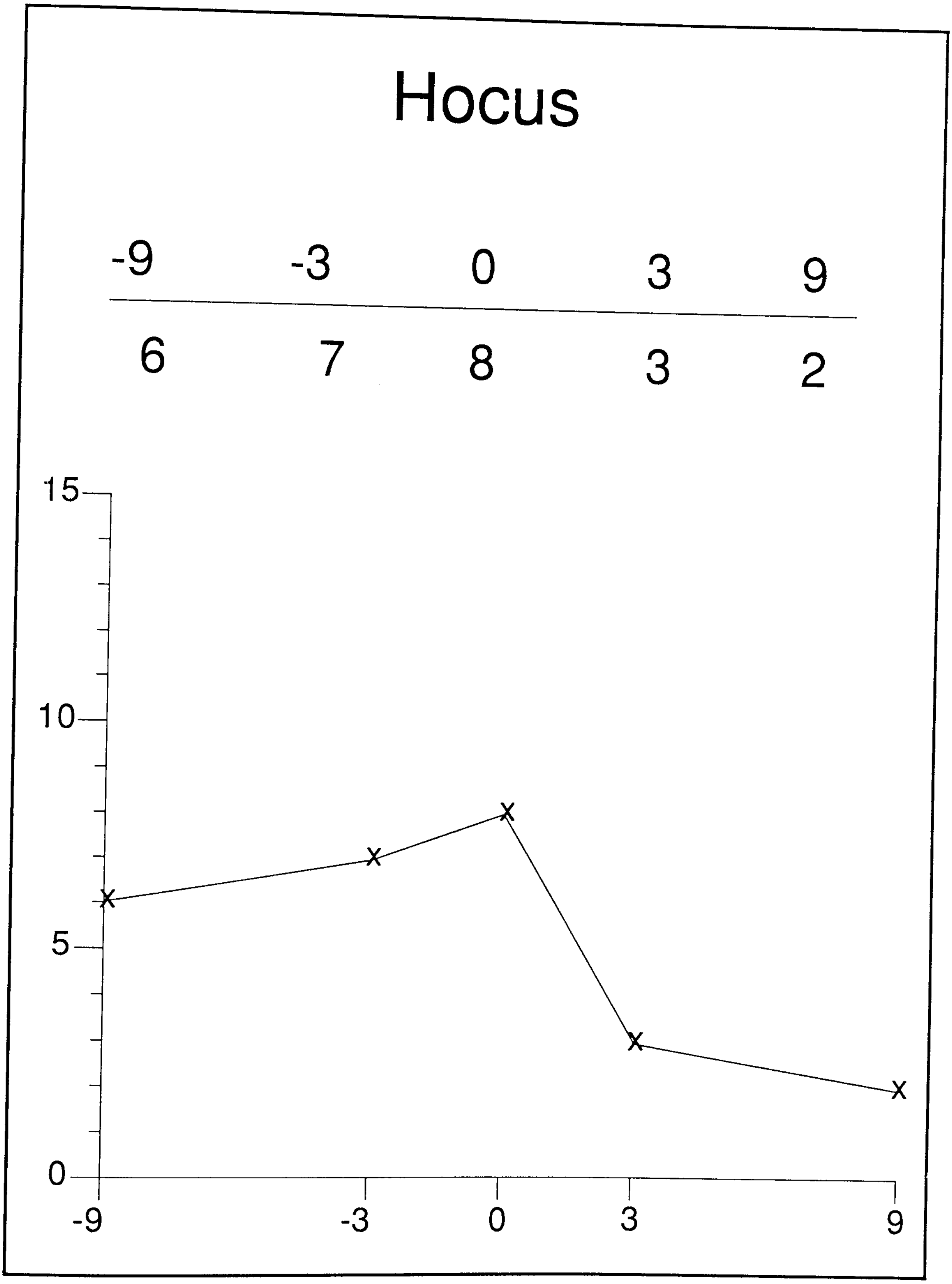


Figure 6.9 QFD Grading - Hocus

any inherent assumptions in the modelling elements inhibiting the application of the simulator. Also models must be able to accommodate and evaluate realistically sized manufacturing systems so they are not restricted to only a handful of applications. Furthermore they must ensure that model evaluation is not too slow as to severely restrict the investigation into alternative design configurations and more thought needs to be given to the graphical display of models.

6.4 Requirements for a Manufacturing Simulator

This chapter has considered the alternative approaches to developing dynamic computer models of manufacturing systems, whilst also identifying user requirements which the approaches must satisfy. It has been shown that for design projects other than high cost, long term ones, the general approaches to model development, which include high level languages, simulation packages and symbolic modellers are inappropriate. They all have unacceptably long development lead-times and are too highly technical. These culminate in ensuring that computer modelling techniques do not aid and support the decision making process involved in the design of a manufacturing system. Instead, such techniques tend to be used to simply check or verify the end result of the design process. Furthermore these restrictions have severely confined the general application of computer modelling techniques over the last eight years. Thus if the modelling strategy defined in chapter 4 is to be implemented effectively it has to be supported by a dynamic system evaluation tool which:

- is accessible by non-experts and experts alike;
- is relevant to a wide range of manufacturing systems;

- allows total user influence over all model features;
- involves short model development lead-times;
- requires only minimum training;
- is able to model partial manufacturing system designs;
- is low cost.

It has been established that there is only one appropriate approach to dynamic design evaluation that will provide the integration of the computer modelling techniques into the manufacturing system design process, as specified in the modelling strategy. That is only the use of pre-developed manufacturing models, in the form of mathematical and simulator systems, can ensure an efficient and effective systematic approach to process design and an increase in the general application of computer simulation techniques.

Having established the need for and appropriateness of pre-developed dynamic computer models, the broad system modelling requirements of such packages need to be defined in order that they be generally applicable to all types of manufacturing systems. These requirements include:

1. Represent different system components
   e.g. machines, transport, operators, tools, etc.
2. Represent different types of a component
   e.g. conveyors, trucks, AGVs, operators, etc.
3. Represent components at various levels of detail
   e.g. first-pass, rough-cut, macro and micro levels.
4. Represent different system configurations
   e.g. Jobbing, batch, FMS, flow and continuous.
5. Represent different control and decision rules
   e.g. MRP, Kanban, OPT, machine scheduling, etc.

Chapter 7 Specification Of A Manufacturing Simulator.

The previous chapters have considered the effects of the inherent complexity that comprises a manufacturing system and which, due to the maze of individual element interactions, are humanly impossible to evaluate. Hence the importance and necessity for dynamic computer modelling techniques has been identified, in order to evaluate and study both existing and conceptual manufacturing systems. More precisely though the relevance and influence of model simulators for simplifying and readily allowing the application of computer modelling techniques by both non-computer and non-simulation experts, has been established. It is realised that, due to their very nature model simulators are very restricted in respect to the range of systems they can emulate. Thus, because of the assumptions and/or lack of features incorporated in a generic model, it is possible for them to be far too limited in application and therefore only relevant to a very small range of unique systems. Chapter seven firstly reviews the functionality and appropriateness of existing model simulators designed for the specific evaluation of manufacturing systems. Then proceeds to identify the relevant areas and features of a manufacturing system which a general purpose model simulator must be able to emulate. A detailed specification is developed for a model simulator, encompassing the necessary flexibility to be generally applicable to discrete batch manufacturing systems, whilst at the same time being comprehensive enough to consider the detail of any individual system.

7.1 Manufacturing Simulators

7.1.1 Introduction

The idea of a configurable manufacturing simulator is nothing new, as nearly all computer models that have been developed include some degree of flexibility, be it only the ability to change operational data such as set up and cycle times. However, as has already been established, an ideal manufacturing simulator for system design must be able to represent a wide range of both different physical and control components which could potentially constitute a manufacturing system. Unfortunately though, simulators at present seem far from comprehensive, being applicable to only a fraction of existing manufacturing systems. Furthermore, within their restricted area of application, current simulators tend not to be completely appropriate. Instead of developing features that would permit the extensive application of a simulator, Bevans [1982] has observed that (when considering the ideal flexible manufacturing system (FMS) simulator):

"...less ambitious FMS simulators have been created;"

Bevans continues by suggesting that the design of general manufacturing system application simulators has been:

".. not as general as one would like.."

Consequently existing manufacturing simulators can be grouped into one of two, rather inadequate categories. However, the groupings are not as clear cut as that suggested by Iwata et al [1984], who said that simulators are:

".. employed only as either design or operation aids.."

Instead the main differences between simulators is more subtle than this and further emphasises the significant inefficiencies and irrelevance of existing generic models. The principal distinction between simulators is hinted at by Bevans, who identified that machine tool builders and owners of existing manufacturing facilities, use simulators to investigate the alternative operation of a specific combination of machine tools. Whilst the potential owner of a new manufacturing facility requires a simulator to investigate a large range of different system configurations. The two categories for manufacturing simulators are:

1. Operational simulators, which allow the study of specific operating problems on a particular manufacturing facility,

   i.e. system components are fixed and certain operating procedures are adjustable.

2. Physical simulators, which allow a range of different manufacturing system configurations to be considered with very similar operating procedures.

This highlights the substantial limitations of existing simulators to be generally applicable to manufacturing systems evaluation. The design of manufacturing systems entailing the study of both system configuration and control, whilst no two operational investigations are ever performed on exactly similar system configurations.

The following sections 7.1.2 and 7.1.3 consider non-commercial operational and physical simulators respectively, whilst 7.1.5 specifically discusses commercially available packages, irrespective of their classification.

7.1.2 Operational Manufacturing Simulators

Operational simulators investigate the detailed control of a restricted range of system configurations. In considering the very complex nature of the production planning and control activity, along with the substantial rewards to be gained through any efficiency improvements in the current procedures, it is inevitable that specific, operational orientated simulators would be developed. Such models allow a precise, unambiguous comparison between the performance of alternative operational procedures by ensuring no variation in system configuration. This illustrates the suitability and relevance of various control procedures, by providing a clear understanding of their exact benefits and weaknesses.

Pai and Mcroberts [1971] produced a model to allow the effects of five different priority disciplines to be studied on a fixed manufacturing facility. The priority rules were first-in first-out (FIFO), component order oriented rule (OQOR), fixed period rule (FPR), dynamic priority rule (DPR), modified dynamic priority rule (MDPR), whilst the system comprised of a work-in-progress (WIP), fabrication (with three machines) and assembly areas (with three work stations). The products were simply X, Y, Z with components A, B, C, D, E and F.

Bassett and Kochhar [1985] described a model able to investigate the influence of individual system elements on the performance of a material requirements planning (MRP) system. The simulator, called MRPSIM, comprised an MRP system and probability generator for order completion. The MRP system included master production schedule (MPS), netting and off-setting of requirements, parts explosion, lot sizing and safety stock facilities. System evaluation was on the basis of production output, inventory value, open order arrival, stock withdrawal and job start and completion analyses. Complete kit and partial kit job release rules were utilized. However, manufacturing operations were not explicitly modelled, instead the completion of a works order, along with the delivery of purchase items was specified by two probability parameters. One determined the actual arrival of an order, either on time or a week or two late, whilst the other established the completed order quantity, as a percentage of that original planned.

GIPSI [Lewis et al, 1980] is a general purpose inventory control simulator developed for people with no computing expertise, to study the appropriateness of four different inventory policies. The inventory policies were re-order level, re-order cycle, re-order level subject to periodic review and max/min. However, like Bassett et al, the manufacturing operations were not explicitly emulated. Instead order lead-times, along with component demand was specified on the basis of a defined series of fixed or statistically distributed values or a relative frequency table.

Mamalis et al [1987] included 15 control strategies in a model simulator developed specifically to investigate a wide spectrum of FMS. The control policies were based upon the combination of five order release and three system operation rules. The model allowed for specific operational data, which for each batch, included component routes and set-up, processing and unloading times for each operation. Though the simulator provided a wide range of control strategies, its application was clearly limited by inadequate representation of the operation of an FMS. This was highlighted by the unrealistic abstraction of such principal elements of an FMS as component queues, AGV control strategies and machine breakdowns. Overall the simulator did not provide enough precision with regard to the physical constituent elements of an FMS to be generally applicable to such systems.

In addition to evaluating inventory control policies, simulators have been developed specifically to investigate the control of material handling systems such as automatic guided vehicle (AGV), overhead crane and conveyer systems.

Cheng [1985] considered the relative effectiveness and impact of four AGV dispatching rules on the performance of an FMS, with attention also being given to the number of AGVs in the system and their speed. The four vehicle dispatching rules analysed by Cheng were:

- select the first available AGV,
- select the AGV with the most cumulative idle time,
- select the AGV with the shortest travel time and
- select the AGV with the longest travel time.

However, the underlying manufacturing system was based on a rather simple, hypothetical layout consisting of only four work stations. One was a loading/unloading station whilst the rest were general purpose machine tools, assumed to be a machining centre, a miller and driller, all under on-line computer control. Furthermore the manufacturing requirements were very elementary, comprising of only two production components, part type 1 and 2, each requiring two and four operations respectively.

Demaire [1973] developed a model to analyse the effects that varying work loads had on the delays that a crane, in a casting plant, incurred and the available capacity of the crane. The model simulated thirty seven discrete types of tasks that the crane was required to do over a period of one month. The tasks classified into three general types:

- fixed time of occurrence,
- random time of occurrence, and
- random time of occurrence with some fixed distribution of known cycle time.

In the model described by Bussey and Terrell [1973], of work passing along a conveyer, only one conveyer could be modelled, although its type, speed and capacity could be altered. However, even though the number of work stations could be altered, this was simply a number and no operations were modelled at any stations.

7.1.3 Physical Manufacturing Simulators

An initial analysis of physical manufacturing simulators would seem to indicate that such models are applicable to a considerably greater range of systems than operational simulators. This is due to the simulator's inherent flexibility to emulate a range of manufacturing system configurations. However, a closer inspection of physical simulators identifies an inadequate provision for replicating alternative control systems. Obviously such a restriction significantly limits the application of a simulator. Furthermore, although physical simulators can accommodate a range of manufacturing system configurations, they do not necessarily represent available resources in sufficient detail or accuracy. In other words simulators can and do contain pre-defined assumptions regarding manufacturing systems which cannot be altered, relating to such things as operator absenteeism, machine breakdown, assembly operations and general operating procedures. It must be remembered that an inaccurate modelling exercise can be more damaging than no exercise at all, but because of the simplicity of simulators people will still use them regardless of the accuracy of the resulting model (section 7.2).

The GEFMS (Graphically Enhanced Flexible Modelling System) simulator described by Duersch et al [1985] could accommodate problems up to a size of 500 batches, 20 machine cells, 10 machines per cell, 15 components, 25 operations per component, 15 resources (tools, fixtures, people) and 20 transporters. Furthermore the simulator allowed queue capacities to be defined, transport activities to be considered, operation times to be statistically distributed and provided four methods of specifying order arrival. These options were inter-arrival times, work-in-progress specification with or without replenishment and scheduled arrivals. However, the application of the simulator is significantly restricted by not supporting assembly operations, shift patterns, alternative machines or explicitly representing manpower. In addition the small number of production components that can be accommodated limits the relevance of the model, as does only providing earliest due date scheduling, along with the standard FIFO option. Cumulatively these restrictions severely confine GEFMS to the evaluation of systems within a subsection of such facilities as FMS.

Ulgen [1983] described a simulator called GENTLE (GENeral Transfer Line Emulation) designed to simplify the simulation of both assembly and transfer line production systems within the Ford Motor Company. GENTLE could handle a maximum of 99 operations, 150 machines, 250 storage spaces, nine machines per operation, up to five operations feeding any other and alternative routes. The model could consider both random and predetermined production stoppages. However, the relevance of GENTLE to the evaluation of general manufacturing systems is severely restricted by its original application as a transfer and assembly line analysis tool. The inherent assumptions of the simulator included only one type of component produced, dedicated operations and machinery and only FIFO scheduling of batches.

Patel et al [1973] presented a generalized manufacturing simulator designed for the evaluation of jobs through a production facility utilizing equipment, manpower and buffer resources. The model could typically handle manufacturing systems comprising of ten products, a total of 300 operations and 350 pieces of equipment. The description of the simulator clearly illustrated its capability to replicate a wide range of system configurations. The simulator could emulate machine breakdowns (random and planned), manpower requirements, rework operations, transfer quantities and daily shift patterns. However, the application of the simulator was mainly limited by being unable to represent assembly operations, operator absenteeism, a restriction to similar daily shift patterns (which is not the norm and cannot account for Saturday and Sunday overtime), accommodation of only ten products and a significant lack of alternative control policies. Other than prioritizing individual products, batch scheduling was simply on the basis of FIFO. In addition order input could only be assumed to be predetermined and there was no method of controlling the allocation of manpower to operations. Therefore although the simulator provided a broad range of modelling features, it was not done in sufficient detail.

Similarly Dunham et al [1981] described a simulator, designed specifically for the evaluation of production lines, which incorporated corresponding features to those detailed by Patel et al. Furthermore Dunham et al identified the simplifying assumptions which limited the simulator's application. These included one machine per operation, no assembly operations, no operation interruptions such as machine breakdowns, no alternative routes and negligible transportation times.

ISL [Industrial Simulations Ltd.], an industrial simulation model was primarily designed for the evaluation of assembly operations and caters for up to 600 live batches, 100 part numbers, ten products, 30 operations per part, 20 machines per operation group and 20 labour groups. The simulator contains two very salient features these being four pre-set scheduling rules and the facility to replicate and examine the performance of an MRP system. The priority rules consist of FIFO, shortest set-up first, earliest due date and least slack per remaining operation in addition to individual part prioritizing, whilst available MRP features included Bill of Material (BOM), component lead-time and economical batch quantity (EBQ). However, the exclusion of a number of facilities does significantly restrict the application of the ISL simulator, e.g. the inability to replicate machine breakdowns, varying shift patterns including overtime, tooling, alternative machines and operators for each operation, precise control over operator job allocation and alternative production control methods like kanban and optimized production technology (OPT). Similar to Patel et al and Dunham et al, ISL does provide a range of standard manufacturing features, but lacks the necessary detail to constitute a simulator generally applicable to the majority of manufacturing systems.

In terms of the physical description of a manufacturing system, the simulator presented by Love [1980] provided one of the most flexible approaches. Initially required to investigate the influence of scheduling rules and the flexibility of labour on the performance of a spares component manufacturing system, it included more extensive features in order to be applicable in other companies and industries. Models are described, using simple terminology, by defining the number, type and attributes of machines, men, components and orders which make-up the system under investigation. Furthermore the package allowed all resources to be referred to by way of their actual company name.

Data entry revolved around four types of resources, machines, men, parts and orders, allowing for machine breakdowns, shift work, absenteeism, sickness, component demand and user defined or statistically generated order input. Four machine queue priority sequencing rules were available, these being minimum due date, minimum setting and machining times, minimum float and random selection. In addition there were extensive monitoring facilities allowing for the study of work-in-progress, lead times and resource utilization, all of which could be tailored to meet specific user requirements. The simulator incorporated three advanced features for defining system behaviour, these were specification of machine groupings, labour operation and setting skills and manual or automatic machine operation. The allocation of operators to alternative machines could be further enhanced by the specification of both single operator multi-machine operation and machine loading and unloading operations.

The simulator is restricted in application primarily due to the size of problem it can accommodate. This is determined by the number of entities which can be described, the maximum being:

- 20 men
- 40 machine groupings
- 75 parts
- 17 operations/part
- 51 orders
- 2 batches/order
- 20 machines
- 3 machines/grouping
- 40 skills/man

The major deficiencies of the package relates to the lack of various decision rules for studying control issues and the provision for resources such as transport, tooling and pallets. The only policy rules available being those for the prioritization of work queuing at machines. Consequently the simulator could not emulate any production control procedures other than MRP.

In referring to all the non-commercial simulators, both operational and physical reviewed for this and the previous section, the simulator most applicable to manufacturing systems in general was the one described by Iwata et al [1984]. The simulator, based on GASP and written in FORTRAN-77 could consider systems up to a maximum of 50 work stations, 999 cutting tools, 100 pallets, ten carts, 100 jigs, 100 fixtures, 100 material handling modules and a buffer capacity of five each. A high degree of modelling flexibility was incorporated into the simulator by apportioning the representation of a manufacturing system into seven modules, which included work station, transport, material handling, auxiliary, storage, operator and part modules. Thus allowing general job shops, along with transfer lines and FMS to be investigated. Furthermore the simulator could explicitly emulate machining, assembly, inspection and cleaning operations. The principal advantage of this simulator over any other non-commercial one, was the provision of a range of various decision rules for a wide spectrum of control issues. The decision rules related to the selection of:

- components to release into a system,
- components to be processed,
- operation resources,
  e.g. work stations, operators, tooling, pallets and carts.
- a component's next operation,
- a transfer path between work stations.

However, even the application of this simulator was restricted due to the limited size of system that could be accommodated together with the inherent inability to specify alternative routes, transfer quantities and control methods such as kanban or OPT.

7.1.4 General Assessment Of Non-Commercial Simulators

The previous discussions regarding specific operational and physical simulators, examines their restricted application due to inadequate provision of modelling features with which to accurately replicate general manufacturing behaviour. Most of the above simulators, regardless of type, are also severely limited in application simply because of the actual availability of the model. All the simulators, except GEFMS and ISL, are implemented on either a mainframe or mini computer, access to which, in an industrial environment is fairly restricted. Such computers tend to be exclusively utilized for the running of company finances and/or actual production planning and control activities. Whereas the significant reduction in the cost of personal computers (PC), combined with the substantial growth in their processing power, has established their use as a general engineering tool in a wide range of companies. Consequently simulators implemented on PCs are more readily accessible by engineers, who could most benefit from such a simplified implementation of simulation techniques.

The overwhelming impression of the above general manufacturing simulators, is that they appear to have evolved out of specific application models, which have been to some degree enhanced by the addition of modelling flexibility, relevant to the initial study. It is evident that the initial design emphasis, for both the previous operational and physical simulators, was on the emulation and investigation of a specific manufacturing phenomenon. The simulators have a fairly restricted area of application, their modelling features being far from comprehensive, as previously observed by Bevans. The above non-commercial simulators cannot therefore be judged to be totally appropriate and efficient tools to support the general design of manufacturing systems.

7.1.5 Commercial Manufacturing Simulators

Perhaps the most appropriate and widely applicable manufacturing simulator, either commercially or otherwise is MAP/1 [Rolston et al 1985] developed by Pritsker & Associates in America. The aim of MAP/1 was to provide a generalized manufacturing model, parameterized to represent specific facilities and which could be used by people with the responsibility for designing, operating and managing such systems. MAP/1 provides six modules for the complete description of a manufacturing system and these are parts, work station, material handling devices, personnel, fixtures and operational characteristics. Thus the model can accommodate system configurations which include machining, assembly and rework operations, pre and post-process storage areas, discrete transport devices, open and closed loop conveyors, operators, tooling, fixtures, machine breakdowns and shift patterns with specified overtime. Furthermore MAP/1 provides a wide range of operation rules. Part arrivals can be scheduled or determined statistically, batch sequencing rules include FIFO, last in first out (LIFO), shortest processing time, earliest due date, and part priority, individual operators can be assigned to equipment and the end of a shift checked before commencing an operation.

MAP/1 unfortunately cannot address semiautomatic machinery and therefore one operator simultaneously running a number of machines or the specification of alternative machines and/or operators or the operation of any production control method other than MRP, like kanban or OPT. However, the biggest constraint of MAP/1, which has severely restricted its application, is the limited availability of the simulator because of only being implemented on mainframe and mini computers (section 7.1.4). This is probably solely due to the memory constraints imposed by PC computers.

One of the best known and most popular of all commercially available computer simulation packages, is Witness [ISTEL, 1986] developed by ISTEL Ltd. Despite the fact that it is marketed on the basis of its "simulator" like features it is neither a true generic model or general purpose simulation package, but is instead a compromise. Witness is menu driven, allows the evaluation of partially specified models and provides a number of pre-developed modelling elements. However, these elements are not detailed or comprehensive enough to totally describe the configuration and operation of a manufacturing system. Therefore Witness incorporates a built-in programming language, which provides the flexibility of standard simulation languages. Although the package is heavily manufacturing orientated, it is also applicable to a wide range of completely diverse systems. This is inevitable considering Witness is the successor to See-Why, the first graphical simulation language.

Witness recognizes seven different types of modelling elements which are parts, machines, conveyors, buffers, labour, tracks and vehicles. Then within the machine and conveyor type elements there are subtypes, which for machines are:

- single, processing one part,
- batch, only process when a batch of parts is present,
- assembly, combining a number of parts into one, and
- production, producing a number of new parts from a single one,

whilst for conveyors they include:

- fixed, which stops if parts cannot be removed when they reach the end, and
- queuing, which allows an accumulation of parts until the conveyor is full.

Witness, however, has lacked in the provision of standard predefined control and decision making rules, like FIFO, shortest set up time or least utilized resource. Though some of these have now been incorporated they are still rather restricted. Therefore in addition there are ten control blocks which, combined with various parameters can model quite complex decisions, but is similar to having to program each rule. Witness also includes a conceptual flaw with regard to the way it describes the operations for a given manufacturing component. Generally in manufacturing operations are defined with reference to a particular part, but in Witness these are specified with respect to machines. Furthermore the operator element is more akin to the modelling of tools or fixtures, that is resources which are available 24 hours a day, as Witness does not allow shift patterns to be specified.

Therefore the lack of sufficiently detailed and comprehensive standard simulation elements and a dependence upon the use of a language (with all its disadvantages) with which to completely describe a manufacturing system, results in a package that simply does not achieve the full advantages of a true simulator.

Simfactory [CACI 1987b], developed by CACI represents a true manufacturing simulator which alleviates the necessity to undertake any computer programming, by providing standard simulation elements in engineering terminology with which to describe a factory. The simulator can consider such resources as work stations, raw material, work-in-progress, component queues, transport devices and tooling. Simfactory supports four different types work stations normal, serial, rotating and chamber, and allows the specification of alternative stations for any given operation. Transport devices include batch and conveyor type, with either accumulating or non-accumulating conveyors. Furthermore there are no arbitrary restrictions on the actual size of model that the simulator can accommodate and the simulation graphics run concurrently with model evaluation.

The major factor that severely limits the application of Simfactory is that it is a physical simulator and provides very few operation algorithms to control the activities within the model. Queues can only be ordered on the basis of FIFO, LIFO or lowest/highest due date. The selection of a station for an operation is either the first available or the lowest utilized. The first available transport is always selected, whilst tools are chosen on the basis of the one which has not been used for the longest time. Therefore Simfactory is very restricted in the production control methods is can emulate, being unable to represent such techniques as Kanban or OPT. Furthermore transfer quantities between various operations cannot be specified, operators are not explicitly defined and shift patterns cannot be easily specified. However, Simfactory does fully support both work station and transport breakdowns.

The approaches adopted to describe a manufacturing system in Simfactory does further restrict the simulator's potential range of application. Set up times relate to specific operations on a given work station and are therefore independent of the component being produced. All work stations which may directly receive a component from a particular station must be listed sequentially. Therefore regardless of the component being passed on, the priority of alternative work stations for a subsequent component operation is dependent upon and fixed relative to the station where the previous operation took place. In addition all assembly operations must always be the first defined in a component's process plan. Simfactory duplicates a lot of effort as all operations have to be precisely defined relative to all work stations which can perform the activity, along with specifying the operation for every part which may require it.

Therefore, although being developed as a general purpose manufacturing simulator, Simfactory is essentially a transfer line model, due to the approach adopted and the restricted features with which to describe a production system.

Possibly the best-known PC based manufacturing simulator and most appropriate to support system design is MAST [CMS, 1989]. Originally designed and developed for the evaluation of FMS, MAST can now represent a wide range of physical and operational characteristics which enables it to study a variety of general manufacturing systems. MAST can accommodate such resources as work stations, assembly, disassembly and rework operations, various buffer configurations, carts, conveyors, operators, tooling and pallets. Although there is only one type of work station (unlike MAP/1, Witness and Simfactory) and the operation time is per pallet, the simulator does provide a number of different cart and conveyor types. For cart there are:

- fork trucks,
- computer controlled systems,
- special service carts, and
- cart and conveyor systems,

whilst conveyor configurations include:

- free conveyor,
- synchronous transfer,
- non-synchronous conveyor and
- labour transportation.

However, the most detailed and advanced part of MAST is in the provision of control algorithms. MAST contains six groups of decision rules including:

- part scheduling with six rules,
- operation sequencing with four rules,
- part queue selection with ten rules,
- station selection with six rules,
- transport selection with six rules, and
- transport control with seven rules.

Furthermore the reliability of both work stations and transport devices can be easily modelled, along with shift patterns and operator work station allocation.

Undoubtedly the feature that most restricts the application of MAST is the limited size of system which the simulator can represent. The maximum capacity of an IBM PC with 640kbyte memory is:

- type of components	40
- operations per station	30
- operations per routing	15
- stations per operation	15
- parts in the system	75
- stations	40
- carts	20
- pallets	75
- queue size	19

Additional restrictions include only one assembly operation per route, no transfer quantities between operations, all cart or conveyor devices treated as identical and operator service is the same (i.e. entire duration, start of operation or specific time) over all work stations irrespective of individual component operation. Furthermore MAST does not truly allow for alternative work stations. All work stations are unique to a specific grouping and individual component operations are assigned to a particular group. This can cause conflict, particular when one operation can be undertaken at a number of work stations, whilst another can only be performed at one of the stations.

Therefore, although MAST is the nearest to a truly combined, generally accessible physical and operational simulator, it is severely deficient in terms of its ability to sufficiently represent the physical elements of a system. Thus MAST is more an operational simulator.

7.1.6 Multi-level Modelling

In general the main limitations of the above manufacturing simulators are specific to the individual packages. However, there is one commonly occurring and important restriction which all simulators, except MAST, suffer from, irrespective of classification or availability. That is they are limited to replicating systems in effect at only one level of detail. Every batch of work, operation, piece of plant, etc. is modelled in detail, the individual elements of a system are given precise consideration. The adoption of a simulator for such thorough and exact modelling though may results in a very inefficient and slow evaluation process. The execution of a detailed model generated in a manufacturing simulator and running on a PC computer can take, as Brown [1988] says:

> ".. a half hour to 45 minutes or even longer for a single run."

Thus the implementation of such simulators does not allow or support the very rapid analysis of alternative designs, even though model development is relatively quick. Consequently, other than MAST, none of the above simulators provide the ability to efficiently model a system at various levels of detail or abstraction. While it has been established that manufacturing simulators are the most appropriate to implement the proposed modelling strategy, it is obvious that such packages can contain significant restrictions limiting the extent to which they may support the strategy. As a result of the protracted evaluation phase, the majority of simulators are only appropriate for undertaking the most detailed system analysis which coincides with the micro design stage. However, this only represents one of four necessary and complementary stages of system evaluation each of which relates to a specific phase of the design process.

In order to compensate for the inefficient evaluation of models implemented within most manufacturing simulators, a number of people [Brown, 1988; Bell et al, 1986; Rathmill et al 1983] have employed mathematical models before commencing a simulation exercise. The adoption of mathematical models provides, early in the design process a quick and rough analysis of alternative proposals before any thorough and detailed consideration has been given to their exact configuration and precise behaviour. This allows unsatisfactory designs to be identified and therefore disregarded before too much valuable time and money has been wasted on their development. The overwhelming advantage of mathematical models is the combined ease and speed of evaluation [Kay, 1984] and the simple and limited data requirements, which do not necessitate any detailed knowledge of system behaviour. The restriction of long-term average evaluation and the inclusion of unrealistic assumptions are overcome by a comprehensive simulation exercise. The application of simulation techniques is subsequently more efficient and effective, having weeded out poor design proposals through highly aggregated system evaluation, effort can now focus on only those designs which justify further investigation.

The combined implementation of both mathematical and simulation modelling techniques has been approached in two ways. Either the use of two discrete and separate models [Brown, 1988; Rathmill, 1983] or as one integral system [Suri et al, 1988; Bell, 1986; CMS, 1989]. Brown discussed the use of two separate modelling packages Manuplan II, for mathematical analysis and Slam II for simulation, whilst Rathmill et al used CAN-Q and GPSS, respectively. However, this approach is inefficient and time consuming, as both mathematical and simulation modelling, to some extent duplicate the data entry activity. Whereas with the integral approach all necessary data need only be entered once, as the basic manufacturing data is entered for the mathematical model and then automatically reconfigured and passed to the simulation system where more detailed information can be added. Suri et al described a system called Simstart which, working independently of the two distinct systems, translated Manuplan II models into basic Siman configuration. Bell and CMS documented interactive modelling packages which incorporated specific programs to collect and transfer necessary data required to configure the two inherent models, which were CAN-Q and a manufacturing simulator and Spar (a capacity planning model) and MAST, respectively.

The above mathematical and simulator modelling configuration currently provides the best support for the multi-level strategy, although it can only implement two of the four levels of evaluation. That is, at present mathematical and manufacturing simulator models can only implement the two extreme levels of evaluation detail, these being first-pass and micro-level. It is still an "either or" option. A system is either modelled at a highly abstract or very detailed level of evaluation, there is no compromise. Therefore critical areas of a system (i.e. bottlenecks) are either considered in isolation and the influences of non-critical areas around it are therefore ignored or the whole system is considered in detail, which can be confusing, with too much unnecessary complexity incorporated in the analysis. Instead what is required is an approach more like that adopted in the evaluation of electronic components [Ghosh, 1987; Whelan, 1985].

The simulation of digital hardware designs start at the highest level of abstraction. This provides a fast functional evaluation, but the results are not very detailed or comprehensive enough to support a thorough system analysis. Therefore when the functional results are unsatisfactory the appropriate system components are expanded to a lower-level implementation which provides a more accurate and precise investigation. However, evaluation is now slower and more time consuming. Hence low-level implementation of individual design subsections is only undertaken when warranted by a higher-level investigation, else design elements remain fixed at the previous levels of abstraction. Consequently unnecessary effort and detail can be eliminated from the evaluation of design proposals, making the process far more efficient.

The evaluation of electronic components is both relevant and applicable to the analysis of manufacturing systems (figure 7.1). At the highest level of abstraction exists the factory. On expansion of the factory, design evaluation completely moves to the lower-level department implementation.

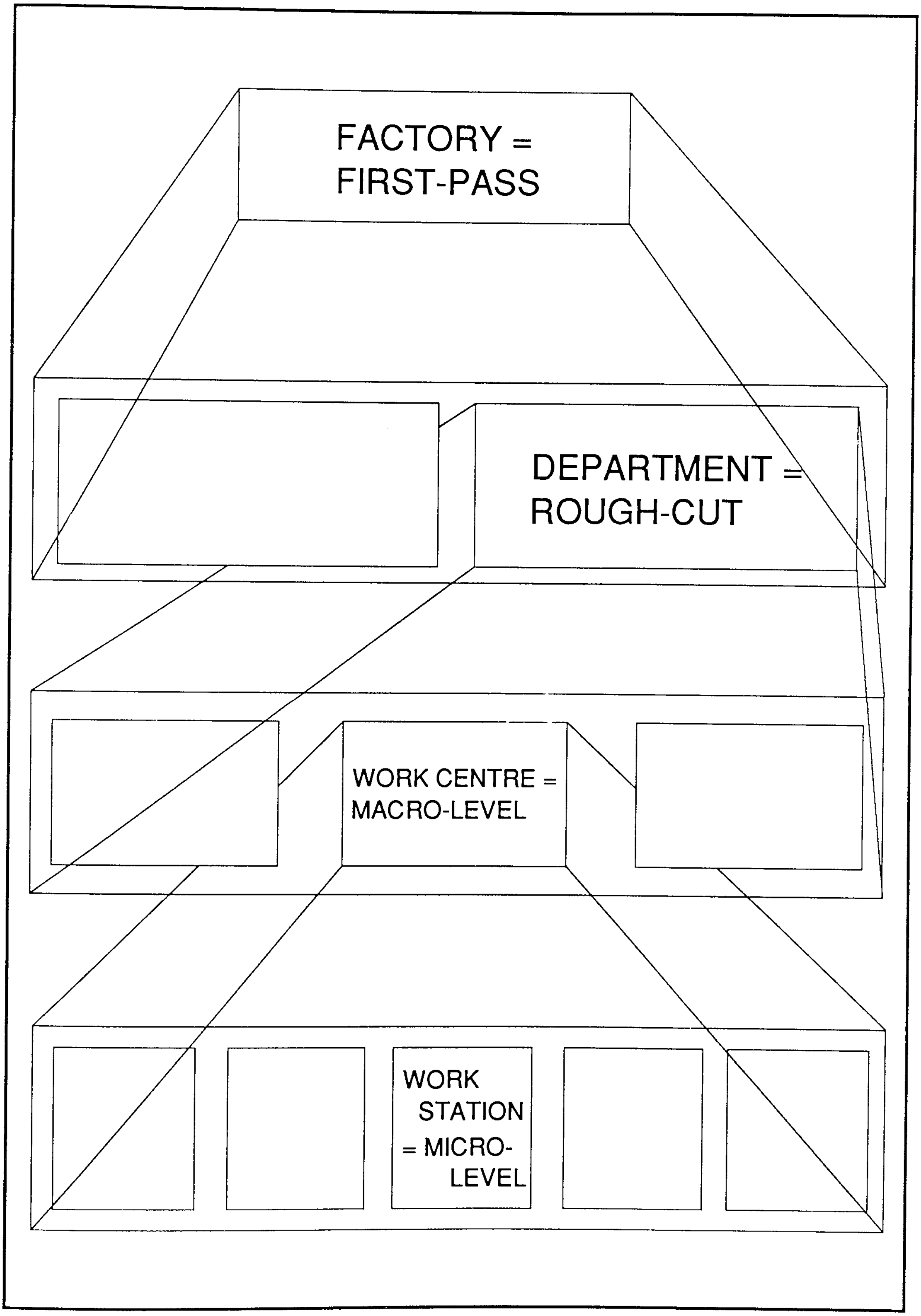


Figure 7.1 Manufacturing Multi-Level Decomposition (a)

Further expansion relates to work centre evaluation, whilst the lowest level of investigation is machine or work station. From the department implementation subsequent expansions relate to specific design subsections thereby permitting system evaluation at more than one level of detail. This infers that the individual components of a system design could, in one model, be replicated at one of three possible levels of detail (i.e. department, work centre or work station), irrespective of the detail of neighbouring elements. Consequently, areas of critical concern can be considered in precise detail, whilst at the same time still taking into account the influences of unimportant areas at a more highly aggregate level. Therefore evaluation is efficient whilst also being comprehensive. This hierarchical expansion of manufacturing systems transposes into the four levels of modelling identified by the multi-level strategy, first-pass, rough-cut, macro-level and micro-level (figure 7.1).

7.2 Identification Of Manufacturing System Features

The previous section, 7.1.6 identified a prevalent and significant restriction in the ability of existing manufacturing simulators to effectively support the proposed multi-level modelling strategy. However, there is a more serious limitation of all available manufacturing simulators, which was touched upon in section 7.1.3. This restriction results in the fact that no simulator is applicable to all types of manufacturing systems. The difficulties arise due to inherent assumptions and lack of available modelling features. The problem is such that simulators are in effect more restrictive to use than actually employing an expert to perform the simulation exercise, in which circumstances it is difficult to retain control of the evaluation process (section 6.2.1). The danger is that because simulators are so readily available to non-experts, then computer modelling is more likely to be used irrespective of whether or not a simulator can accurately replicate the specific system. Therefore this can only be alleviated by either restricting the availability of simulators or potentially producing a package capable of replicating all the features of a manufacturing system. At present no true manufacturing simulator can achieve the latter (section 7.1). Therefore a generally applicable manufacturing simulator has to be specified.

To specify a generally applicable manufacturing simulator one, or a combination of three alternative approaches can be employed. Model specification can be achieved either by relying solely upon a designers previous experience, combining the unique features from all existing manufacturing simulators or undertake a structured and detailed study of individual operations and therefore resources within a production facility. The latter approach provides a more coherent and comprehensive approach to model specification and can be subsequently verified by comparison with individual manufacturing simulators. Therefore a study was undertaken concerning the range and type of decisions made within a manufacturing system, and later identified the resources which were directly effected. The study was documented by way of a decision tree (Appendix B).

The starting point for the study (figure 7.2) was a desire to increase profits, which would be measured by return on investment. To increase return on investment either an

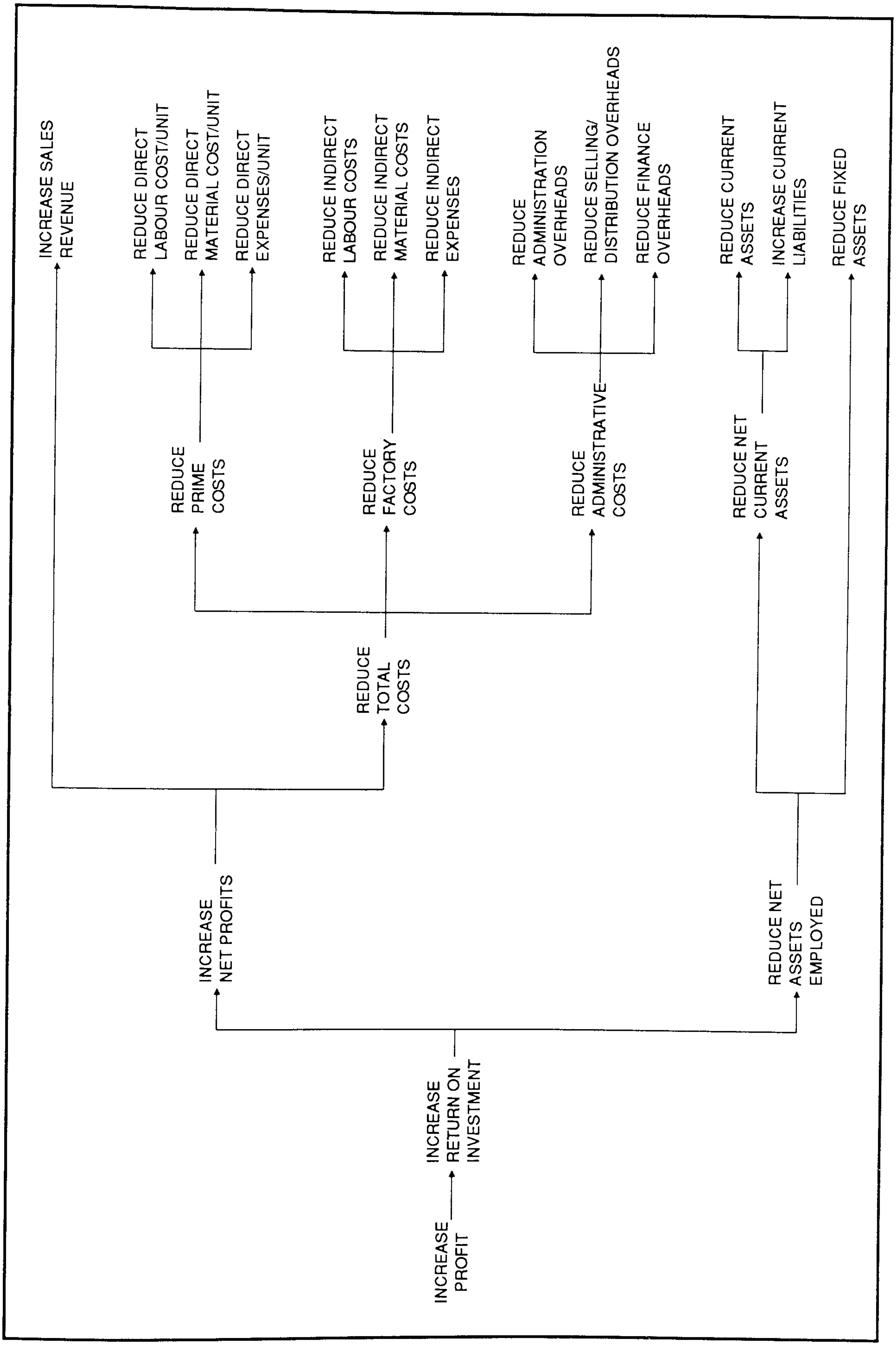


Figure 7.2 System Decision Tree - Initial Branches

increase in net profits or reduction in net assets employed was required. To achieve an increase in net profits entailed either an increase in sales revenue or a reduction in total costs, which cover both prime and factory costs along with administrative overheads. Whilst to reduce net assets employed required either a reduction in net current or fixed assets. This lead to the identification of five main areas of decision making, relating to sales, direct costs, indirect costs, overheads and company assets, with sub-categories in both direct and indirect including labour costs, material costs and expenses. Subsequently, therefore the range of decisions which directly effected these areas were established. Whilst finally the resources, which these latter decisions related to, were identified. The full decision tree is detailed in appendix B.

Through the manufacturing system decision analysis it was possible to identify the physical resources which generally constitute a manufacturing system, together with the type of decisions that are normally taken with respect to their operation. This then forming the bases of a manufacturing system simulator specification.

7.3 Specification Of A Manufacturing Simulator

The following specification for a manufacturing simulator, developed by the author, focuses on the requirements of two separate areas of operation, detailing both the necessary system and modelling features. The system being the environment in which modelling will take place, while the latter details the specific features that should be available for replicating a manufacturing system.

7.3.1 System Specification

The modelling environment of a manufacturing simulator should at least provide the following features:

1. Efficiency:
   - model specification,
   - data storage, accessibility and retrieval,
   - model execution,
   - overall system operation,
   - system accessibility.

2. Data input and output:
   - input of model specification from an external computer database,
   - built-in model data input and editing facilities,
   - hard copy of all data entered,
   - summary report of model specification,
   - comprehensive standard output reports,
   - tailorable output reports,
   - transfer of output data to presentation packages,
   - graphical representation of model configuration and operation.

3. Error checking:
   - capture of all model data specification errors from either external databases or the built-in editor,
   - capture of all possible run time errors,
   - prevention of incorrect system operation.

4. Statistical routines:
   - random number generator,

- range of common statistical distributions,
- unique random streams for all statistical sampling.

5. On-line help:
   - for system operation and model data entry.

6. Model Size:
   - no limit on the number of total or individual resources.

7. Model Manipulation:
   - multiple week evaluation,
   - termination of model execution either by time or pre-set parameter,
   - reset model to the original state before last run,
   - reset model to time zero.

8. Model Initialization:
   - pre-load queues,
   - set the state of individual resources.

9. Interactive modelling:
   - user interrupt of model execution,
   - on-line model interrogation,
   - editing of model parameters.

7.3.2 Modelling Specification

The aim of the following specification is to identify the necessary modelling features required to represent any manufacturing system configuration and operation. Although it is intended that this will provide the basis for a simulator to support the proposed multi-level modelling strategy, this is not the specification of such a model. Instead the modelling specification defines the features which should be available at one level of evaluation at least, in a multi-level manufacturing simulator. The specification of modelling features include:

I. Physical

1. Work Station (Individual machines):
   - name,
   - operational behaviour,
     e.g. single/multiple batch processing, assembly/ disassembly operation, inspection operation, indirect operation, etc.
   - machine efficiency.

2. Work Centres (group of similar work stations):
   - name,
   - name/number of work stations,
   - work input and output queues.

3. WIP Buffer:
   - name,
   - queue capacity.

4. Transport:
   - name,
   - type,
     e.g. open/closed conveyor, AGV, fork-lift truck, etc.,
   - number of discrete devices,
   - speed,
   - load capacity.

5. Material:

   - name,
   - type,

     e.g. raw material, bought-in, work-in-progress or product.

6. Operators:

   - name,
   - performance rate,
   - number of individuals,

7. Tooling, jigs, fixtures and pallets:

   - name,
   - number of items.

8. Routes:

   - material name,
   - operation number,
   - work centre/WIP buffer name,
   - set up and cycle times,
   - components per cycle,
   - operator name and quantity,
   - tooling name and quantity,
   - operation efficiency,
   - operation scrap,
   - transport name,
   - transfer batch quantity,
   - alternative routes.

9. Shift patterns:

   - limited resource availability.

10. Distance matrix:

- distance from a work centre (or store/WIP buffer) to every other one.

II. Operational

1. Resource breakdowns:
   - work station and transport,
   - mean time between failures,
   - repair time,
   - repair operator,
   - repair tools.

2. Queue sequencing:
   - first/last in first out,
   - shortest/longest set up/cycle time,
   - due date priority,
   - component priority.

3. Job selection:
   - minimise set up times,
   - minimum set quantities,
   - only jobs completed within the current shift,
   - confined to first job in a queue.

4. Material ordering:
   - works/purchase orders,
   - MRP ordering,
   - kanban ordering,
   - OPT ordering,
   - reorder point ordering.

5. Operator job allocation:
   - primary/secondary job classification,
   - duration of operator requirement.
     e.g. whole or part duration.

6. Transport control:
   - transport paths,
   - transport operation.
     e.g. uni- or bi-directional AGVs.

7. Resource selection (for an operation):
   - first available,
   - least used,
   - nearest.

Although the above specification identifies the minimum modelling features essential in a general, discrete batch manufacturing simulator it should, however, not be necessary to specify all these parameters before running a particular model application. Ideally a simulator should be able to run without certain specified data, such as operation times, operational resource requirements, etc. It is important therefore, that this is taken into account when developing a manufacturing simulator, and to have standard default values for all model parameters as required.

Chapter 8 Multi-level Manufacturing Modelling.

The preceding chapters have established the importance and advantages of a hierarchical approach (figure 8.1) to manufacturing system design, arguing that such a proposal produces a more effective and efficient design procedure. Partitioning the design task into four discrete decision making stages, which successively extend the amount of detailed consideration. Allowing therefore a clear understanding of the behaviour and operation of a system as the design complexity increases. In addition the procedure introduces regular phases of evaluation (in terms of overall performance criteria) at each stage of design, in order to control and monitor the development of individual specifications. Ensuring that only a relatively small number of decisions are made between each evaluation and are therefore continually validated, so reducing the likely occurrence of design errors.

To implement the proposed modelling strategy requires an ability to consider the overall dynamic behaviour of a manufacturing system, accommodate the continuous development of designs and provide both a quick and accurate method of evaluation, though not necessarily simultaneously. Hence the adoption of computer simulators, which are pre-written and verified models designed for the evaluation of a specific type and range of system. Such packages being far more comprehensive than specific application models, in which the odd parameter can be changed but are not as widely appropriate as symbolic modellers or simulation languages. Chapter seven reviewed currently available manufacturing simulators and concluded that in general they were applicable for either

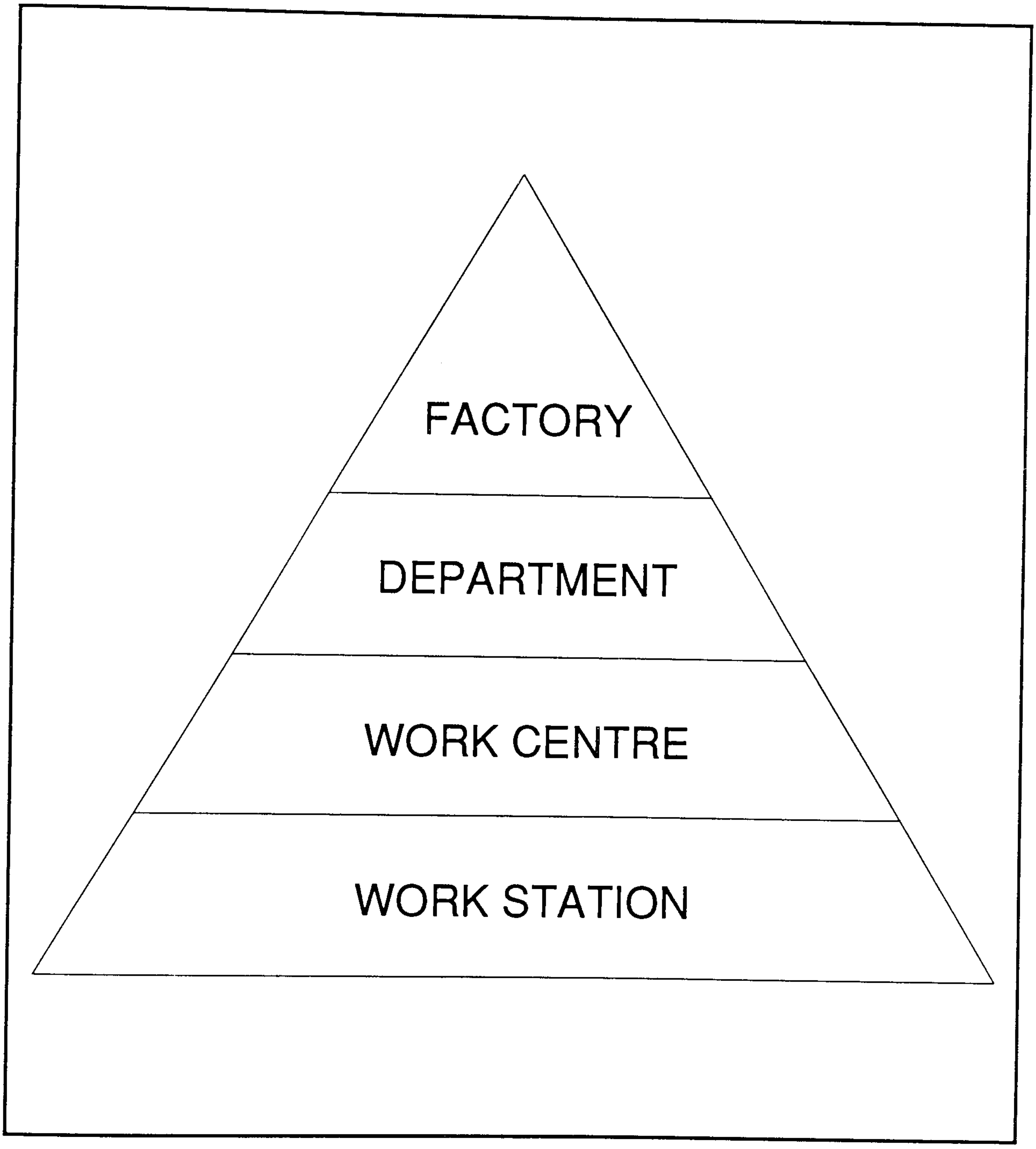


Figure 8.1 Manufacturing System Hierarchy

operational or physical system considerations, there being few exceptions which could address both issues. The chapter therefore detailed the minimum specification for a general purpose manufacturing simulator. However, and perhaps more importantly the review did not identify any system capable of supporting the four stages of evaluation identified by the multi-level or hierarchical design procedure. Chapter eight therefore, develops a detailed specification of the logic and functionality of a generally applicable, multi-level manufacturing simulator, necessary to implement the proposed modelling strategy.

8.1 Requirements Of Multi-level Modelling

8.1.1 Multi-level Requirements

The initial or first-pass phase of the hierarchical approach to manufacturing system design represents the highest level of detail aggregation, corresponding to an overall system investigation or whole factory representation. No detailed attention is given to any specific elements of a manufacturing system, instead designs are viewed in terms of the general capability and performance of the overall factory and not of any subsection of it. Consequently the factory representation considers all system components, though highly aggregated, within one logical framework. To then focus on any particular element of the design, the factory model has to be "peeled" open, in order to expose or gain access to the required area. Though in doing so, all design elements are exposed. Subsequent design evaluation is more detailed, with the total decomposition of the factory model into a number of department representations, entailing a more accurate and reliable logical and functional representation of the system. The department representations can then be decomposed into more detailed work centre definitions, which in turn can be reduced to work station descriptions (figure 8.2), as more detailed and precise representation is required of critical design areas.

Hence from the above description the various elements of a particular manufacturing system can be represented at any one of three levels of detail. In a multi-level modelling environment therefore department, work centre and work station representations should be able to coexist in the same model, to allow an efficient (in terms of detail) description of a manufacturing system. Consequently there is an important requirement for an ability to consider and emulate multi-level interactions between the three lowest levels of aggregation.

8.1.2 Data Requirements

The major advantages of a hierarchical design procedure are predominately due to the way a detailed and complex manufacturing system specification is built up over a number of consecutive design stages. Ideally therefore, the data requirements from one level of investigation to another must be coherent. Successive design phases expanding upon earlier information and not disregarding or duplicating it, but progressively building upon previous inputs. Consequently there needs to be a combined data base for all levels of evaluation. In addition output reports should support this progressively detailed and accurate investigation of system designs. Each level of analysis providing appropriately detailed reports, which clarify, confirm and expand upon

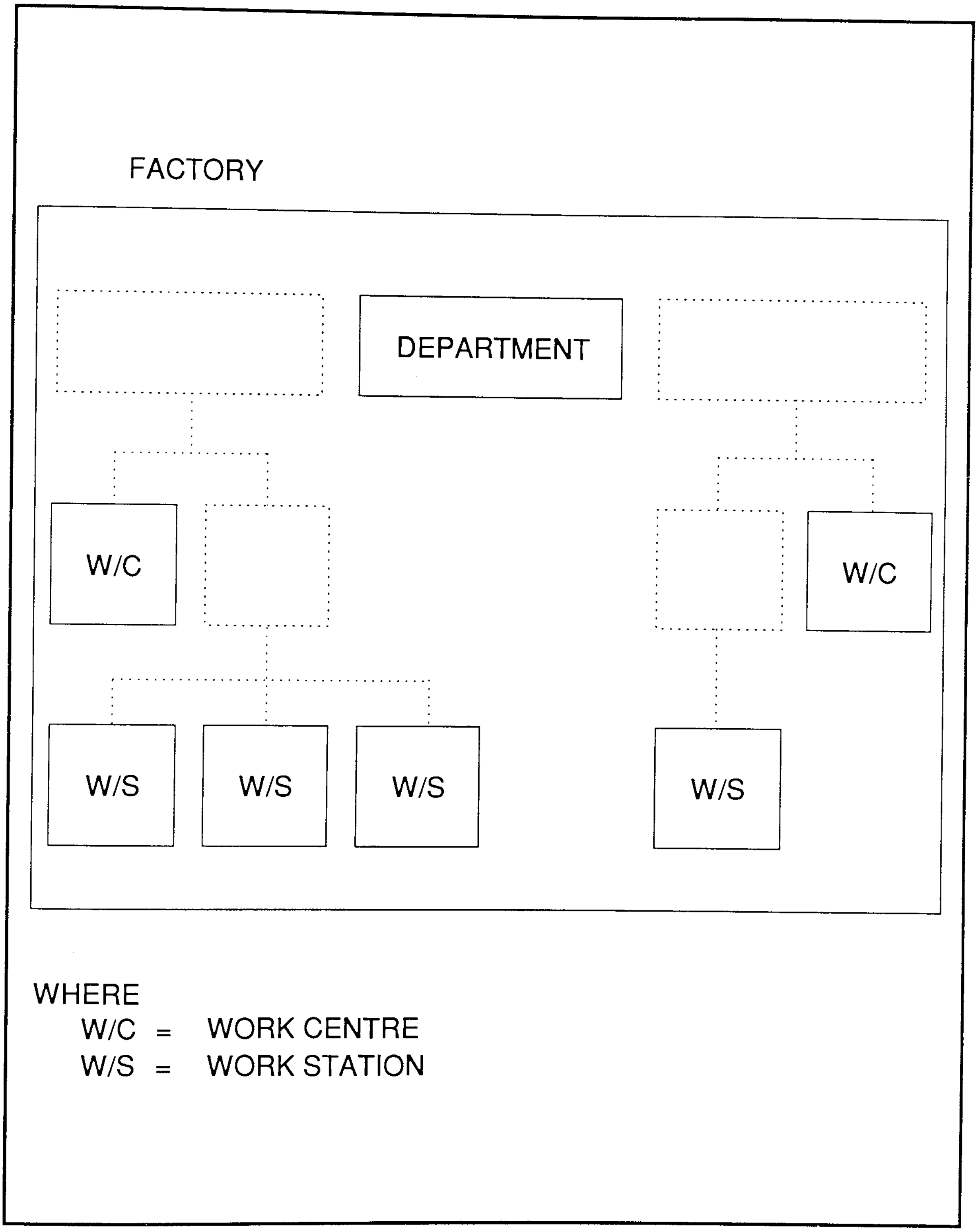


Figure 8.2 Manufacturing Multi-Level Decomposition (b)

previous results.

8.1.3 Efficiency Requirements

A major advantage of a multi-level approach to manufacturing system design is that initially it simplifies the complexity of the problem, in order to make it easier to investigate and understand alternative solutions. Furthermore it provides a structured method of introducing and evaluating additional design detail and therefore complexity. Therefore to support and fully realize these advantages, the execution and evaluation of all models at each level of design must be efficient. It as has already be established (section 7.1.6) that overall current manufacturing simulators are only relevant for detailed system analysis because of their slow model execution. This is partially due to the generality of the simulators which, having been designed to accommodate a wide range of alternative features undertake, for a specific application, a lot of "redundant" checking to determine parameter settings. More appropriately, however, slow execution can be attributed to a simulator's "view" of a manufacturing system, which is often very detailed, with every machine, operator, etc., defined explicitly. This produces a very accurate system evaluation, though relatively slowly. Whereas a more aggregated view of manufacturing would execute more quickly, though, having fewer resources and containing less detail, it would not be as accurate. Each of these alternative approaches are relevant, but at different stages of design. Consequently manufacturing systems have to be viewed conceptually very differently at each level of investigation, to ensure that the corresponding models are efficient, with the three lower level representations being coherent and hence allowing combined multi-level modelling.

8.2 Multi-level Representation

Having identified the relevance of a multi-level approach to the design of manufacturing systems, the question remains as to what exactly is being represented and investigated at the various levels of aggregation. Fundamentally a manufacturing system simply comprises a number of operations through which material components pass, with all operations being performed at a specific machine or work station. Multi-level modelling therefore relates to the level of detail to which manufacturing operations are represented, and the appropriate description of corresponding work areas. Whilst all other elements of a system (e.g. transport, operators, tools, etc.) merely support the basic manufacturing operation, where necessary and are therefore not always relevant.

Theoretically a manufacturing system incorporates a number of individual work centre "islands", where operations take place and which contain a specific number of discrete work stations, all capable of undertaking exactly the same jobs. These "islands" are then linked together by material components visiting the appropriate ones and possibly being moved by some form of transport mechanism, although this is not a prerequisite. Multi-level modelling therefore is concerned with how precisely the processing capacity of all work centres is evaluated. This principally translates into how accurately the work stations, within a particular work centre, are represented and therefore the necessary detail required to describe individual component operations. Whilst material components and transport devices are only described at one level of accuracy and hence detail, irrespective of work centre representation. Whereas operator, tooling and pallet resources, which have a fixed definition, are not represented at all levels of abstraction. Like transport devices, they are not always relevant to a particular manufacturing system design analysis and therefore are neglected, even when the level of investigation allows them to be considered. Consequently in a multi-level model specific types of resources can only be defined at certain levels of abstraction:

- work centres = defined at all levels of investigation;
- material = defined at all levels of investigation;
- transport = defined at all levels of investigation;
- tooling = defined at CENTRE and STATION levels;
- pallets = defined at CENTRE and STATION levels;
- operators = defined at STATION level;
- work stations = defined explicitly at STATION level;

8.3 Multi-level Evaluation

8.3.1 The Factory

The first-pass stage of design requires a very quick approximate evaluation of relevant system specifications on the basis of minimal data requirements. The investigation focusing entirely on highly aggregated and generalized system designs and therefore does not consider a detailed analysis. The first-pass or factory representation is independent of any lower level investigation. Thus factory evaluation is accomplished through mathematical queuing theory, the most frequently used models being those based on CAN-Q [Solberg 1976 and 1977].

CAN-Q (Computer Analysis of Networks of Queues) represents a manufacturing system in terms of work centres, which comprise one or more work stations or machines, all connected by a transport mechanism. The evaluation technique is based upon closed-loop queuing network theory and as a result system models are specified containing a constant number of parts. Conceptually this can be viewed as the same set of parts continually re-circulating or the introduction of a new part immediately the processing of an existing one is completed (figure 8.3). The full input and outputs of the model are as shown in figure 4.9.

The full mathematical derivation of CAN-Q is developed by Solberg [1977] and summarized below.

Let M represent the number of work stations plus the material handling devices which exist in a particular manufacturing system, where the M^{th} station denotes the transport facility. Let n_k represent the number of parts at station k. Hence the "state" of the system, at a given time is indicated by $\bar{n} = (n_1, n_2, \ldots, n_M)$, whilst the total number of parts is represented by $N = (n_1 + n_2 + \ldots + n_M)$.

For station k the average utilization per server is u_k/s_k, where s_k denotes the number of servers at station k, whilst u_k denotes the average number of busy servers at station k. If $1/W_k$ is the average processing time at station k, then the output rate is $W_k u_k$. Whilst for the transport facility the rate is $W_M u_M$. If q_k denotes the probability that the transport facility will deliver a part to station k, then the input rate for the station is $q_k W_M u_M$.

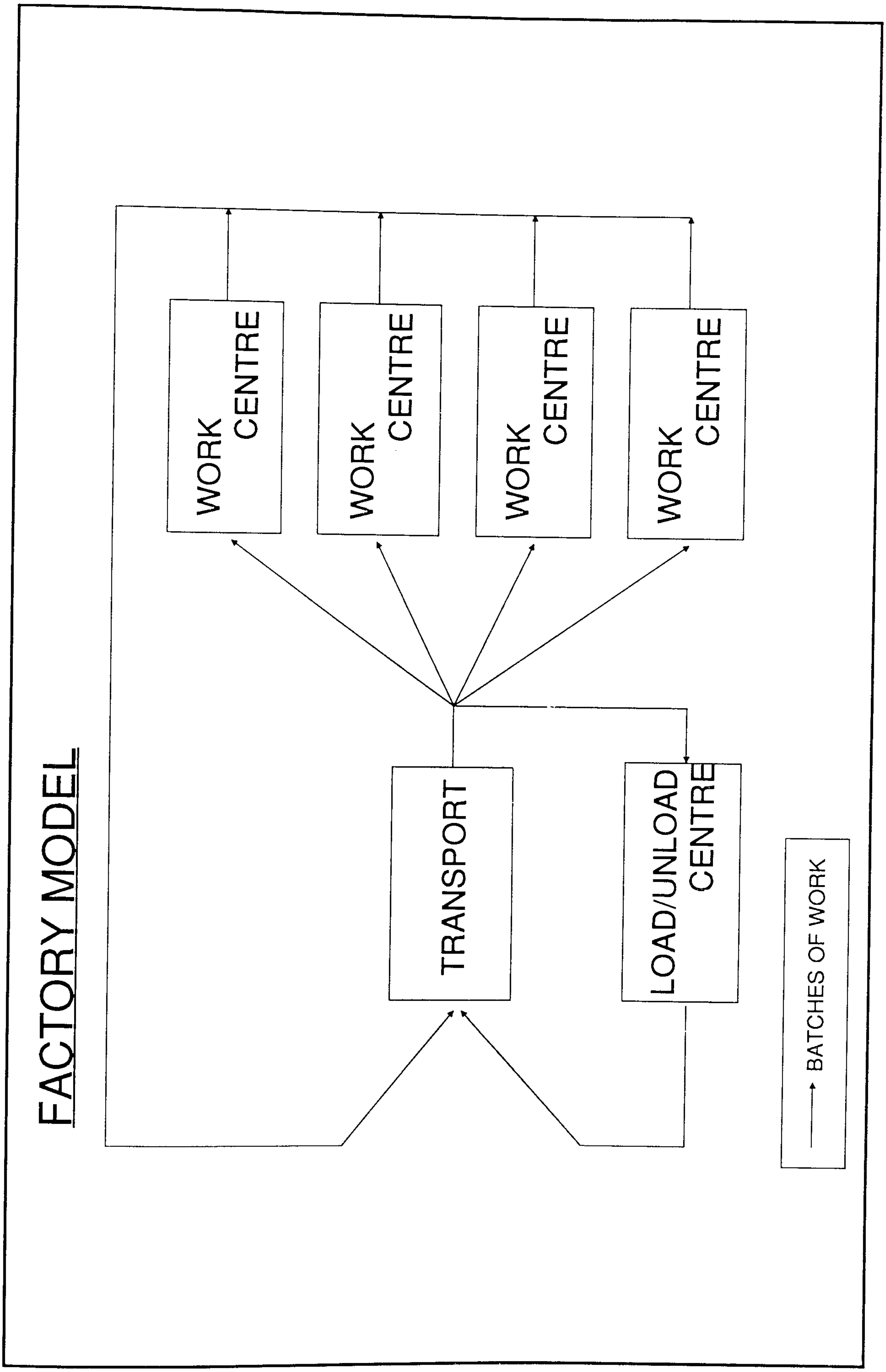


Figure 8.3 Factory Representation (After Solberg)

Hence

$$q_k W_M u_M = W_k u_k$$

or

$$u_k = \frac{(q_k W_M)}{W_k} u_M = r_k u_M$$

where

$$r_k = \frac{q_k W_M}{W_k}$$

For a single server work centre, Gordon and Newell [1967] have shown that the steady-state probability for a system being in state n is:

$$P(n) = \frac{1}{G(M,N)} r_1^{n_1} r_2^{n_2} \ldots r_m^{n_m}$$

where the normalizing constant $G(M,N)$ is such that all the P(n) can be summed to one.

Hence

$$G(M,N) = \sum_n r_1^{n_1} r_2^{n_2} \ldots r_m^{n_m}; \qquad \sum_{k=1}^{m} n_k = n$$

A recursion relation can then be derived [Solberg, 1977]:

$$G(m,n) = G(m-1,n) + r_m G(m,n-1).$$

For multi-server stations, $r_k^{n_m}$ is replaced by:

$$\frac{r_k^{n_k}}{A_k(n_k)}; \qquad \text{where } A_k(n_k) = n_k! \quad \text{for } n_k \leq s_k$$
$$\text{and } A_k(n_k) = S_k^{(n_k-s_k)} S_k! \quad \text{for } n_k > s_k$$

and the recursion relation is modified to:

$$G(m,n) = \sum_{k=0}^{n} \frac{r_m^{k}}{A_m(k)} G(m-1,n-k).$$

Buzen's recursive formula [1973] is used to compute the normalizing constant $G(M,N)$. Once $G(M,N)$ is determined, it has been shown [Solberg, 1977] that:

$$u_M = G(M,N-1)/G(M,N)$$

Furthermore

$$P = q_M u_M [G(M,N-1)/G(M,N)]$$

where P = the system's average production rate, and average flow time can be computed using Little's formula, i.e. $T = N/P$.

The principal advantages of CAN-Q are its ease and speed of use, together with the simple data requirements and disregard for any detailed knowledge of system interactions. Whereas the disadvantages mainly coincide with its inherent assumptions. The basic characteristics of the CAN-Q analysis include:

- system equilibrium assumed, evaluation is not time phased;
- only long-term average results, assumes system equilibrium;
- work centres assumed to have unlimited buffer storage, so blocking never occurs;
- probability routing, calculated from the frequency of individual work centre visits;
- an averaged, exponential work centre operation time;
- constant number of parts in the system;
- averaged transport time;
- does not consider assembly operations; and
- no consideration of control systems.

8.3.2 The Department

The department evaluation or rough-cut design, like the factory model retains a relatively simplistic view of work centres, with no discrete representation of the individual machines of which they are composed. Though highly aggregated, this stage of design does consider discrete batches of work along with a more detailed analysis of individual operations. Hence there is a significant increase in data requirements from the previous stage of design (figure 8.4), and contributes to a more accurate system evaluation. This produces more precise, medium to long term performance results for the overall system, than the corresponding factory model. The trade-off being a slightly slower evaluation process, though because of the previous analysis stage there are fewer design alternatives to consider and therefore there is less emphasis on speed of evaluation.

The most significant requirement for this stage of design is that it should be comparable with the two lower levels of abstraction. The nature of the evaluation process at this stage has to coincide with that at the micro-level, which is a highly meticulous and explicit analysis of all aspects of a manufacturing system's dynamic behaviour. Hence the department evaluation has to be time phased and therefore mathematical models are inappropriate.

Southern [1986a; 1986b] presented a methodology which predicted both the performance of a manufacturing system and completion of discrete work batches, from a simplistic model, designed for low cost evaluation. The overall aim being to simplify the manufacturing system complexity in order that an iterative approach to simulation could be adopted on small

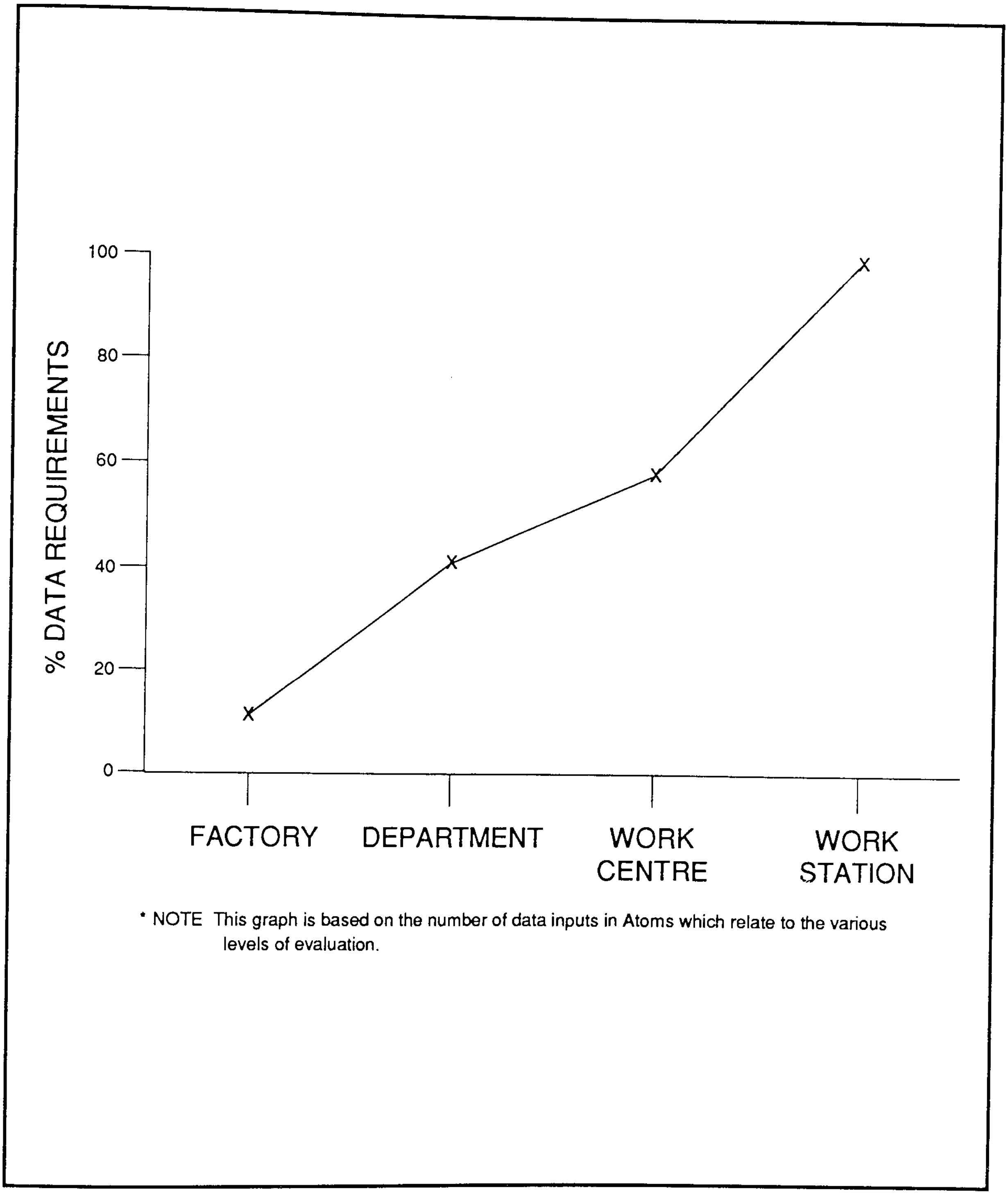


Figure 8.4 Multi-Level Modelling Requirements

micro-computers.

The evaluation process analysed the manufacturing performance of a system over a standard period, generally a week. The week was divided up equally into sequential time periods, and all similar machines were treated as a single resource. Work therefore being processed simultaneously on all alike machines. The machine groups are identified either on a traditional process-type basis or through group technology techniques [Burbidge, 1979]. Then for each time interval, all machine groups are loaded up to one job over the capacity limit for that period. To verify the approach Southern [1986b] compared the results from the computer simulation model, with those from a real-time, real-life manual simulation of a factory's performance. The exercise demonstrated that of all the batches predicted to be completed by the computer model, 84% were correct, this rising to 92% for high priority batches. The model therefore, as Southern says:

> ".. gave good predictions of job completions for planning and control purposes."

The department representation of a manufacturing system therefore corresponds to Southern's concept, in that work centres are envisaged as one resource, with the capacity equal to the sum of the machines of which it is composed. However, in order to be comparable with lower levels of abstraction, the finite time-phasing is ignored for the more realistic continuous representation of time, that is generally adopted in discrete simulation models. No consideration is given to any additional types of resources, other than those evaluated in the previous stage. The analysis process simply comprises of discrete work batches being passed to an appropriate work centre queue or buffer to await processing, before moving on to an other work centre for the next operation or to the stores as a completed job (figure 8.5). The only other resources therefore to be considered, besides work batches are work centres, having a certain availability pattern associated with them, and transport devices, which are assumed to be available at all times. The full inputs and outputs of the model are shown in figure 4.10.

The main advantages of this approach include a more realistic representation of manufacturing operations than that provided by mathematical models, as consideration is given to individual work batches. Whilst at the same time providing a far simpler description of activities than those usually defined in discrete simulation models. It is relatively quick and easy to develop an appropriate rough-cut manufacturing model, and the evaluation process is faster than normal system simulators. The evaluation provides medium to long term performance results which are both time phased and take into account the system's dynamic behaviour. In addition the analysis process can consider assembly operations, explicit routes, shift patterns, machine blocking (caused by downsteam queues being full and unable to accept work from upstream operations, the work therefore having to remain on the machine until space becomes available in the queue) and production planning techniques such as material requirements planning (MRP) and kanban.

The disadvantages generally relate to the way in which work centres are visualized and include:

- all machines are unique to specific work centres;
- all machines in a particular work centre are

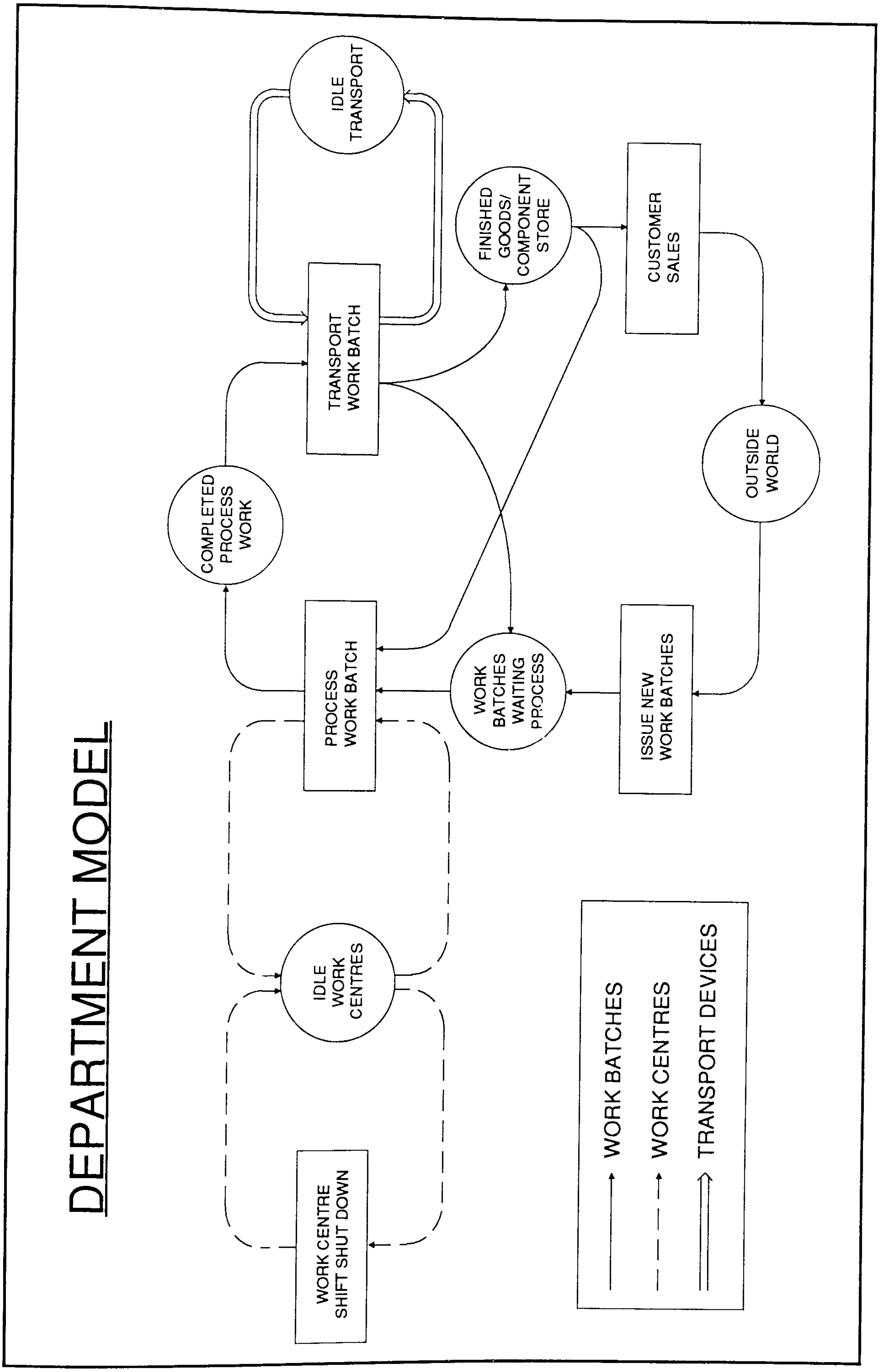


Figure 8.5 Department Representation

identical;

- irrespective of how many machines are allocated to a work centre, each centre is represented by only one machine, which has a capacity equal to the total number of machines within the centre;
- each job is in effect simultaneously processed on all machine within a work centre;
- the evaluation tends to over estimate the maximum number of batches queuing at a work centre because only one job can be processed at a time, whereas in reality each machine may be working on a different batch;
- the completion time for a batch is generally quicker than that actually realized, as conceptually all work is simultaneously loaded on to all similar machines;
- evaluation only provides medium to long term results because of the simultaneous loading of machines;
- evaluation does not take in account additional resource limitations such as tooling, pallets and operators;
- evaluation does not take into account operation interruptions like machine breakdowns; and
- very little consideration is given to control systems, every queue being sequenced on a first come first served (FCFS) basis.

8.3.3 The Work Centre

The work centre representation is primarily concerned with the accuracy of evaluation rather than the speed. At this level of consideration there is only a relatively small number of appropriate design specifications left. Therefore a more thorough and detailed analysis can be undertaken, although not being the most comprehensive evaluation of manufacturing activities, the macro-level design does consider individual machines in order to assess the work centre's appropriate operating capacity. At this level of evaluation consideration can be given to the precise control of manufacturing operations, in terms of work scheduling and selection procedures. However, the work centre abstraction does include some degree of aggregation with respect to the detail to which manufacturing processes are replicated and the neglection of both discrete operators and equipment breakdowns. The effects of such factors on a machines production or output rate only being considered in the form of fixed percentage functions. These being equivalent to the RATES of flow in a system dynamics model, which alter the LEVELS or state of a system and are set by particular process variables [Roberts 1978]. Hence a macro-level analysis provides medium term performance results which focus on the operation of individual work centres.

Parker et al [1986] presented a simple manufacturing model which allowed production foremen and managers to understand the inherent complexity of interactions within a factory. The model considered the constraints imposed by the availability of people, material and machines. Although a simplistic representation, the model incorporated sufficient validity to provide adequate awareness of the factors that could be controlled within a manufacturing system, whilst the simplicity of the model allowed users to quickly assimilate and understand its principles.

The model, called Alterfax, was based on continuous simulation techniques and emulated the manufacturing activities of individual machine groups in a very straight forward manner. The production or output rate for each group, in a specific time period, related to the minimum of available material, labour, and machine capacity. Each being calculated from certain system variables with the minimum value representing a groups maximum possible output and therefore called "total production". Material availability was simply affected by raw material and work in progress levels, whilst labour capacity was calculated on the number of workers, their labour efficiency, miscellaneous labour losses, average available hours and standard minutes per 100 units. Machine capacity was based on number of machines, average available machine hours, number of shifts, machine downtime and machine cycle time. A major restriction of the model though was that each machine group only processed one component and all individual machines and operators were unique to a specific grouping, thus significantly simplifying the manufacturing problem. Furthermore no discrete batches of work were considered, instead production was represented as a continuous process.

The work centre representation therefore applies Parker et al's conceptual view of manufacturing operations to individual machines within a discrete model, thus maintaining the compatibility with other levels of analysis. The discrete implementation of the model implying that the output rate calculations are simplified, for material availability no longer has to be determined because the system can represent individual work batches. The machine and labour capacity calculations are reduced. Machine capacity is based on machine downtime, machine performance and standard processing times, whereas labour capacity relates to labour efficiency, miscellaneous labour losses and standard processing times. This is a direct result of considering individual machines, assuming one operator per machine, having explicit shift patterns and performing the calculation for every manufacturing operation.

The evaluation process has not significantly changed from that defined for the previous level of abstraction, except for the additional consideration of tooling and pallet resources (figure 8.6). However, the actual "process work" calculations have changed, together with the ordering and selection of work in the "waiting process" queue. Previously this queue was simply ordered on a first in first out (FIFO) basis, but now a range of algorithms are available to determine the queuing priority at individual work centres. Consideration is also given to the selection of work from the queues, taking into account such things as minimum set up quantities, reduced number of set ups and the splitting of work batches into transfer quantities. The full inputs and outputs of the model are shown in figure 4.11.

The main advantages of the macro-level include the consideration of individual machines and the specification of control systems, hence providing a more precise and realistic representation of particular work centres. As a result of

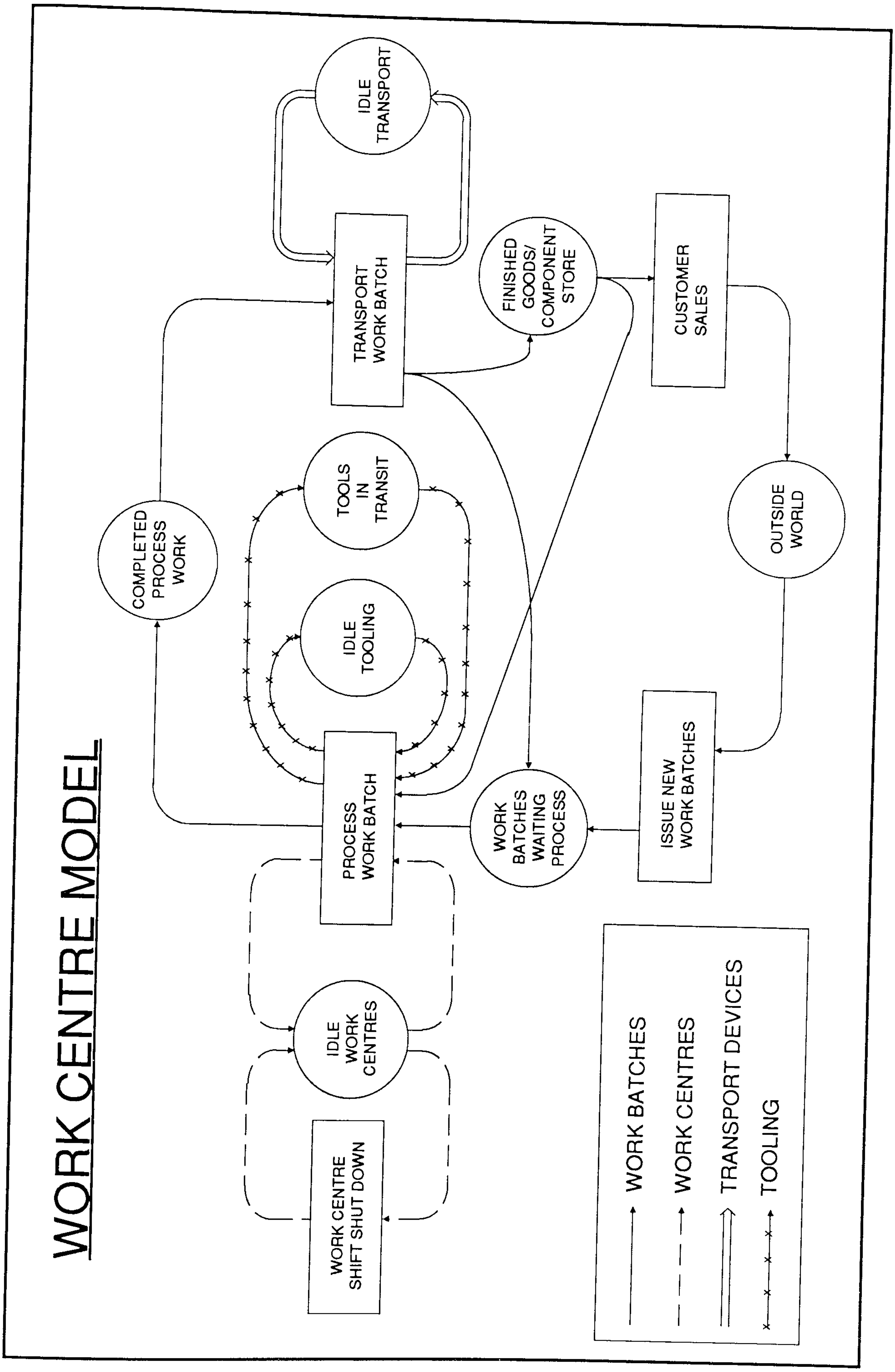


Figure 8.6 Work Centre Representation

discrete machine analysis, far more accurate assessment can be made of both the expected WIP levels and the exact completion time of individual work batches. However, this is still achieved in a simpler, aggregated form than that generally adopted in discrete simulation models. Even so the effects of operator and machine capacity limitations can be considered. The evaluation process is quicker than a micro-level implementation and provides medium term, time phased results. In addition to the considerations of previous levels of analysis, work centre modelling can include tooling resources, work scheduling and selection algorithms, specification of transfer batches and the representation of OPT [Jacobs, 1984] planning techniques.

The disadvantages generally relate to the conceptual view of machines, and include:

- all machines are unique to specific work centres;
- all machines in a particular work centre are identical;
- one operator per machine implicitly assumed;
- evaluation only provides medium to long term results because of the abstract representation of manufacturing operations and machines;
- evaluation does not include discrete operators;
- discrete interruptions, like machine breakdowns cannot be addressed;
- maximum work centre queue sizes are not accurately predicted because no discrete interruptions occur, i.e. production never stops, although it may possibly run at a slower rate;
- no alternative component routes.

8.3.4 The Work Station

The micro-level design stage or work station representation is intended to be the most comprehensive and meticulous evaluation of the behaviour and performance of a manufacturing system required by a system designer. At this stage of design only one or two alternative system specifications remain. Furthermore it is here that final, detailed consideration is given to the preferred design specification which will be proposed for implementation. Hence speed of evaluation is no longer the main consideration, it is the accuracy and reliability of the results that is important. Thus the evaluation process is a very precise short term analysis of all the major activities and operations which affect the processing capacity of a manufacturing system. Consequently this evaluation is equivalent to the explicit nature of the simulators discussed in chapter seven. Therefore work station modelling incorporates the most detailed logical and functional representation of a manufacturing system of all four of the proposed levels of evaluation.

The work station analysis corresponds to the most exacting application of discrete manufacturing simulation techniques and coincides with the most commonly adopted approach to the dynamic evaluation of such systems. All production capacity limitations are explicitly defined, including operators, tooling and equipment breakdowns, together with a precise step-by-step emulation of the exact stages involved in a manufacturing operation.

The evaluation process therefore is very complex with the "process work" activity, defined in the two previous levels of abstraction, being replaced by a series of five discrete activities (figure 8.7). These start with "set up machine" which brings together all the resources necessary to undertake a particular operation, such as machines, operators, tools and assembly components, and prepares the machine for the intended operation. Next "load waiting work" places the batch of work on the machine in order that the manufacturing process can start, "start processing work". On completion of the operation, "finish work processing" the machine is ready for the work batch to be unloaded, "unload work" and moved, by way of a transport device to the next work centre or finished goods store. After being unloaded the machine, tools and operators become available to undertake another operation. At this level of evaluation machines are assumed to be available at all times, 24 hours a day, except when processing a job or having broken down and thus are represented similarly to transport resources. However, the operators have finite availability. Furthermore it is assumed that after all activities, except "start processing work" and "start transporting work" the operator becomes idle and therefore available to undertake another activity. Although priority is initially given to the next activity that a particular batch of work is moving on to.

In figure 8.7 it is noticeable that the processing and transporting work operations have been split into start and finish events. This is in order to accommodate the breakdown of machines (figure 8.8) and transport (figure 8.9) resources. Again these activities are ones which operators participate in. Hence the control system, in addition to providing work scheduling and selection algorithms, caters for the control over the allocation and prioritization of individual operators

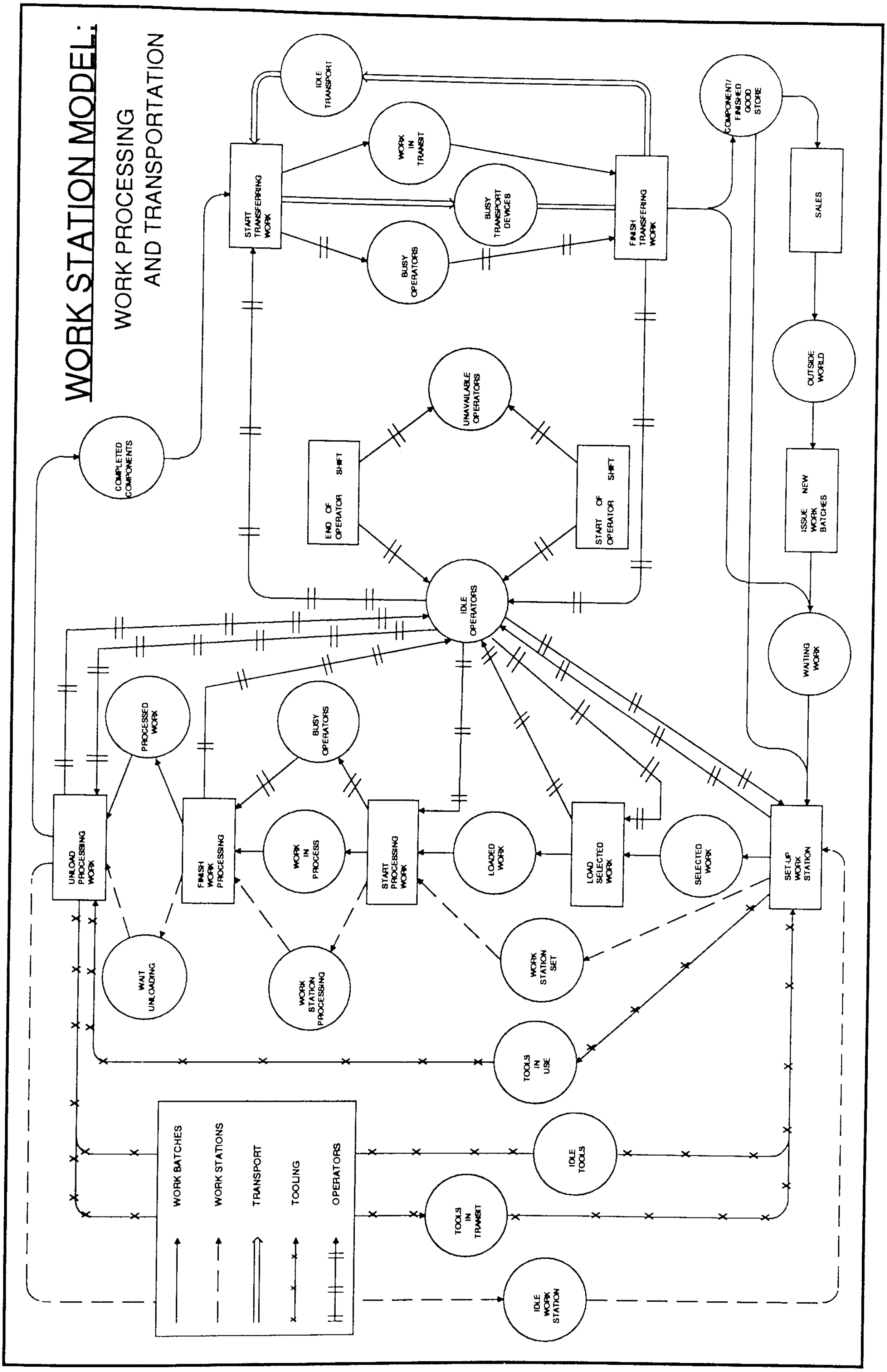


Figure 8.7 Work Station Representation (a)

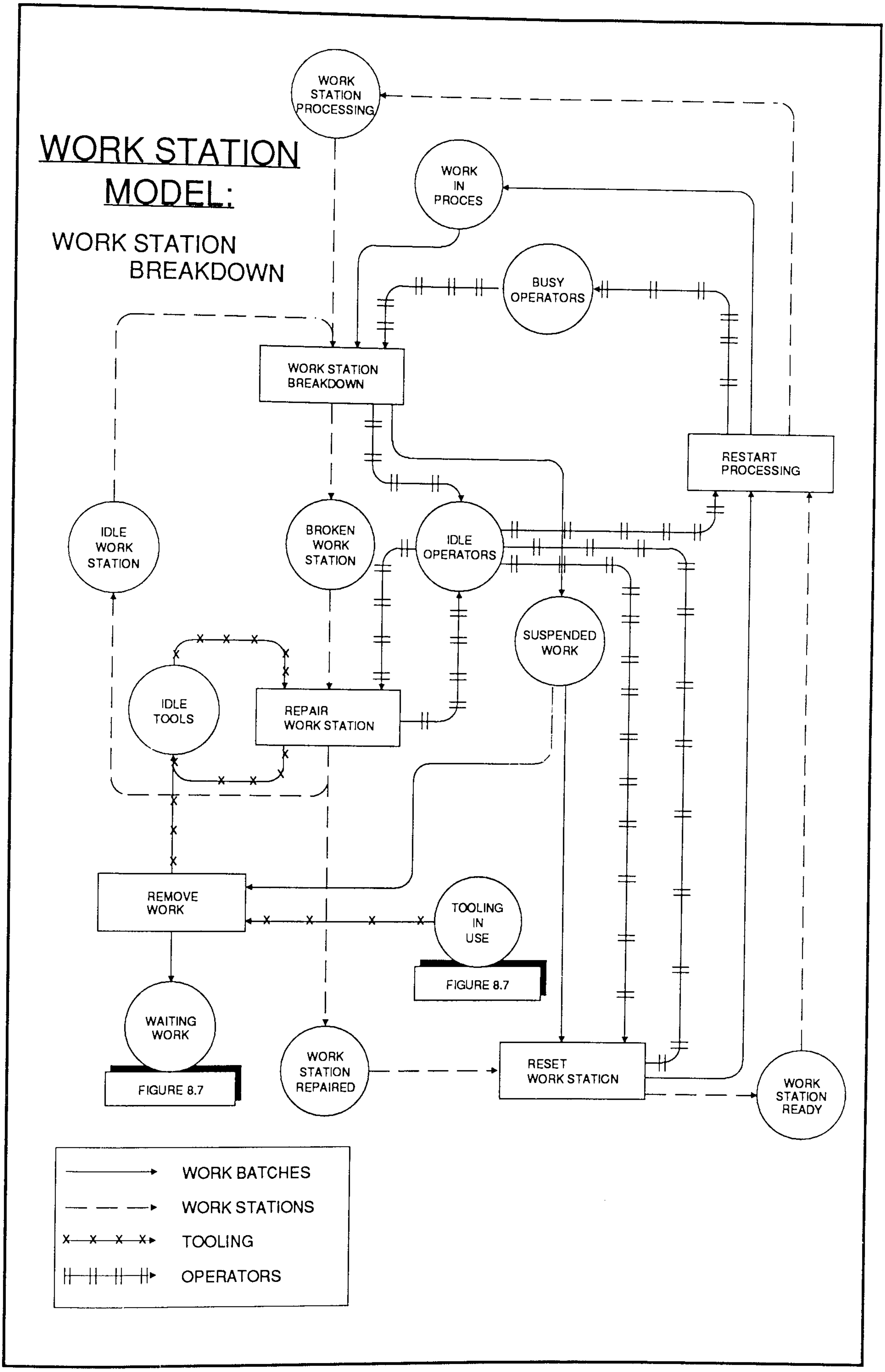


Figure 8.8 Work Station Representation (b)

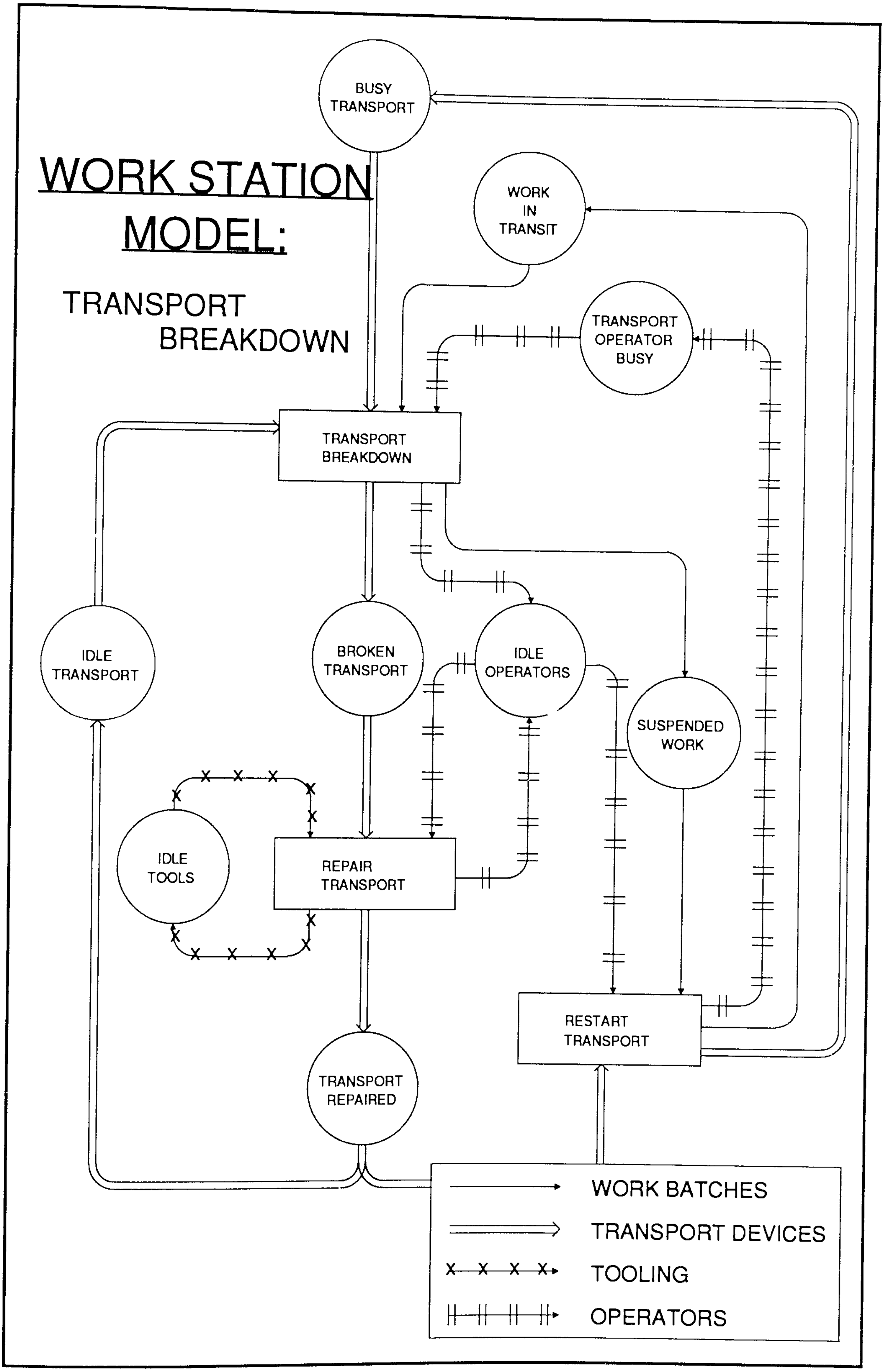


Figure 8.9 Work Station Representation (c)

and their jobs, respectively. The full inputs and outputs of the model are shown in figure 4.12.

The overwhelming advantage of the work station representation is in providing a meticulous and comprehensive evaluation of manufacturing system activities, with very few inherent assumptions. This produces short term, reliable performance measures. However, the data requirements are the most substantial of all levels of abstraction (figure 8.4). Individual machines are considered independently of any work centre descriptions, thus allowing the true production capacity of a system to be determined, as machines are no longer unique to specific centres. Instead work centres are now simply conceptual groupings of machines with similar capabilities, as individual machines can be members of more than one classification. This allows the specification of alternative machine routes for particular operations. The full accuracy of this level of evaluation comes from the implementation of such capabilities as:

- machines represented independently of work centres;
- specification of alternative machines;
- evaluation of discrete equipment breakdowns;
- evaluation of discrete operators;
- specification of the precise stages of a manufacturing operation;
- allocation of operators for all or part of a manufacturing operation;
- specification of alternative operators.

All of which are in addition to the capabilities specified by the previous levels of abstraction.

The disadvantages revolve around the detailed analysis of manufacturing operations and include:

- slow model evaluation;
- very significant data requirements;
- results are very complex and difficult to interpret, because of the range of system interactions which are considered.

8.4 Computer Implementation

8.4.1 The Correct Development Tool

The simplest and most obvious approach to implementing a computer manufacturing simulator has, without question, to be through the use of either a general purpose simulation package or symbolic modeller. Such packages provide a range of very useful and appropriate pre-defined routines which generally simplify the development of a computer simulation model. Furthermore most systems allow the linking in of code written in high level languages such as FORTRAN. However, there are significant problems and restrictions associated with the use of simulation packages which limit or diminish there usefulness.

The major disadvantage of using a special simulation package to develop a manufacturing simulator is that the resulting model cannot be used independently of the system from which it evolved. This means that to simply execute a particular model the simulation package or a run-time version is necessary which is generally very expensive to buy, entails the purchase of a user licence and often requires a non-standard computer hardware configuration in order to run. In addition the requirement for run-time software to execute a pre-developed model, is a significant overhead which restricts the available computer memory, therefore severely limiting the maximum size of manufacturing system that can be accommodated. Though some systems use virtual memory or the spooling of data to disk to overcome this constraint. Furthermore, a simulation package inevitably imposes certain restrictions on how and in what form a model is developed. Many packages provide only one approach to developing a discrete computer simulation model (i.e. event, activity or process) and also confine a user to a specific high level language, generally FORTRAN. However, FORTRAN does have some significant limitations in comparison to structured high level languages such as Pascal and C. The main advantages of using Pascal instead of FORTRAN are program clarity and flexibility. Unfortunately FORTRAN is not an ideal environment for the development of computer simulation models because, as highlighted by Quandt [1984] and Jennergren [1984], of its bottom-up design approach and lack of dynamic record variables.

Simulation languages and symbolic modellers provide a very effective and highly flexible general purpose modelling environment in which to develop specific system models. However, such packages are highly inappropriate to implement generic model simulators which, although resembling specific models, exhibit an inherent flexibility and therefore capability to represent a variety of different system configurations. Consequently generic simulators are significantly more difficult and complex to develop, requiring a high degree of functionality, whilst potentially being both relevant and applicable to a broad range of issues and situations. The effectiveness of developing a manufacturing simulator in a simulation language or symbolic modeller is questionable in terms of:

- the availability and cost of the resulting simulator. Owing to the interpretive nature of a lot of simulation packages, the simulator may not be able to run stand alone;
- being confined to a specific simulation approach for the development of a simulator, which may be insufficient or inappropriate;
- being restricted to only one programming language (e.g. FORTRAN) and/or unable to use new programming techniques (e.g. object-oriented programming).

High level languages, however, though not the easiest approach to developing a simulator, do allow for preferences and provide the appropriate flexibility to create both a relevant and practical generic manufacturing simulator.

8.4.2 High Level Language Implementation

High level languages provide the best approach to implementing a manufacturing simulator. They produce models which generally require no additional software or special hardware in order to run and do not impose any particular modelling approach. There are in affect three principal languages which could be utilized, FORTRAN, Pascal and C, though FORTRAN, as previously stated is not a viable alternative. Pascal (as typified by Borland International's Turbo Pascal), unlike FORTRAN does not restrict variable and subroutine names to only six letters. Instead it allows up to 256 characters, with both upper and lower case letters available. Names therefore tend to describe the function to which it is applied. Also the language encourages line indentation to show the limits of a logical block of code, whereas FORTRAN languages tend to consider indentation as a syntax error. Well-written Pascal programs are self-documenting and easy to read.

Pascal is also a more flexible language than FORTRAN. As the latter requires all data structures to be declared before program compilation. Memory space has to be allocated before program execution, whereas Pascal provides dynamic variables which allow programs to allocate memory storage at execution time, thus utilizing memory more efficiently. Furthermore Pascal is more appropriate for computer simulation because of its record type declaration. This is composed of fields which do not have to be of the same type e.g. real, integer and boolean. A further benefit of the highly structured nature of Pascal is that its programs tend to run between 25% and 50% faster than comparable FORTRAN code [Quandt 1984]. Hence the choice is really only between Pascal and C.

C provides all of the features that Pascal does, but in addition gives more freedom and power to programmers. C allows users to program on a variety of levels. This could be as detailed as machine code or on a par with FORTRAN. C lacks forced declarations and permits programmers to produce code that is both cryptic and difficult to understands and as Miller et al [1984] says:

> ".. gives them all the rope they need to tie themselves into knots."

Consequently, because of its inherent rigidity which keeps users out of trouble, Pascal is the most appropriate and practical approach to developing a manufacturing simulator prototype. Pascal allowing attention to focus on the functionality and structure of the system and not on its computer implementation.

Chapter 9 ATOMS: A Manufacturing Simulator.

To investigate the capability of a hierarchical modelling and evaluation procedure to provide an effective mechanism to monitor and control the design of manufacturing systems, the proposed multi-level modelling strategy (section 4.4) was incorporated within a tactical and operation manufacturing simulation (ATOMS) model, developed by the Author. In addition ATOMS was produced to demonstrate that a model simulator could contain sufficient inherent flexibility so as to be generally applicable to a wide range of typical discrete batch manufacturing systems. Hence ATOMS is based upon the modelling logic and functionality necessary for a generic multi-level manufacturing simulator, as described in chapter eight. However, the system is not intended to be "another" tool for simulation specialists. Instead it is targeted at manufacturing system engineers who need to use computer simulation techniques to help solve particularly complex and abstract problems, but whose proficiency and main responsibilities lie else where. ATOMS allows inexperienced users, to undertake simulation exercises. Use of the simulator does not require learning special purpose computer languages or general model building principles, as models are described in normal engineering terminology, such as machines, part numbers, operator, work centres, etc. Through the use of English prompts the models are self-documenting, with specifications entered via a pro forma during a "question and answers" session, controlled by the system. The sessions are therefore efficient, with only those questions relevant to a particular specification, being asked. Sessions can at any time be stopped and restarted at a later date, or previous questions can be backtracked. Hence there are full data editing facilities and inputs can be saved to disk for future simulation exercises or further amendments. Consequently the process of simulation is totally transparent to a user, with output reports automatically generated.

9.1 The Modelling Environment

9.1.1 Hardware Requirements

ATOMS, written in Turbo Pascal supplied by Borland International, runs on an IBM PC-XT, PC-AT, PS/2 and compatible computers, requiring at least 512k of random access memory (RAM). The system operates under MS or PC Dos version 3.2 or above and requires 700k of disk memory, whilst specific model files, on average occupy between 200k and 500k of disk memory. ATOMS can either be used from a high density diskette or a hard disk. A simple mono text screen is required to run the package, although a colour monitor makes the system easier to use. The programs will run either with or without a maths co-processor and all inputs are entered through by the keyboard.

9.1.2 Software Configuration

The structure of the ATOMS manufacturing simulator package is summarized in figure 9.1. The system is comprised of seven main subsections called: Manual Model Input, Automatic Model Input, Work-In-Progress Input, View Existing Model, Mathematical Model, Simulation Model and File Manager (all detailed in the user documentation in Appendix C). All subsections, except for Automatic Model Input are divided into subroutines. The system is totally menu driven, with options

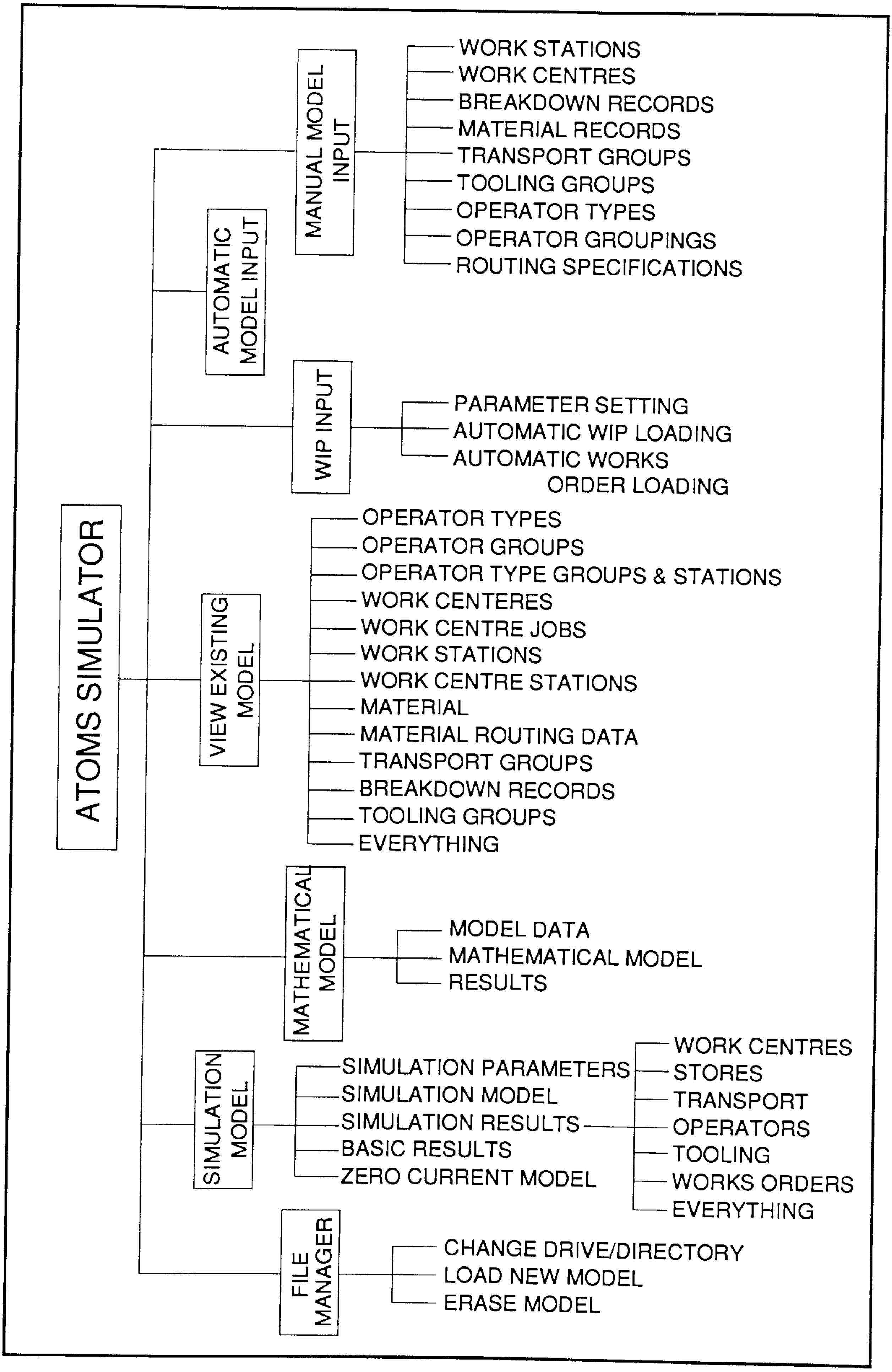


Figure 9.1 ATOMS Simulator - Menu Structure

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19 April 1990          8:21 am          Model          Version


                    1.  Input Model Data
                    2.  Automatically Build A Model
                    3.  Add Work-In-Progress
                    4.  View An Existing Model
                    5.  Run Mathematical Model
                    6.  Run Simulation Model
                    7.  File Manager

                    0.  Quit ATOMS [F2 = Save]


Memory Available (in bytes) 164719                    Select
Action : \
================================================================
```

Figure 9.2 ATOMS Main Menu

being selected either by the appropriately highlighted number or letter or by moving a bar selector to the relevant choice and pressing return.

A standard screen format is used throughout ATOMS (figure 9.2). This comprises of upper and lower screen margins with a main work area in between. The upper margin shows the current date and time along with the name of the model being worked on and its version number. The lower margin displays all user inputs, whether they be in response to data requests or menu options, in addition to informing the user of how much RAM is available and his current location within the system. Whilst the main work area lists all operational information including menus, data input requirements and both simulation and mathematical run-time results.

All model data inputs fall into one of two categories; those which require a numerical response, or have only a limited range of alternatives. For instance the modelling level of work centres can only be department, centre or station. So that the user does not have to remember the alternative responses, the system will toggle through the options when the space-bar is pressed. The selection of the appropriate option is then simply made by stopping at the relevant one and pressing return.

9.1.3 System Subsections

The first subsection of ATOMS is the manual model input. This allows the input and editing of all data necessary to describe and construct a coherent computer model for evaluation. The required data are entered, in an interactive mode, in response to the "questions" or messages displayed in the main work area of the computer screen. The principal function of this section is to provide the user with a simple and friendly approach to adding new data and modifying and/or deleting previous inputs. The input routines control data entry thereby making the process very efficient by only requesting information relevant to a particular model specification. Furthermore the editor checks all inputs in order to isolate data errors and therefore prevent the specification of inconsistent models. Hence this suite of routines enhances the manipulation and usability of the manufacturing simulator by providing a user friendly interface to the model database.

The automatic model input option further simplifies and expedites the process of describing a computer model. This subsection reads in ASCII formatted text files which describe the underlying structure of a manufacturing model. The generated model can then be enhanced by the addition of more detailed information manually entered via the previous subsection. The automatic model input supports an outlined definition of work stations, work centres, material components, operators and component operations, such that a manufacturing model, comprising of approximately 2600 operations, 240 part numbers and 40 work centres can be generated in a matter of minutes (section 12.3.1). Furthermore it incorporates full error checking to prevent the incoherent specification of a particular model. This section therefore significantly reduces the laborious task of typing in the description of a large manufacturing system, by providing a convenient and automated link to external information sources, such as a mainframe engineering database.

The third subsection is the work-in-progress (WIP) input which allows the specification of the initial starting conditions of a computer model. This is in regard to work initially queuing at specific work centres to be processed and the issue or release of future works orders. Once again there are error checking routines. Generally therefore, in addition to improving the usability of the simulator this section increases its validity.

The "view an existing model" subsection provides a summary of all resources and operations previously defined. This section works in conjunction with the manual model input routines. The manual input routines require the identification of resources in order to add new or modify existing descriptions or specify logical relationships between various types, but does not help by listing those which have already been defined. Furthermore the view routines can provide a permanent record of the complete specification of a model via either a computer printout or an ASCII text file.

The fifth subsection is the mathematical model which controls the queuing theory based manufacturing system evaluation. The routines within this section obtain the necessary description of a mathematical model automatically from the simulation specification within the internal database, re-configuring it into an appropriate format. Furthermore it controls the execution of the model and prepares the relevant statistical results, in addition to displaying them in an easily understandable form. Although not many, there are some data requirements specific to the mathematical model, and in particular the user can determine whether all or only part of the pre-defined components are to be evaluated, allowing attention to focus precisely on families of similar components.

The simulation model subsection constitutes the main body of the manufacturing simulator containing all the event and executive routines, run-time control parameters and evaluation results. The events depict future state changes in a system. The executive organizes the events in chronological order and therefore selects the next event to occur, in addition to updating the simulation clock and maintaining the status information regarding the the model. ATOMS uses 34 events to full describe the dynamic behaviour of a manufacturing system and these are defined in section 9.5. The system automatically collects certain statistical data on the operation of the model, however, addition information can be requested. An event log can be produced, either to disk or line printer, which traces a simulation run one event at a time. Thus helping to determine a models validity. Also hourly snap shots can be taken of work centre queues. Statistical data is collected and processed in order to prepare it for output in the form of tabulated reports. The reports provide a detailed analysis of a particular model and are the basis for decisions regarding the configuration and operation of the corresponding system. The output results are further described in section 9.3.

The final section is the file manager which is to do with the procedures relating to the computer operating system. The file manager allows the default drive and sub-directory to be changed, along with loading a new model from disk and deleting an existing model.

9.2 System Specification

9.2.1 The Flexibility Of A Simulator

The application and flexibility of a simulator is derived from its ability to represent and emulate specific manufacturing operations and methods of material flow control. It is important when developing a simulator, to clearly identify the users to which it is targeted and hence the nature of its application. Consequently careful consideration has to be given as to the types and range of system components that are to be accommodated. System flexibility then corresponds to its capacity to represent different types of elements which, combined together, describe the operational behaviour of a manufacturing system. The major system elements or components include work centres, labour, material, transport and tooling.

In examining the large range of work centres that exist, it is possible to classify the manufacturing operations that they perform and therefore the centres themselves into one of five groups:

- manual operation, where a number of identical parts are simultaneously processed from start to finish before any other work is started;
- index operation, where a number of identical parts are only partially processed when work on other similar components is started;
- process operation, where a number of dissimilar parts are simultaneously processed;
- assembly operation, is similar to the manual one except that the process entails two or more parts combining together to form a new one;
- flowline assembly operation, is similar to the previous one, but it is assumed that all parts are beside a work centre. Consequently if the parts run out the operator has to collect more components from store before the operation can resume.

The choice of one of the above five groups to correspond to a particular operation is significantly helped by the inclusion of additional information within each group, such as:

- minimum set-up quantity (i.e. number of parts required before an operation can start);
- load quantity (i.e. number of parts simultaneously processed);

- transfer quantity;
- process percentage (i.e. the percentage of a batch of work which must be processed).

9.2.2 Modelling Entities

The alternative modelling entities provided in ATOMS (figure 9.3) are summarized in the following subsections.

I. Work Centres

All operations are performed at a particular work centre. A work centre therefore is a group of one or more machines or work stations which can undertake similar operations. Centres contain two queues, one of work waiting to be processed, the other comprising work ready to be moved to the next operation.

```
================================================================
19 April 1990          8:21 am        Model            Version
              Input  : 1.  Work Station
                       2.  Work Centre
                       3.  Breakdown Record
                       4.  Material Record
                       5.  Transport Group
                       6.  Tooling Group
                       7.  Operator Types
                       8.  Operator Groupings
                       9.  Routing Specification

                 Or  : 0.  Quit [F2 = Save]
Memory Available (in bytes) 54859                      Select
Action : \Model Input
================================================================
```

Figure 9.3 ATOMS Manual Model Input Menu

Furthermore they can be represented at any one of three levels of detail (i.e. department, centre and station; see section 8.3). However, regardless of modelling level, the basic information for any work centre includes:

- name;
- type (i.e. manual, index, process, assembly, flowline);
- modelling level (i.e. department, centre, station);
- input queue size, in terms of total batches, parts or process time;
- output queue size, in terms of total batches, parts or process time.

Additional data for particular levels of detail include:

department
- shift patterns, with number of work stations per shift;
- work centre efficiency.

centre
- shift patterns, with number of work stations per shift;
- input queue scheduling algorithms (i.e. FIFO, LIFO, least slack, shortest set-up, schedule);
- job selection algorithms;
- machine breakdown percentage;
- work centre efficiency;
- direct operator losses percentage.

station
- priority list of work stations which constitute a work centre (and must be of the same type);
- input queue scheduling algorithms (i.e. FIFO, LIFO, least slack, shortest set-up, schedule);

- job selection algorithms;

II. Work Stations

A work station is an individual machine or work area which may be subject to discrete breakdowns and which constitute a work centre at the micro-level stage of design. Work Stations are therefore only represented at the lowest level of detail, that is the station modelling level. The data associated with work stations include:

- name;
- type;
- individual breakdown specification;
- operating efficiency;
- priority list of operator types capable of working at this station.

III. Material Components

Material components are the resources which enter a manufacturing system and visit a number of appropriate work centres before leaving. They are therefore represented at all levels of modelling detail. There are two sets of data which relate to material components. There is the basic information such as:

- name;
- purchase lead time;
- attributes (e.g. weight, colour, size, etc.);
- production ordering method (i.e. MRP, kanban, OPT, reorder point and statistical ordering);
- current quantity in finished goods stores.

Then depending on the selected production ordering method, individual batches of components have to be specified, which represent the work passing through the system. The data required for each separate batch includes:

- component name;
- batch quantity;
- launch date;
- due date;
- works order number.

IV. Transport Devices

A transport device represents a resource which moves components from one operation to another. That is from the output queue of one work centre to the input queue of another or, for completed components, to the finished goods store. There are two types of transportation entities either a truck, which is a discrete device with limited availability or conveyor, fixed between two work centres and always available, but with a capacity limitation. They are represented at all levels of modelling. The relevant information includes:

- name;
- type (i.e. discrete, conveyor);
- number of discrete devices or maximum capacity of conveyor;
- average response time;
- travelling speed.

V. Tooling

This refers to cutting tools, jigs, fixtures and pallets and simply represent a limited manufacturing resource, which is available 24 hours a day. Tools are only represented at the work centre and station levels of modelling. The data includes:

- name;
- group quantity.

VI. Operator Types

Operators represent a further limited manufacturing resource, but unlike tooling have a limited time availability. Operators can support various operations including machine set-up, work loading and unloading, job processing, material handling and also the maintenance and/or repair of work stations. Operators are only modelled at the station or micro-level of evaluation. Relevant data requirements include:

- name;
- shift patterns, with the number of operators per shift;
- operator efficiency;
- job priorities (i.e. operation, set-up, repair, material handler).

VII. Operator Groups

The grouping of operator types into one or more job capability classifications, which are specified when needing an operator to perform an activity, allows for alternative operators for individual jobs. As in the case of operator types, this module is only utilized at the detailed, station modelling level. Relevant data requirements include:

- group name;
- priority listing of relevant operator types.

VIII. Breakdown Records

This is the detailed description of work station breakdowns and are individually numbered for reference within a work station definition. There are three types of breakdowns depending on the manner in which they occur. Breakdowns can occur on the basis of elapsed time, work station processing time or work station unit output. Hence this module can represent both random breakdowns and planned maintenance. As work stations are only defined at the micro-level stage, breakdown records are therefore only utilized at that level. Data requirements include:

- record number;
- breakdown type (i.e. simulation time, time producing, units produced);
- mean duration between breakdowns;
- repair time;
- operator maintenance group.

IX. Component Route Specification

All the previous modules represent and describe specific types of resources available in a particular manufacturing system. The route specification, however, defines how all these individual resources interact. Hence for each manufacturing component a route is specified which defines the individual operations, including all necessary resources, through which it must pass before leaving the system. The operational data requirements depend upon the level at which the corresponding work centre is modelled, remembering that all operations are performed at an appropriate work centre. However, there are basic data requirements irrespective of the level of representation and include:

- work centre name;
- set-up time;
- standard/cycle time;
- load quantity;
- transport device (i.e. required to pass work on to the next operation);
- transport time or distance to next operation;
- scrap percentage;
- assembly items (i.e. for assembly and flowline operations only);

Then depending on the work centre level of representation, additional data requirements include:

department	- processing factor;
centre	- minimum set-up quantity;
	- transfer quantity;
	- tooling requirements;
	- start operation check (i.e. to see that the operation finishes before the end of a shift);
	- processing factor;
station	- as for work centre plus
	- operator set-up group;
	- operator process group;

- material handler group;
- load and unload times;
- release process operator between work loading and unloading.

X. Control Systems

There are five alternative control systems available within ATOMS, namely Material Requirements Planning (MRP), Kanban, Optimized Production Technology (OPT), reorder point (or two bin ordering) and statistical ordering, all of which, except for OPT are independent of the level of work centre modelling. (OPT can only be implemented when modelling at the macro and micro-levels because of having to schedule precisely the operations at a particular work centre, section 9.2.2 I). Consequently ATOMS allows either separate (e.g. MRP or kanban) or a combination (e.g. MRP for purchases and kanban work orders) of control systems to be modelled. Furthermore through a standard order input facility (for both works and purchase orders), coupled with the inventory records maintained for all stock items, individual models can be "hooked" up to existing control systems, ranging from a bolt-on control module to a full functional and operational mainframe MRP system. Hence allowing actual production schedules to be used either to assess their feasibility before implementation or as a basis for model validation.

All the above modules concentrate on the specification of a simulation model at any one or a combination of three different levels of detail definition. There is, however, no particular specification of a mathematical model. The factory evaluation considers all work areas in similar detail. The description of work centres at any of the three lower levels of detail contain more than sufficient information for a mathematical model. The data necessary for a mathematical evaluation is automatically retrieved, irrespective of the level of work centre modelling, and re-configured into the appropriate format. This process is transparent to the user.

9.3 Output Reports

ATOMS provides only tabular output reports which, since no graphical representation is available, are very thorough and detailed. There are two different types of reports. One being the rather limited results from the mathematical evaluation which simply state the average system production rate and standard batch lead-time, together with the average utilization and queue size for individual work centres. Whilst the simulation results are far more precise and comprehensive.

Firstly there are the weekly summary results. These can be viewed on the screen, although ATOMS automatically builds-up a weekly record of key system parameters within an ASCII text file, regardless of the length of an evaluation run. The results, relating to the previous weeks evaluation, include: total system work-in-progress, number of released orders, number of completed orders, total incurred processing time, number of completed operations and number of parts sold on time. More detailed and specific reports relate to individual resources, but these can only be obtained between consecutive evaluation runs. The reports detail the state of a system at the end of the previous evaluation, in addition to presenting the statistics relating to that run. The automatically generated reports include:

for each work centre	- total available, setting, operating and blocked times;
	- total good and scrapped production;
	- current, maximum and average queue sizes;
	- maximum and average queue waiting times;
	- current queuing batches.
for each work station	- total setting, operating, down and repair times;
	- total good and scrapped production.
for each component	- number of parts issued, produced, scrapped, sold and un-delivered;
	- current store quantity;
	- average batch lead-time;
	- all outstanding batches.
for each transport	- number of parts transported;
	- total transport time;
	- current, maximum and average queue sizes;
	- maximum and average queue waiting times.
for each tool	- total utilization.
for each operator	- total available, setting, operating, transporting and repair times;
	- current jobs.
for completed batches	- total flow time;
	- total component yield and scrap;
	- total queuing, setting, operating, transport, breakdown and operator

waiting times.

Furthermore there is a user-defined report which collects hourly statistics concerning the size, of up to four work centre queues. In addition to viewing the reports on the screen, either all or selected reports can be sent to a line printer or ASCII text file.

Finally there is an event log which describes every change in system state, the time it occurred and which resources were involved.

9.4 Maximum Model Size

A major advantage of developing ATOMS in Pascal, as apposed to FORTRAN, is the inherent flexibility of the resulting system in terms of the varying model configurations it can accommodate, because of the efficient use of available computer memory (section 7.1.3). Pascal allows the dynamic allocation of memory at run-time, rather than having to declare fixed length arrays, and therefore pre-assign memory, before program compilation, which restricts model size to a specific, pre-determined configuration. Fixed memory allocation sets an upper limit on the total number of particular type (such as machines, part numbers, tooling, etc.) components that can be specified within a simulator, and is independent of how many other type components have been defined.

In contrast ATOMS utilizes computer memory very efficiently, through a combined declaration of a variable record type and an array of records. The system allocates memory, as needed, in accordance with a particular manufacturing model specification. The simulator can accommodate up to 4500 system components, which includes all resource and individual operation descriptions, along with a maximum of 400 work batches. The limiting factor being available RAM. If the computer has 640k of base memory, ATOMS provides 270k for model development. Obviously the more detailed the model or the lower the level of evaluation, the quicker memory is used. However, ATOMS can accommodate vastly varying model configurations, such as 200 part numbers, 30 operations per part and 100 machines or 2000 part numbers, 3 operations per part and 40 machines. There are no specific limits on the number of components of individual types in ATOMS.

9.5 Model Events

The simulator is based on discrete-event techniques, thus simulation time advances from one event to another in chronological order. ATOMS describes the dynamic behaviour of a manufacturing system using 34 different types of event, which are summarized in the following list:

- Start shift; the commencement of either a work centre or operator shift.
- End shift; the completion of either a work centre or operator shift.
- End fixed overtime; finish of an operators compulsory overtime, as apposed to variable overtime which operators do so long as they are not idle.
- Works order; the launch of a new batch of work into the system.

- Purchase order; issue of a purchase order to an external supplier.
- Purchase delivery; arrival of a purchase order.
- Sales order; required delivery of a finished product or component spares.
- Start schedule; commence processing a pre-planned operation.
- Machine set-up; completion of a set-up operation on a work station.
- Loading; completed loading part of a work batch.
- Unloading; finished off-loading part of a work batch.
- Transfer batch; completed processing a transfer quantity of components.
- Transfer batch unloaded; finished off-loading a transfer batch of components from a work station.
- Batch operation complete; completed processing a whole batch of components.
- Complete batch unload; finished off-loading a complete batch of components.
- Transport requested; start transporting a work batch.
- Transport arrived; arrival of a work batch at the next "operation".
- Random breakdown; a random failure of a work station.
- Machine breakdown; failure of a work station whilst in operation.
- Job waiting; removal of a stranded work batch from a broken-down work station.

- Finished repair; the restoration of a work station.
- Machine reset; restart of an operation after a work station has been repaired.

The execution of each event and effects of its occurrence are implemented by corresponding event subroutines under the control of the executive, described in section 9.1.3.

9.6 ATOMS Modelling Validity

In order to establish computer modelling as a practical and effective general purpose manufacturing system design technique, implementation must be quick, easy and efficient, not dependent upon any specialist expertise. Specific application models or simulators, allow users, with no previous practical expertise to utilize computer modelling techniques, by removing responsibility for model logic formulation, programming and verification (section 5.3.6). The three principal stages in the development of a computer model which greatly rely upon computer programming and simulation expertise. A model simulator contains sufficient inherent flexibility to accommodate a pre-defined range of system configurations, through a set of parameterized features.

The simplicity of the simulator approach, however, can only be realised by restricting the generality of the modelling system. Although previous manufacturing simulators have tended to be too restricted, lacking the necessary functionality to be generally applicable to manufacturing systems and instead are only capable of representing a small, unique range of high technology systems. Development of the ATOMS manufacturing simulator therefore had five basic objectives:

flexibility,	scope to be generally applicable to a broad range of manufacturing systems;
efficiency,	models are efficient in both use of memory (RAM) and speed of execution;
accuracy,	appropriate functionality to accurately reflect reality;
usability,	easy to use, both in model generation/ modification and execution;
understandability,	easy to learn system procedures and interpret the results.

Hence to prove that computer modelling techniques are practical and that manufacturing simulators can be valid, it is necessary to demonstrate that ATOMS (and the multi-level modelling principals upon which it is based) is efficient, flexible and accurate. Usability and understandability being intrinsic to model simulators.

Chapter 10 Experimental Objectives.

10.1 The Reasons For Experimentation

The previous chapters have identified and discussed various problems associated with the design of manufacturing systems and in particular have examined the role and application of dynamic computer modelling techniques. As a consequence of deficiencies in the current use of computer simulation in system design a new multi-level modelling procedure has been developed. In order to understand and put into context the objectives of the subsequent experiments into the new modelling approach, the principal issues arising from the earlier discussions will first be reviewed.

The lack of a prescriptive solution to manufacturing system design, coupled with the inter-dependencies and overall complexity of the problem, creates the need for a methodology to monitor and control the formulation of appropriate solutions. In order that the monitoring function is effective, system development has to be continually assessed in direct relation to the design objectives, which are generally specified in terms of overall dynamic performance measures. Otherwise, due to the very nature of the design process, future decisions, such as those associated with control system design, will be based upon previously invalid performance assumptions. Design therefore needs to proceed in stages, with decisions and assumptions being validated before further progress is made, and so significantly reducing the likely occurrence of system errors.

In support of a design methodology one of the most important and valuable tools available is computer simulation, as it provides the only effective means of predicting the overall dynamic behaviour and performance of a manufacturing system. The importance of computer simulation being derived from its ability to represent the various elements which comprise a manufacturing system, together with the interrelationships which simultaneously exist between them. All other design techniques tending to concentrate on only certain aspects of system behaviour, and therefore only achieving local design optimization, which may conflict with the broader, overall performance objectives, to which they give very little, if any consideration.

Consequently a multi-level modelling procedure has been proposed, providing a frame work for continuous system evaluation throughout the course of a design exercise and which can be superimposed over current methodologies. The new modelling approach identifies several stages of evaluation through which designs proceed. Each stage fully assessing and validating those specific decisions and assumptions made during that phase of design, through the use of computer modelling techniques. Furthermore the proposal recognizes the application of appropriate modelling techniques at each stage of evaluation, thereby encouraging investigation into all potential design solutions.

The adoption of computer simulation, like any other techniques, directly relates to the potential benefits to be gained over the cost of implementation. The main approaches to computer simulation require the user to take responsibility for the specification of model logic, development of the corresponding computer code and program verification. However, the excessive time, cost and expertise associated with such an implementation has resulted in very little use of the technique. In addition these characteristics are totally inappropriate to support the proposed multi-level modelling procedure. System evaluation early in the design process having to be quick, so encourage investigation into all possible solutions, and reliable though based upon limited data availability and assumptions. However, as designs evolve and assumptions are quantified, then ultimately evaluation is primarily concerned with accuracy of both representation and analysis. In addition implementation of modelling techniques need to be by the problem owners (i.e. designers), thereby removing the necessity to rely upon experts and so do away with the model builder/decision maker relationship and its associated problems.

The nature of the proposed multi-level modelling procedure suggests that its implementation through the use of a configurable, manufacturing simulator offers the best prospects for success. A configurable model alleviating the user from most of the model specification and development activities, by reducing the modelling scope. However, it is recognized that current simulators lack a generality which would make them applicable to a broad range of manufacturing systems and instead tend to be highly specific, relevant to only a small, unique range of applications. The requirements for and description of a general purpose manufacturing system simulator have therefore been discussed.

As a result of the above work, there are two primary objectives of the following experiments, these are:

- establish the benefits of multi-level modelling on manufacturing system simulation, and
- establish that a manufacturing system simulator can be generic, in terms of being generally applicable to a broad range of modelling problems.

The remainder of this chapter considers separately each of the above goals in order to identify the more specific objective functions. The two following chapters then discuss the nature, configuration and results of the experiments relating to the objective functions and therefore the primary objectives.

10.2 Multi-Level Modelling Objectives

The requirements for a multi-level modelling strategy have been logically derived from current manufacturing system design methodologies. Hence a primary objective of subsequent experiments is to prove that multi-level modelling does work (in terms of providing significant benefits to manufacturing system simulation). Having done so there is a secondary objective to establish a practical procedure to multi-level modelling. The objective functions are therefore:

- to demonstrate that there are significant benefits from evaluating manufacturing systems at alternate levels of detail,
- to demonstrate that the disadvantages of such an approach are not significant,
- to identify and explain any anomalies in evaluation at alternate levels of detail, and
- to establish guidelines for multi-level modelling.

10.3 Generic Application Objectives

It is acknowledged that configurable model simulators are inherently restricted in application. Hence a primary experimental objective is to demonstrate that such a system can be generally applied to discrete batch manufacturing systems. This implies proving that it is applicable to all such manufacturing systems. Ultimately this is an "ideal" objective, as it is obviously impossible, requiring all conceivable system configurations to be replicated under all possible scenarios. These experiments therefore are not intended to provide absolute proof of the complete generic application of a simulator. The extent of the experiments required to test such an objective makes such a proposal impractical. Consequently two less comprehensive primary objectives are proposed. These are:

- to establish that the configurable simulator concept works,
- to establish that the concept is useful and viable in the "real world".

Following on from this, the objective functions are therefore:

- to demonstrate that the simulator satisfies a broad range of system modelling requirements (section 6.5), and
- to demonstrate that the simulator is applicable to real problems.

Chapter 11 Multi-Level Modelling Experiments.

11.1 A System Modelling Problem

11.1.1 System Identification

The aim of these experiments was to investigate and understand the consequences of undertaking the evaluation of a manufacturing system at various levels of detail approximation or representation, in terms of:

- input data requirements,
- speed of model evaluation, and
- output data.

Experimentation therefore was based upon the study of one specific manufacturing system configuration and a comparison of its evaluation over the four successively detailed levels of dynamic computer modelling, as described in chapter eight. The underlying system having to reflect general manufacturing facilities, in terms of both configuration and operation, in order to ensure that the experiments were representative of typical modelling exercises, involving the representation of:

- different types of entities (e.g. machines, operators, transport),
- discrete stoppages (e.g. machine breakdowns),
- different types of operations (e.g. manual, automatic, assembly),
- various operational procedures (e.g. transfer quantities, operator allocation, scrap),
- both high and low component demand patterns,
- bought-in components, and

- customer sales.

The above list of modelling requirements representing the issues most commonly encounted in manufacturing system evaluation, though it is difficult to identify a single system implementation which incorporates the full complexity. Certainly at the time of the study such a system was not available. However, as the experiments were primarily concerned with the contrast between the various multi-level emulations, the actual existence of the system was of no relevance, so long as it was functionally representative of general manufacturing facilities. Consequently a detailed, hypothetical system, called cell 12, was used. The system containing the necessary scope and considered to be authentic, having been part of a major training case study that had been developed over a number of years and validated by numerous manufacturing managers.

11.1.2 Cell 12 Manufacturing System

The overall system of which cell 12 is a component, produces a range of consumer products manufactured from raw material, bought-in components and sub-assemblies. The customers are typically retail outlets with varying demand patterns, based upon either weekly or monthly deliveries.

The primary function of cell 12 is the manufacture of four types of gear and spindle assemblies; the two components having first been machined from bar material. Manufacturing operations therefore are split into three distinct areas (figure 11.1), gear and spindle fabrication and component assembly.

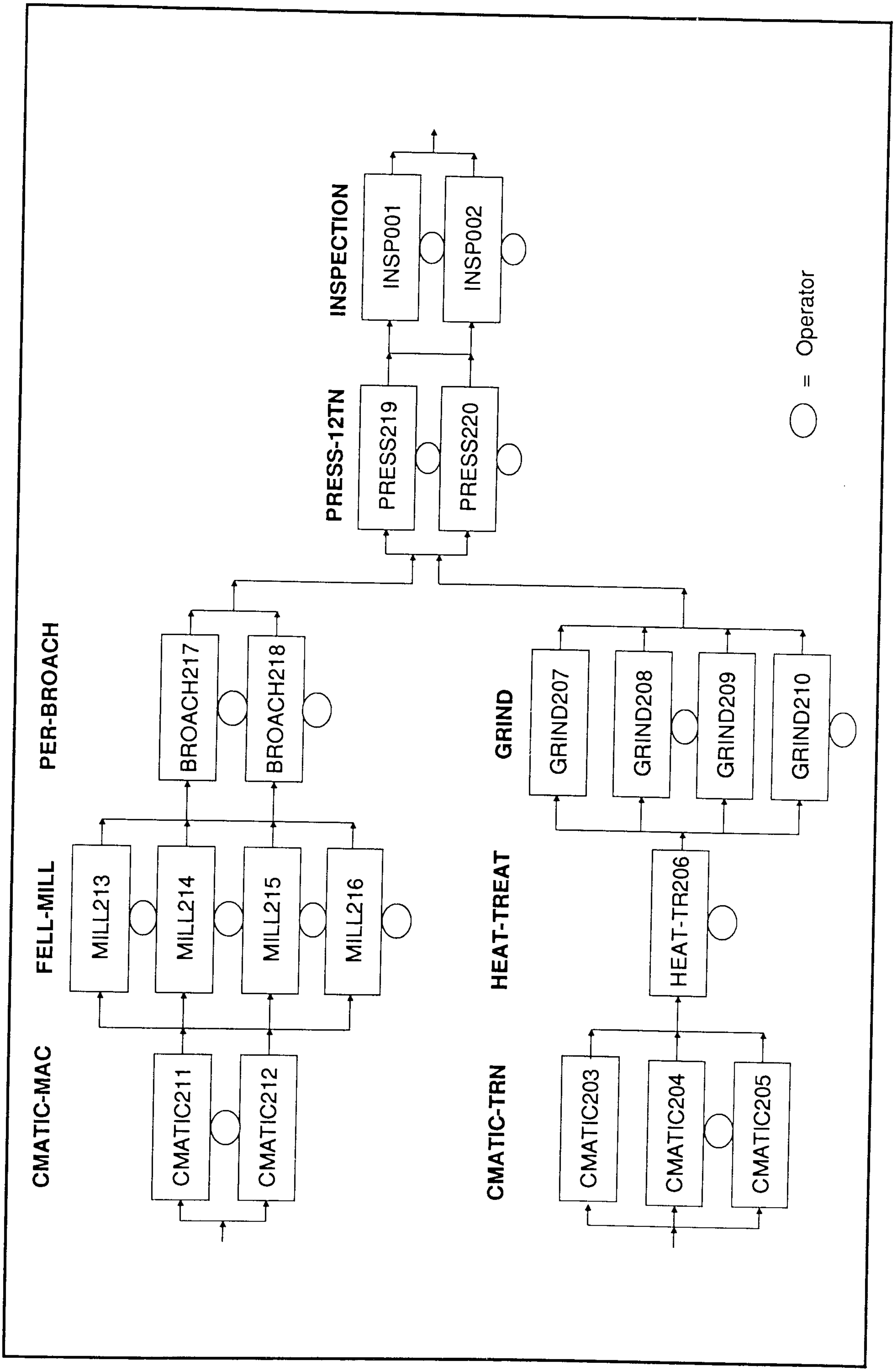


Figure 11.1 Cell 12 Manufacturing Procedure

1. Gears (i.e. GEAR_A, GEAR_B, GEAR_C, GEAR_D) are produced from bar material, ranging in diameter from 40 to 55mm (i.e. BAR_40MM, BAR_45MM, BAR_50MM, BAR_55MM), which go through three manufacturing operations:

   a. TURNING produced through an automatic operation performed on two machines (i.e. CMATIC211, CMATIC212), with one dedicated operator per shift (i.e. AUTO_OP_GR).

   b. MILLING produced through a manual operation performed on four machines (i.e. MILL215, MILL216, MILL217, MILL218), with four dedicated operators per shift (i.e. MILL_OPS).

   c. BROACHING produced through a manual operation performed on two machines (i.e. BROACH217, BROACH218), with two dedicated operators per shift (i.e. BROACH_OPS).

2. Spindles (i.e. SPINDLE_A, SPINDLE_B, SPINDLE_C, SPINDLE_D) are produced from bar material, ranging in diameter from 12 to 18mm (i.e. BAR_12MM, BAR_14MM, BAR_16MM, BAR_18MM), which go through three manufacturing operations:

   a. TURNING produced through an automatic operation performed on three machines (i.e. CMATIC203, CMATIC204, CMATIC205), with one dedicated operator per shift (i.e. AUTO_OP_SP).

b. HEAT TREAT produced through a manual operation performed on one machine (i.e. HEAT-TR206), with one dedicated operator per shift (i.e. HT_OPS).

c. GRINDING produced through an automatic operation performed on four machines (i.e. GRIND207, GRIND208, GRIND209, GRIND210), with two dedicated operators per shift (i.e. GRIND_OPS).

3. Gear and spindle assemblies (i.e. SP_ASSY_A, SP_ASSY_B, SP_ASSY_C, SP_ASSY_D) are produced from the appropriate combination of gears and spindles (i.e. 40mm-12mm, 45mm-14mm, 50mm-16mm, 55mm-18mm), which pass through two manufacturing operations:

a. PRESS produced through a manual operation performed on two machines (i.e. PRESS219, PRESS220), with two dedicated operators per shift (i.e. PRESS_OPS).

b. INSPECTION produced through a manual operation performed on two machines (i.e. INSP001, INSP002), with two dedicated operators per shift (i.e. INSPECTORS). Scrap is also incurred at this operation, being the only inspection carried out in the cell.

As indicated above all operations have a number of dedicated operators, but in addition require a craftsman (i.e.

CRAFTSMEN), of which there are five per shift, in order to set the machines. In addition, a craftsman is also required to undertake the repair of all machines which breakdown. Most machines, except for those in inspection, being subject to two types of discrete breakdowns. The first being a minor one, similar to tool changes, whilst the other is more significant, with work batches being off-loaded and re-scheduled onto alternative machines if downtime is greater than 60 minutes.

The transfer of work between operations is undertaken by material handlers (i.e. MTRL_HDLRS, 2/3 per shift) using carts (i.e. TRUCKS).

An MRP production control system is used to release work into the cell, with individual operations being performed on a first come first served (FCFS) basis. All operations, where possible are performed on transfer quantities of 1500, and so batches are split amongst all available work stations. As a consequence individual batches are not necessarily produced at one single work station, but at several simultaneously. Bought-in components are also controlled by the MRP system and all deliveries are assumed to contain no rejects. There is a weekly cyclical demand for completed assemblies, repeating over a 10 week period.

The factory operates two basic 7.5 hour shifts per day, although individual operators may do an additional number of hours overtime.

11.2 Modelling Considerations

11.2.1 Stochastic or Deterministic Modelling

One of the objectives of these experiments was to identify and explain any anomalies in system evaluation at the various levels of representation. A deterministic approach was therefore adopted and no statistical distributions were used. Though normally this would not be the case, as statistical distributions do allow a more realistic representation of system behaviour by providing an element of randomness in the occurrence of events. The results from such a model, however, exhibit noise, making it difficult to identify general trends. Emshoff et al [1970] suggests that a deterministic model is helpful in understanding how a system operates, whereas a stochastic model makes it difficult to identify precise behavioural patterns. Emshoff et al go on to say:

> "The deterministic abstraction captures the essence of the system sufficiently well to draw conclusions about the effects of decisions."

As a consequence of adopting a deterministic modelling approach therefore, any conclusions can and are only based upon observations, as the statistical analysis of output data is only appropriate for that generated by a stochastic model. As Hodges et al [1970] explains, statistics have been developed to handle random or stochastic based experiments. However, undertaking a deterministic modelling exercise in this instance does not diminish the validity of ATOMS itself, which has been used in other studies to evaluate stochastic models. Remembering that an objective of this investigation is to understand the implications of applying a hierarchical modelling procedure to the evaluation of a manufacturing system. Then a deterministic model offers a more unambiguous indication of the differences between the various levels of detail than a stochastic model, whose output tends to comprise some degree of random noise.

11.2.2 Transient or Steady-State Analysis

Regarding the analysis of a simulation model, the current literature, with few exceptions considers only steady-state based experiments [Law et al, 1982]. To such an extent that it may be imagined that transient experimentation should be avoided at all cost. This could be due to the fact that statistical analysis relies so heavily on the assumption that the output from a stochastic process exhibits steady-state distribution characteristics. Law et al, however, identifies that steady-state analysis is not appropriate:

> " - when the input distributions for the system change over time,
> - when interested in studying transient behaviour."

Therefore, in general manufacturing systems do not have steady-state distributions, as their characteristics are continually changing with time. Hence the above suggests that steady-state modelling may not be as relevant as first imagined, in particular when systems are being tested for robustness to changes over along period of time (e.g. changes in product demand, production scheduling rules, etc.). Furthermore simulation is especially used to study system performance whilst implementing changes. In effect evaluating up to "normal" or steady-state conditions, considering therefore only transient behaviour. Consequently, in relation to manufacturing system evaluation, transient and steady-state analysis are both as important and relevant as each other.

To fully investigate the benefits of multi-level modelling, experimentation therefore must include evaluation of both transient and steady-state system behaviour. However, to provide conclusive and absolute proof of the advantages of hierarchical modelling, rigorous and extensive experimentation is necessary. Involving the separate evaluation of all transient and steady-state behaviour for each possible system configuration, in addition to every conceivable state change. Any thing less than complete investigation cannot establish unequivocally the relevance of multi-level modelling. Instead limited investigation can only demonstrate or provide experimental proof of the potential benefits of the technique.

To demonstrate conclusively the advantages of multi-level modelling is in effect impracticable. These experiments therefore are intended to provide justifiable proof of the practical benefits of the modelling technique. Evaluating general system behaviour, incorporating the transition from transient to steady-state performance. Experiments are performed over a 30 week period, the models initially empty of work and output data collected through both the transient and steady-state phases. The run length being sufficiently long enough to allow the system to reach steady-state or equilibrium conditions (figure 11.2).

11.3 Configuration of Multi-Level Models

The intention is that, as a manufacturing system design evolves, system evaluation shifts from one based on a high degree of approximation to a more detailed and factual model. In the following experiments, to ensure that the assumptions included in the more approximated models reflected a reasonable degree of reality, their formulation was based upon the results of the station level emulation. So that the various multi-level models were consistent and therefore comparable. Consequently this section reviews the multi-level

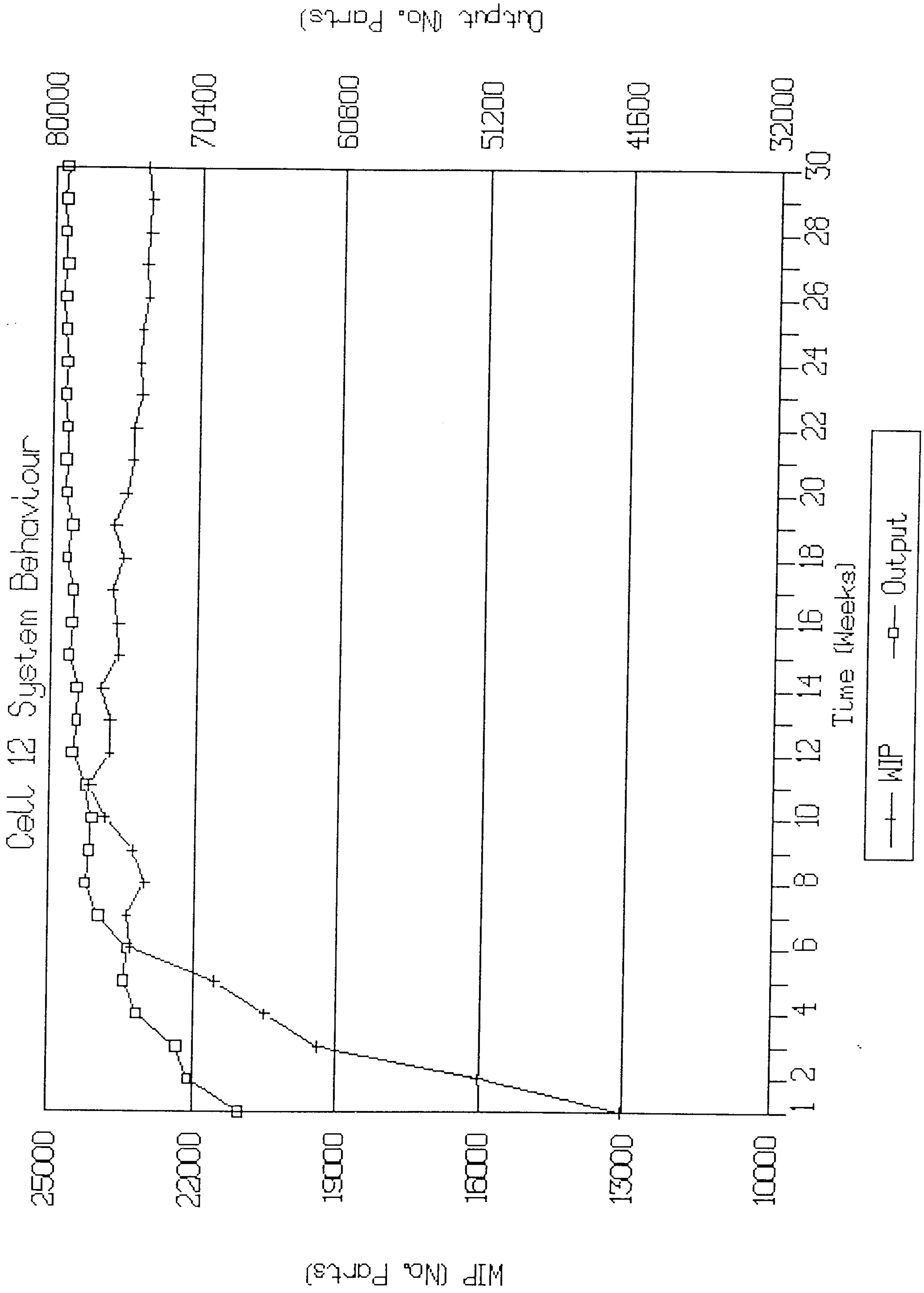


Figure 11.2 Transient To Steady-State Performance

models in reverse order to that which they would normally be approached.

11.3.1 Station Level Model (Station)

As one of the primary concerns at the station phase of evaluation is the accuracy of system duplication, the cell 12 station model was configured (Appendix E) as near as possible to the actual system description (section 11.1.2). This resulted in:

- the specification of 8 raw material items, 8 manufactured components and 4 assembly components,
- individual operators working specific shift patterns,
- operators assigned to particular work stations (table 11.1),
- specification of a percentage operating efficiency for both work stations and operators,
- work stations grouped uniquely into work centres i.e.

  CMATIC-MAC (MAC) = CMATIC211, CMATIC212;
  FELL-MILL (FELL) = MILL213, MILL214, MILL215, MILL216;
  PER-BROACH (PER) = BROACH217, BROACH218;
  CMATIC-TRN (TRN) = CMATIC203, CMATIC204, CMATIC205;
  HEAT-TREAT (HT) = HEAT-TR206;
  GRIND (GRD) = GRIND207, GRIND208, GRIND209, GRIND210;
  PRESS-12TN (PRESS) = PRESS219, PRESS220;
  INSPECTION (INSP) = INSP001, INSP002;

- all work station incurring two types of discrete

	INSPECTION	AUTO_OP_SP	HT_OPS	GRIND_OPS	AUTO_OP_GR	MILL_OPS	BROACH_OPS	PRESS_OPS
INSP001	X							
INSP002	X							
CMATIC203		X						
CMATIC204		X						
CMATIC205		X						
HEAT-TR206			X					
GRIND207				X				
GRIND208				X				
GRIND209				X				
GRIND210				X				
CMATIC211					X			
CMATIC212					X			
MILL213						X		
MILL214						X		
MILL215						X		
MILL216						X		
BROACH217							X	
BROACH218							X	
PRESS219								X
PRESS220								X

Table 11.1 Cell 12 Operator Skills Matrix

breakdowns (except for INSP001 and INSP002),

- craftsmen assigned to all work stations for set-up and repair activities,
- specification of all set-up and standard times,
- specification of loading and unloading times for all automatic operations,
- specification of the load quantity for each operation,
- all batch transfers between operations being specified in terms of distance,
- specification of an operating speed for the transport device,
- material handler and transport device assigned to the transfer of work batches between all operations,
- a transfer quantity of 1500 for all operations,
- a percentage scrap rate for all inspection operations,
- kitting requirements for all first of operations,
- fixed weekly order input for both purchase and manufactured components (Appendix L),
- weekly customer demand (varying over a 10 week cycle, see Appendix L) for a 30 week period.

11.3.2 Centre Level Model (Centre)

In comparison to the station model, a centre level model contains a number of simplifying assumptions relating to:

- work station emulation,
- work station breakdowns,
- work station loading/unloading,
- operator emulation.

At this level of modelling work stations (i.e. machines) are not explicitly defined. Instead of defining individual work stations and then assigning them to particular work centres, only the number of work stations available at a particular work centre is quantified. This assumes work stations are unique to a particular work centre and that they are precisely the same. Furthermore the current set-up for a particular work station is not recorded, therefore idle work stations will always incur a set-up irrespective of whether the next job is the same as the last.

In order to simplify the evaluation process discrete breakdowns are not explicitly modelled, neither are work station load and unload activities. In addition labour capacity constraints cannot be addressed, as operators are not modelled.

Configuration of the cell 12 centre model (Appendix F) therefore is similar to the station level specification, except that:

- percentage breakdown factors are specified instead of discrete breakdown events. These are based upon downtime figures from the station emulation and are a percentage of a week i.e. 120 hours,
- work station loading and unloading times are incorporated into the standard time,
- individual work centres are assigned a specific shift pattern (instead of Operators).

11.3.3 Department Level Model (Depart)

With respect to both the station and centre levels, a department model contains far more assumptions, relating to:

- breakdowns,
- operating policies, and
- job evaluation.

At this level of evaluation individual work stations are not considered. As at centre level, the number of work stations available at a particular work centre is quantified, though only a single work station is considered with the combined capacity of the total number of stations at the centre. This simplifies the evaluation process, although jobs will be completed in a fraction of the actual time (i.e. 1 / number of work stations) and corresponds to work being split exactly between all work stations allocated to a particular work centre. Furthermore work station breakdowns are not considered at all, even as a percentage factor. In addition the operating rules are significantly simplified and do not allow for the consideration of work scheduling, job sequencing or transfer quantities.

Configuration of the cell 12 department model (Appendix G) is similar to the centre level specification except that:

- a percentage breakdown factor is incorporated into the work station working efficiency percentage,
- there are no transfer quantities, the whole batch has to completed before it is passed to the next operation.

11.3.4 Factory Level Model (Factory & Max. Fact'y)

Here model specification (Appendix H) is exactly the same as for department except that:

- customer demand cannot be considered,

- weekly order input has to be changed to a statement of component demand, entered within the model data menu option off the mathematical model main menu option, and
- average work-in-progress (WIP) is specified based on the result of the station emulation.

Early experiments with the factory model quickly identified a major operational problem, which is highlighted by the last item on the above list of exceptions; the need to identify an average WIP level. This is not realistic as it represents one of the major issues that dynamic modelling is most often used to resolve. The use of the factory model in a practical sense is therefore difficult, as it represents the first stage of dynamic evaluation at which point there can only be rough, steady-state, and so incomplete, estimations of WIP on which to base the analysis. However, the model can be tested over a range of WIP levels to obtain an indication of bottlenecks, work centre utilization and queue sizes. Consequently the model was executed with varying WIP levels, ranging from 1 to 50 batches, each containing 1500 components. The predicted utilization and queue size was then graphically represented against WIP for each work centre (figures 11.3 and 11.4). The bottleneck work centre could then easily be identified as the one whose utilization approached nearest to 100% and had an exponential shaped queue size graph; all other queue size graphs plateauing at a certain level.

With regard to the main experiments and in order to ensure the completeness of the investigation, however, the WIP level for the factory model was based upon the average predicted by the station evaluation. Although in reality this

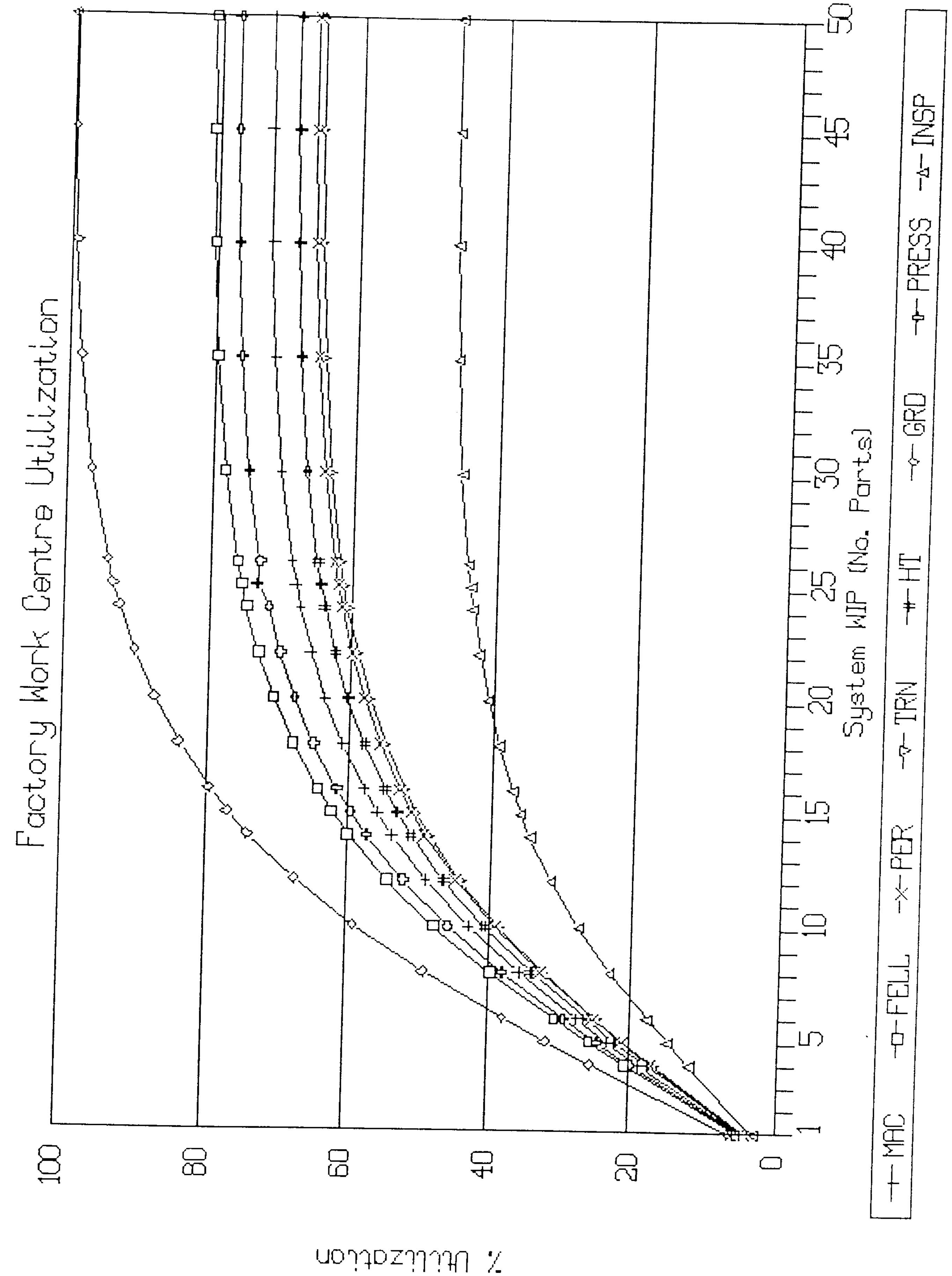


Figure 11.3 Factory Predicted Work Centre Utilization

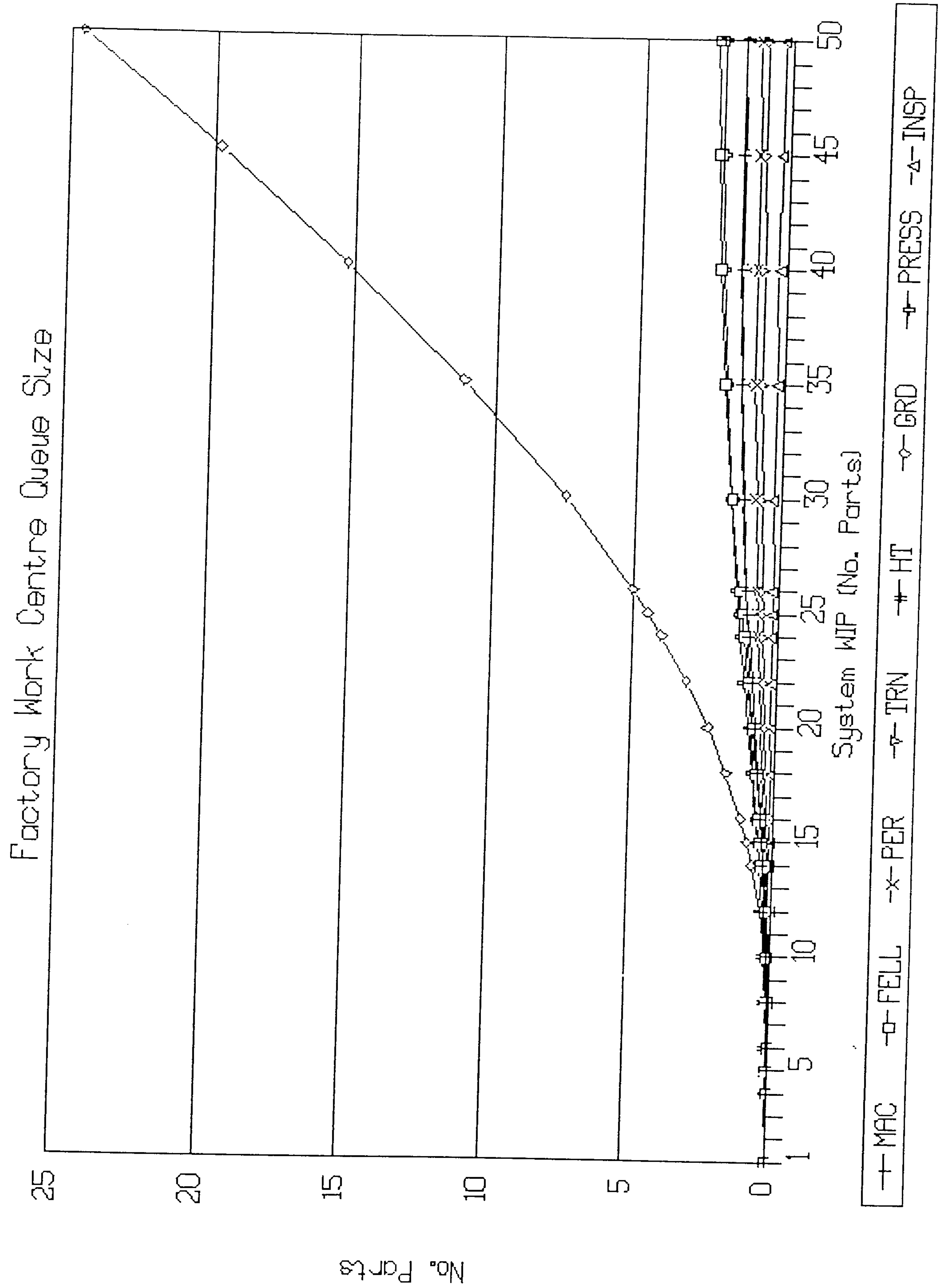


Figure 11.4 Factory Predicted Work Centre Queue Size

would not be practical. Therefore the results, obtained from the above experiments with 50 batches WIP, were used as a comparison in certain instances, and termed the "maximum" factory model (Max. Fact'y).

11.3.5 A Combined Multi-Level Model (Combined)

One of the main requirements in the specification for a multi-level simulator, was an ability to accommodate a model that had been defined across a number of different levels of detail. Also an objective function was to establish multi-level modelling guidelines. To investigate these requirements a combined multi-level model of cell 12 was produced (Appendix I), based upon the work centre utilization results obtained from the department, centre and station representations (Appendix N.1). The results from the corresponding models being ranked into three groups (table 11.2) and the rankings for each work centre, then compared to determine the

	DEPARTMENT		CENTRE		STATION	
Work Centres	Util.	Group	Util.	Group	Util.	Group
CMATIC-MAC	78.59	1	87.99	1	89.65	1
FELL-MILL	66.87	2	65.98	2	66.24	2
PER-BROACH	55.37	3	58.21	3	56.76	3
CMATIC-TRN	77.56	1	89.95	1	90.26	1
HEAT-TREAT	75.27	1	76.25	2	76.05	2
GRIND	82.31	1	82.07	1	83.58	1
PRESS-12TN	63.89	2	66.71	2	67.20	2
INSPECTION	48.49	3	49.93	3	49.96	3

Util. = Utilization

Table 11.2 Work Centre Utilization Rankings

appropriate level of representation. The rankings were arbitrarily selected, on the basis of:

- utilization under 50%, DEPARTMENT level or group 3, indicating that less than half the available capacity is being used. The resource is of no critical concern, able to accommodate additional demand or variation in operating behaviour relatively easily, with little knock on effect.
- utilization 50 to 75%, CENTRE level or group 2, indicating satisfactory use. The resource is able to accommodate some additional demand or behaviour variation but could quickly become a constraint on system performance.
- utilization over 75%, STATION level or group 1, indicating a critical or bottleneck area. The resource is potentially constraining system performance and consequently changes in demand or operating behaviour can have a significant effect on overall system performance.

Although the rankings were also affected by the distribution of the figures within a given model. This being a particularly easy and practical approach to identifying the appropriate level at which specific work centres should be modelled, and one that could be readily adopted during the actual design of a manufacturing system (section 11.5).
The model contained at:

station level

- work centres CMATIC-MAC, CMATIC-TRN and GRIND,
- work stations CMATIC211, CMATIC212, CMATIC203,

CMATIC204, CMATIC205, GRIND207, GRIND208, GRIND209 and GRIND210, with relevant breakdowns,
- operator types AUTO_OP_GR, AUTO_OP_SP, GRIND_OPS, CRAFTSMEN and MTRL_HDLRS, and
- all operations assigned to the above work centres;

centre level
- work centres HEAT-TREAT, FELL-MILL and PRESS-12TN, with appropriate percentage breakdown factors, and
- all operations assigned to the previous work centres;

department level
- work centres PRE-BROACH and INSPECTION, and
- all operations assigned to the previous work centres.

Independent of levels were:
- raw material BAR-12MM, BAR_14MM, BAR_16MM and BAR_18MM,
- components GEAR_A, GEAR_B, GEAR_C, GEAR_D, SPINDLE_A, SPINDLE_B, SPINDLE_C and SPINDLE_D,
- sub-assemblies SP_ASSY_A, SP_ASSY_B, SP_ASSY_C and SP_ASSY_D,
- transport device, TRUCKS, and
- 30 week order input and customer demand.

11.3.6 Steady-State Capacity Model (Spread Sheet)

In order to put all the multi-level modelling experiments into context and compare them with current approaches to system design evaluation, a steady-state capacity model was produced. This simply accumulated the weekly component loading on a work centre, in terms of standard times, and included four set-ups as each centre performed one operation on four components, be they GEAR_A/B/C/D or SPINDLE_A/B/C/D or SP_ASSY_A/B/C/D. The total loading was then divided by the product of number of work stations, hours available/day, number of days/week and a work station percentage efficiency (including a breakdown factor). This was then multiplied by a 100 to give a percentage work centre utilization figure.

11.4 Results

The objective of these experiments was to identify and understand the differences in undertaking a system modelling exercise at the various levels of detail representation. The investigation was concerned with the effects multi-level modelling has on input data requirements, speed of evaluation and output results. Corresponding multi-level models of one system specification were, therefore compared on the basis of actual modelling characteristics and over a range of predicted manufacturing performance measures. The results consequently are presented in two corresponding sections.

11.4.1 Evaluation Speed and Data Requirements

The execution time for the various multi-level models were taken on an Apricot XEN-i 386/45 IBM PC compatible computer utilizing an 80386 processor, operating at 16MHz and running under DOS 3.3. Data requirements on the other hand, were an estimation of the information required to configure the respective models. The five models compared were:

- four multi-level models; factory, department, centre and station, and

- a combined multi-level model.

Whilst evaluating the performance of cell 12 at the factory level it was very noticeable that the speed of the model deteriorated dramatically as the number of WIP batches was increased. The time ranging from less than 1 second to over 1.25 minutes for the factory model containing 1 or 50 WIP batches, respectively. The time used for model comparison therefore was taken with WIP equivalent to the average WIP level predicted by the station analysis.

The times for model evaluation are illustrated in figure 11.5. The most noticeable characteristic of these times is the sizeable difference between centre and station models. The time escalating from a mere 8 to 102 minutes, an increase of approximately 1200%. To understand the causes of such a significant increase, it is necessary to recognize the differences between the various multi-level models in terms of the detail in which they represent manufacturing operations. Since the representation of such activities denotes the area of greatest variation in the respective approaches to manufacturing system evaluation, with all other modelling aspects remaining relatively constant. An investigation (Appendix M) into the total number of operational events occurring per week in the various models, identifies a difference of approximately 3804 events (table 11.3) between the two extreme evaluations, (i.e. the department and station representations) assuming that the weekly schedule is completed within a particular period. This analysis clearly suggests that the reasons for the increase in the number of events and therefore the decay in run time execution of a model, are due to:

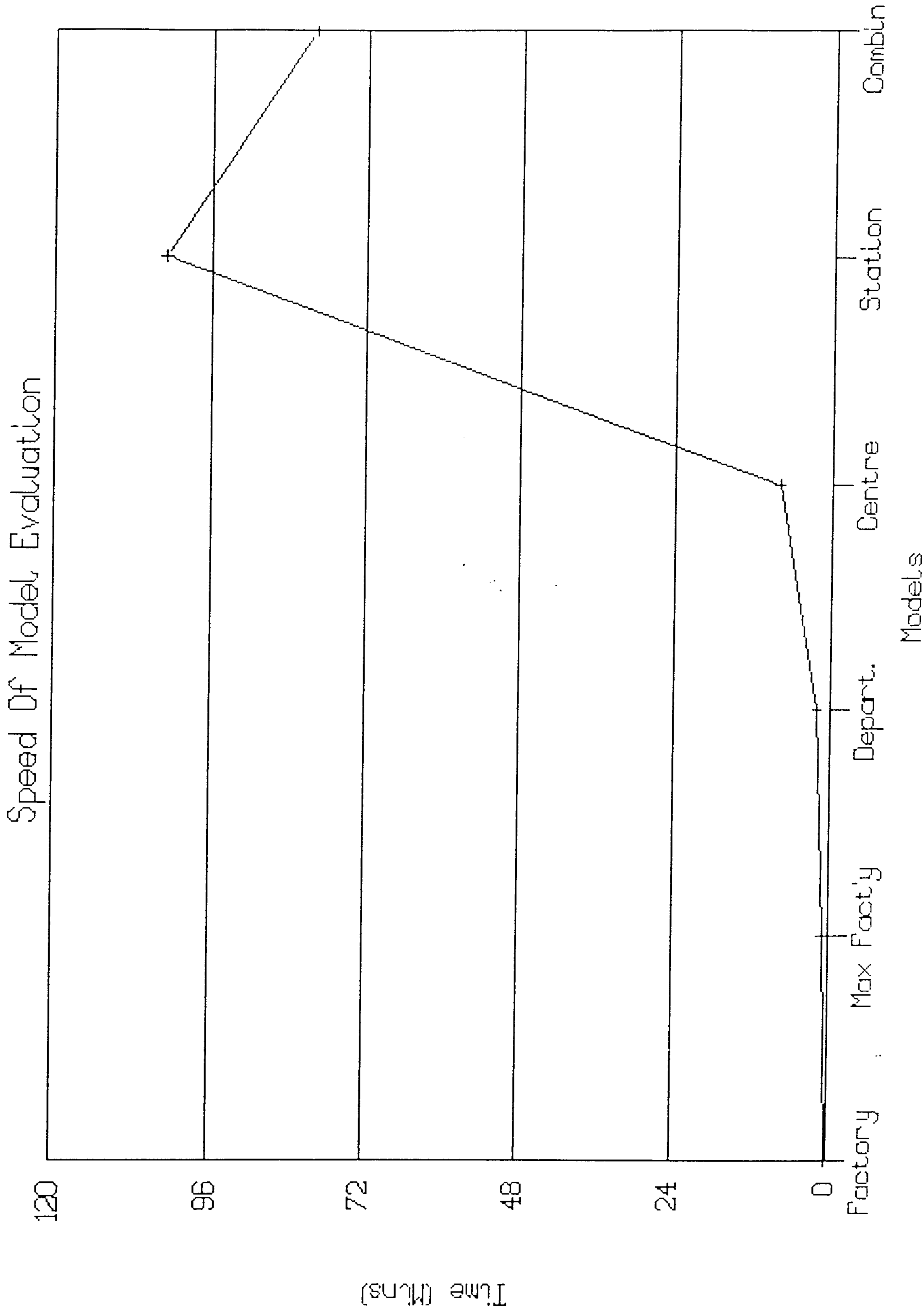


Figure 11.5 Multi-Level Model Evaluation Times

30 Week evaluation of cell 12

	Department	Centre	Station
Execution Time (Mins)	2	8	102
Total No. of Events	1920	10080	116040

Table 11.3 Speed of Evaluation Vs. Number of Events

- evaluation of loading and unloading activities,
- specification of discrete breakdowns, and
- inclusion of transfer quantities.

The combined multi-level model, though incurring a significant evaluation time (i.e. 80 minutes) in comparison to the department and centre investigations, is still a reduction of approximately 20% over that incurred by the station model. The excessive time being due to the representation of CMATIC-MAC, CMATIC-TRN and GRIND work centres at the detailed, station level. Furthermore the combined model offers additional advantages by reducing data requirements, with respect to the station model, by 30% (where a centre model reduces data requirements by 50% and department by 62%, approximately). Together the combination of quicker evaluation and reduced data requirements clearly illustrates the potential advantages of a combined multi-level model.

11.4.2 Predicted Measures of Performance

To identify the differences between alternative multi-level models, the corresponding representations of cell 12 were compared on the basis of six standard measures of performance. These were work centre utilization, work-in-progress, component output, batch lead-times, work centre queue sizes and batch queuing time. The results are discussed fully in Appendix N, with the major findings presented below.

The differences between system performance predicted by the factory evaluation and all other investigations, represents the most significant and conflicting variation between the alternative multi-level models. The measures of performance predicted by the factory model consistently, and in certain circumstances quite substantially, contradicting those produced by subsequent evaluations.

Work centre utilization predicted by the factory representation, varied from between 14 to 32% in comparison to the corresponding mean values, based upon the average result calculated across all models. The predicted batch lead-times differed so dramatically that the graphs sloped in exactly the opposite direction to those of other models (figures N.6 to N.8). Work centre queue sizes compared favourable with other evaluations except in relation to first operations, which were constantly underestimated. Differences in average queue size for the PRESS-12TN work centre ranging from between 15,483 to 28,918 parts, in comparison to alternative models. In addition the factory model could not predict expected WIP levels or batch queuing time, the measures of performance being either an input into the model or simply not an available output. In comparison of component output, however, the factory representation did closely reflect other models, differing in the worst case, with the department model, by only 5%.

A number of the differences between the factory and alternative evaluations can be attributed to its inability to reflect the true arrival of components, arising from the mathematical model, (upon which the factory representation is based) being derived from closed-loop queuing theory. Consequently there has to be concern over the accuracy and reliability of the factory results. The results differing so dramatically from those obtained from other evaluations, combined with the difficulty in re-examining and questioning both the evaluation procedure and any included assumptions. Whereas the validity of the various simulation based models and steady-state capacity calculations can be quickly established through verification of the evaluation process and a clear understanding of the underlying assumptions.

The differences between the three alternative simulation models relate primarily to how detailed and therefore accurately manufacturing operations are represented. The contrast being clearly highlighted when comparing the expected performance of cell 12 predicted by the respective approaches. The more approximated department and centre models predicting performance measures which are both above and below the corresponding figures indicated by the detailed station representation (table 11.4). Though all measures of performance do differ to some degree, the major variations can be directly attributed to two principal issues. The disruption of operations and the transfer of batches.

Differences between the respective centre and station models are primarily due to the inclusion of breakdowns, as the centre model does not explicitly represent discrete work station breakdowns. Instead a percentage breakdown factor is included, based upon average work station downtime, and therefore work continually flows through the system uninterrupted. As a result operations take slightly longer

* Performance Measures / Model	Utilization		Work-in-Progress	Component Output	Batch Lead-times	Work Centre Queue Size	Batch Waiting Time
	Set-Up	Cycle					
Centre	Over Estimated due to: Previous set-up	Over Estimated due to: No discrete breakdowns	Under Estimated due to: No discrete breakdowns	Under Estimated due to: No discrete breakdowns	Under Estimated due to: No discrete breakdown	Under Estimated due to: No discrete breakdown	Under Estimated due to: No discrete breakdown Operator restrictions
Department	Under Estimated due to: Transfer quantities Dedicated work stations	Over Estimated due to: Transfer quantities	Over Estimated due to: Transfer quantities	Over Estimated due to: Transfer quantities	Over Estimated due to: Transfer quantities	Under & Over Estimated due to: Transfer quantities	Under Estimated due to: Transfer quantities

* Centre and department measures of performance compared with those predicted by the station model.

Table 11.4 Department and Centre Model Comparisons than the stated standard time, although they never actually stop. However, the existence of discrete stoppages within the station model results in operations being continually disrupted, and hence stopping the flow of work. This in the station model obviously leads to higher predicted WIP levels, queue sizes and batch queuing time, in addition to longer batch lead-times. This phenomenon would also be demonstrated if the model included operator absenteeism.

Variation between the department and station evaluations can also be attributed to the presence of work station breakdowns, the department model being unable to incorporate discrete breakdowns. However, differences can also be directly related to the specification of transfer quantities within the more detailed models. This being clearly demonstrated when comparing the department and centre models, which in the main only differ in this one respect. By working in transfer quantities, a batch passes quickly through a system, as it allows a number of consecutive operations to be performed on a batch simultaneously. In the department model, however, a batch has to wait at each operation until the last component has been processed before it can move on. In addition with transfer quantities, batches can be split across all available work stations capable of undertaking a particular operation. Hence a number of components from the same batch can be processed through the same operation simultaneously, so that specific operations are completed much quicker. Consequently being unable to specify transfer quantities within the department model can effect the accuracy of estimated measures of performance, resulting in greater predicted WIP levels and batch lead-times along with smaller batch queuing times.

In addition to the main factors discussed above, the operator to work station ratio can also be responsible for differences between models (Appendix N.6). In respect to operators both the department and centre models assume a one to one operator to work station relationship. However, if this is not a true reflection and in effect operators have multi work station and/or task responsibilities then this can be represented within the station model. This is illustrated by the variation in predicted performance of the CMATIC-MAC, GRIND and CMATIC-TRN work centres and the specification of CRAFTSMEN operators for the repair and setting up of work stations.

The relevance and validity of a combined multi-level model is substantiated when the predicted system performance for cell 12 is compared with that of the alternative single level representations. The combined model consistently agreeing with that of the station evaluation, across all measures of performance, although only three of the eight work centres are defined at the most detailed, station level. The only significant (Appendix N) differences between the two models being the discrepancy in predicted average batch queuing time at the PRESS-12TN work centre. The differences being attributed to the combined effects of variation in specified transfer quantities and work station breakdowns. A major factor being that the PRESS-12TN work centre was described at the centre level in the combined model and therefore did not incur discrete breakdowns. However, this was the only serious instance when the differences in work centre representation was noticeable and of any cause for concern.

A further cause of possible variation between combined and station models is the difference in the availability of operators, particularly the CRAFTSMEN. In the combined model, where there are fewer discrete work stations for the CRAFTSMEN operators to set and repair (in comparison to the station model), the operators are not as busy and can therefore respond quicker to individual requests. One potential result is that less downtime is incurred, because of less time waiting for a repair operator, therefore more work can be processed which could lead to work stations actually incurring more breakdowns. Hence cancelling out the shorter downtimes. This phenomena possible explaining why there is little difference between the maximum and average work centre queue sizes predicted by the respective station and combined models.

The comparison between station and combined evaluations demonstrates that there is little to be gained from modelling non-bottleneck or non-critical operations in a very detailed or precise manner. The exercise illustrating how difficult it can be to identify any differences between the two alternative models in terms of predicted system performance.

11.5 Conclusions

The objectives of the above experiments were concerned with the dynamic evaluation of manufacturing systems at alternative levels of detail or consideration. The results that have been achieved through these experiments are indicative of the benefits to be gained in adopting a multi-level approach to system evaluation. In particular it has been demonstrated that there are no significant benefits (in terms of any improvement in the prediction of system performance) to be gained in modelling and evaluating non-critical or non-bottleneck areas in a precise and detailed manner. A more approximate or less detailed representation of system components can significantly reduce the amount of time and effort required in undertaking a simulation exercise, without greatly impinging upon the accuracy of the results. The major benefits of a multi-level approach are:

- reduced data requirements,
- quicker evaluation process,
- focused effort on critical areas whilst not ignoring the more insignificant system elements,

Discrepancies between the various levels of consideration have primarily related to the inability of the more superficial models to approximate fairly detailed operational issues, as would be expected. Hence there are certain circumstances which necessitate a more detailed consideration as cursory considerations cannot adequately provide an indication of true system performance.

Operational issues which cause variation in results between alternative levels of approximation include:

- transfer quantities,
- assembly operations (of manufactured components),
- discrete breakdowns,
- work station sequencing, and
- labour constraints.

The inclusion of such considerations may make the department and/or centre models inappropriate for investigating performance measures other than predicted average results. However, it must be remembered that the intention of the two, more aggregated levels of modelling was to provide a means of undertaking long and medium term evaluation of expected system behaviour, quickly with minimum data requirements. The accuracy of the day to day evaluation not being the prime concern. The issues therefore which effect speed of evaluation include:

- consideration of loading/unloading of work stations,
- discrete breakdowns,
- transfer quantities.

From the experiments it is apparent that the application of CAN-Q, can in certain circumstances be inappropriate within the multi-level approach, and further questions the usefulness of a mathematical representation for the factory model. The benefits of the department model at times significantly out weighing the potential advantages of CAN-Q.

Finally the experiments have presented two multi-level modelling procedures. The first and most obvious approach, comparing the results of modelling at each level of approximation in order to identify the most appropriate representation of individual system elements (section 11.3.5). This is a reasonable and effective procedure particularly when establishing a model, of a completed system specification for subsequent experimentation and investigation. The approach, however, does not take full advantage of the potential offered by the multi-level modelling technique. Rather than being efficient, it actually wastes a lot of effort by requiring a detailed description of non-critical areas, which ultimately would be modelled in a more cursory manner. Furthermore it is not an efficient and structured procedure for manufacturing system design, neither does it focuses attention and resources effort on critical, high risk areas.

The approach adopted in the above experiments therefore, was to base the decision of whether to consider a specific part of a system in more detail, on its predicted measure of performance from the previous level of approximation. In the experiments the decision was based upon work centre utilization, i.e. the more critical the work load on the area the more detailed the consideration. As a consequence a combined multi-level model was developed which, through subsequent experiments was clearly proven to be a good approximation to the straight forward station representation.

The identification of the appropriate level of approximation for the various elements of a particular system needs to be independent of any other system specification. There can be no arbitrary, pre-determined utilization values which are rigidly applied to all systems to determine the level of detail. Ultimately a degree of common sense has to be used in identifying the appropriate levels of modelling. However, there is one issue which may determine the degree of detail, and that is labour constraints, as operators are only represented at the station level. Therefore issues such as operators running multiple machines can only be truly addressed through a detailed, station model. Although an approximation of the effects can be provided through modelling at more cursory levels of consideration. However, the decision relating to the appropriate level of modelling manufacturing operations and machines has to be based upon specific system measures of performance.

Chapter 12 Generic Application Experiments.

12.1 The Approach

The underlying assumption of the proposed multi-level modelling strategy is that a generic computer simulation model can contain sufficient inherent flexibility to be applicable to a broad range of conventional manufacturing systems. However, it has been clearly identified that generic models, by removing the necessity to perform model formulation and translation activities, are restricted in terms of the range of systems to which they can be applied [Crookes, 1987]. Previous manufacturing simulators have tended to be too limited, relevant to only specific system applications [Bevans, 1982]. Simulators generally being designed either for the evaluation of physical resources or certain operational policies, but not, unfortunately, both (section 7.1). Commercial manufacturing simulators in particular focus primarily on high technology systems (e.g. flexible manufacturing systems) and the configuration and control of such facilities. These representing a relatively small subset of manufacturing systems, but which best justify a computer simulation exercise because of the high risks and costs associated with their implementation. However, through careful and thorough investigation into the configuration and operation of conventional manufacturing systems, and identification of their inherent similarity, the specification of a generally applicable manufacturing simulator has been logically derived. Incorporating, in addition those features necessary to effectively support manufacturing systems design, arising from the development of the multi-level modelling strategy. The aim of these experiments therefore is to demonstrate the adaptability of the ATOMS simulator, based upon the above specification, to evaluate real manufacturing systems, in terms of:

- representing various system components, and
- being applicable to real problems.

Hence the experiments are classified into two groups, relating to the verification and validation of the manufacturing simulator.

12.2 Concept Verification

The objective of these experiments is to demonstrate that a manufacturing simulator can contain sufficient flexibility, as defined in section 6.5, to make it generally applicable to conventional systems:

- represent different system components,
- represent different types of a component,
- represent components at various levels of detail,
- represent different system configurations, and
- represent all types of control policies and decision rules.

A good illustration of the facilities within ATOMS is provided by the evaluation of cell 12 in the previous chapter.

12.2.1 Cell 12 Basic Representation

The cell 12 manufacturing system contained extensive and representative features which relate to the various areas of considerations listed above. Cell 12 incorporated a variety of system components:

- material,
- machines,
- operators, and
- transport,

each with a number of different types or alternative settings, for example:

- material
  e.g. bought-out components, manufactured components and high and low volume demand items,
- machines
  e.g. manual, automatic and assembly,
- operators
  e.g. machine setters, process operators, maintenance engineers and material handlers,
- transport
  e.g. transfer in minutes or distance.

System evaluation was performed at all four levels of approximation (i.e. factory, department, centre and station) with additional consideration being given to a combined multi-level model.

In addition to its ability to represent physical system elements, it is just as important for the simulator to be able to emulate operational control policies. This being an area where most simulators are much too specific. In modelling cell 12 the simulator reflected the use of a material requirements planning (MRP) system to control the issue of both purchase and works orders. Work orders progressing through the system on a first come first served (FCFS) basis. Consequently the cell experiments demonstrated the ability of ATOMS to represent one type of production control mechanism, but further investigations were required to consider alternative methods. Hence a kanban system was introduced into cell 12 to control component part (i.e. GEAR_A/B/C/D and SPINDLE_A/B/C/D) manufacture, with MRP being retained to control both raw material purchase and assembly manufacture. This demonstrating the ability of the simulator to represent different production control systems, and also the flexibility to include a combination of methods which have very practical application [Parnaby, 1988a].

12.2.2 Cell 12 Kanban

With the introduction of a one card kanban system, the configuration of cell 12 remained the same except for the storage of both gears and spindles in individual kanban boxes each containing 1500 components. All full kanbans were situated at the press operation (entered in ATOMS within the PRESS-12TN work centre record) as this was where the components were assembled. As the components were consumed, the empty boxes, along with the accompanying kanban card, were passed back to the appropriate first operation (i.e. CMATIC-MAC or CMATIC-TRN) in order to be replenished and therefore authorise the manufacture of 1500 gears or spindles, respectively. Once the components had been completed and the kanban box refilled they were sent back to the press operation. At the press operation assembly manufacture was controlled by the weekly specification of a schedule, issued through the MRP system. The supply of raw material was also controlled in a similar manner.

The results from the kanban model were compared with the station model across the same measures of performance as discussed in chapter 11. The results are illustrated graphically in figures 12.1 to 12.12.

The comparison of work centre utilization (figure 12.1) clearly indicates the critical loading of certain machines through the introduction of kanban. This is caused by a significant increase in the number of set-ups (figure 12.2), compared with the station model. With an increase at CMATIC-MAC of over 50%, whilst there is very little difference in the total standard hours produced (figure 12.3). This is typical of a kanban system which, through the specification of much smaller batch sizes (e.g. 1500 as apposed to 9048 for type B components), generally requires considerably more set-ups to produce a comparable output.

The problems of implementing a kanban system are further highlighted by the weekly work-in-progress (WIP) and component output results (figures 12.4 and 12.5). These clearly illustrate the potential consequences of increased set-ups on system performance, predicting as they do a significantly higher level of WIP and a deteriorating component output, with respect to the station model. Attributable to the sizeable reduction in the flow of components through respective operations.

The predicted work centre queue sizes highlights distinctively the difference in arrival of new work batches into the system under kanban control (figures 12.6 and 12.7). Without exception the estimated average and maximum centre queue sizes for all first operation work centres were

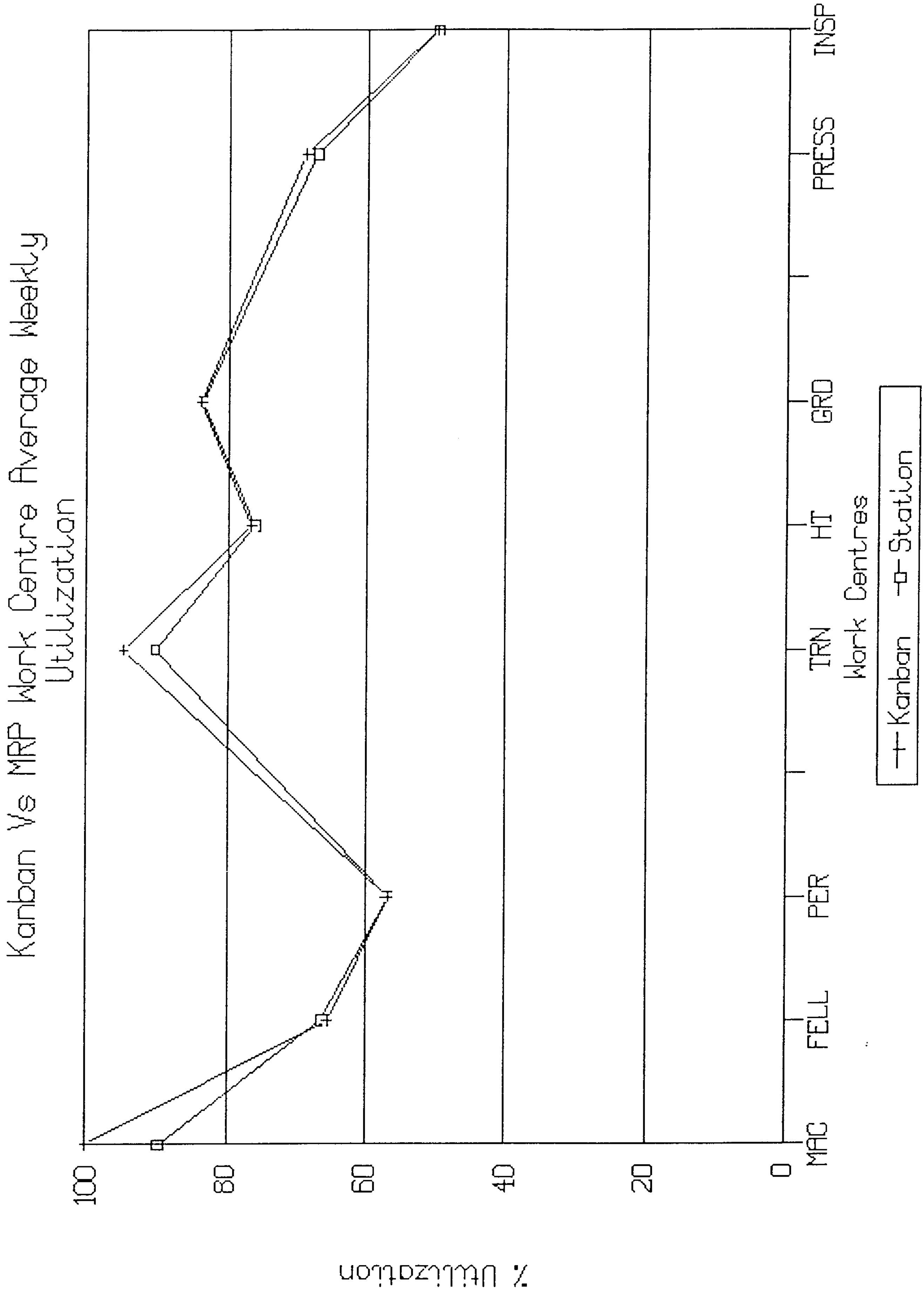


Figure 12.1 Kanban Work Centre Utilization

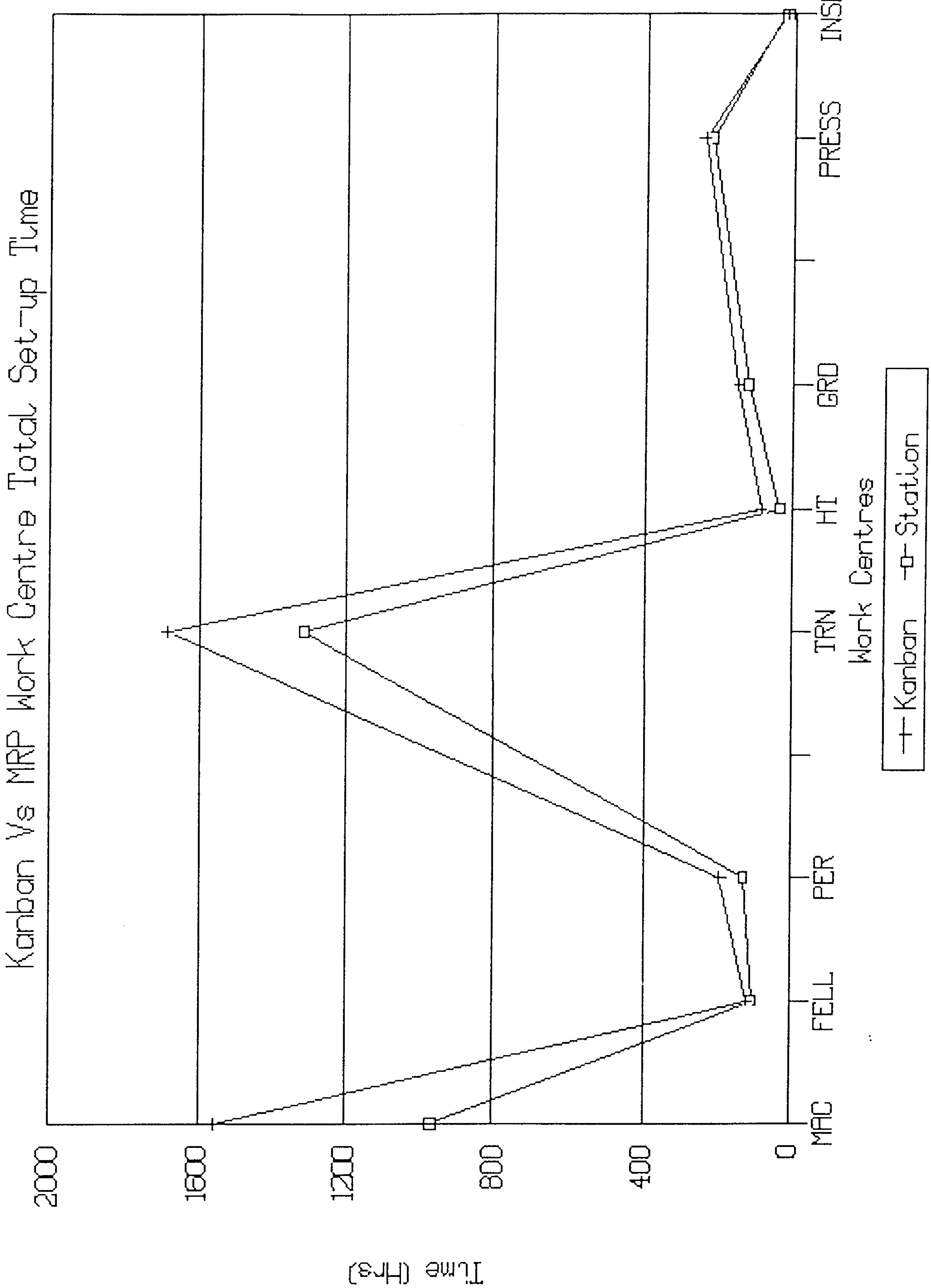


Figure 12.2 Kanban Work Centre Set-up Time

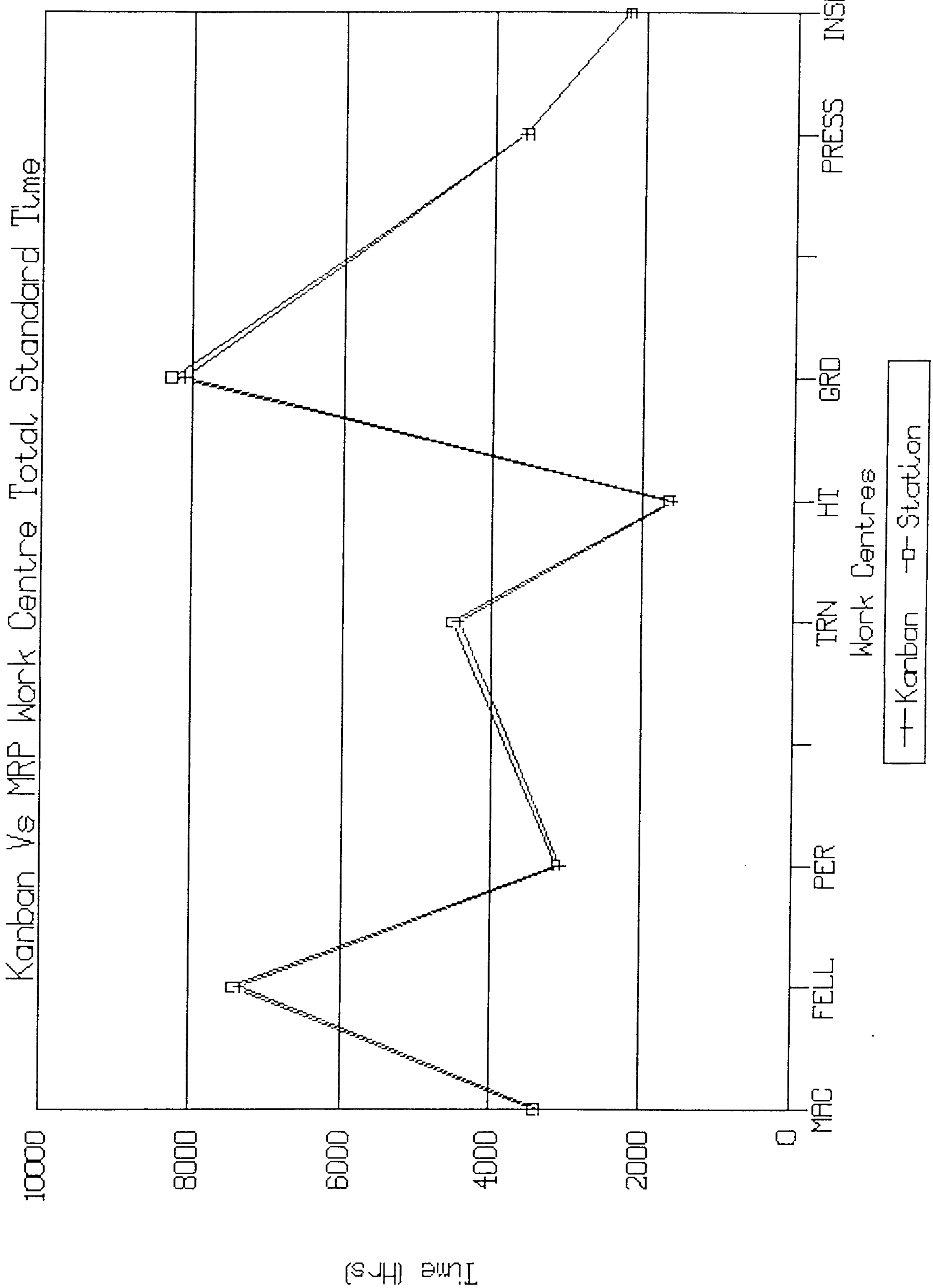


Figure 12.3 Kanban Work Centre Standard Time

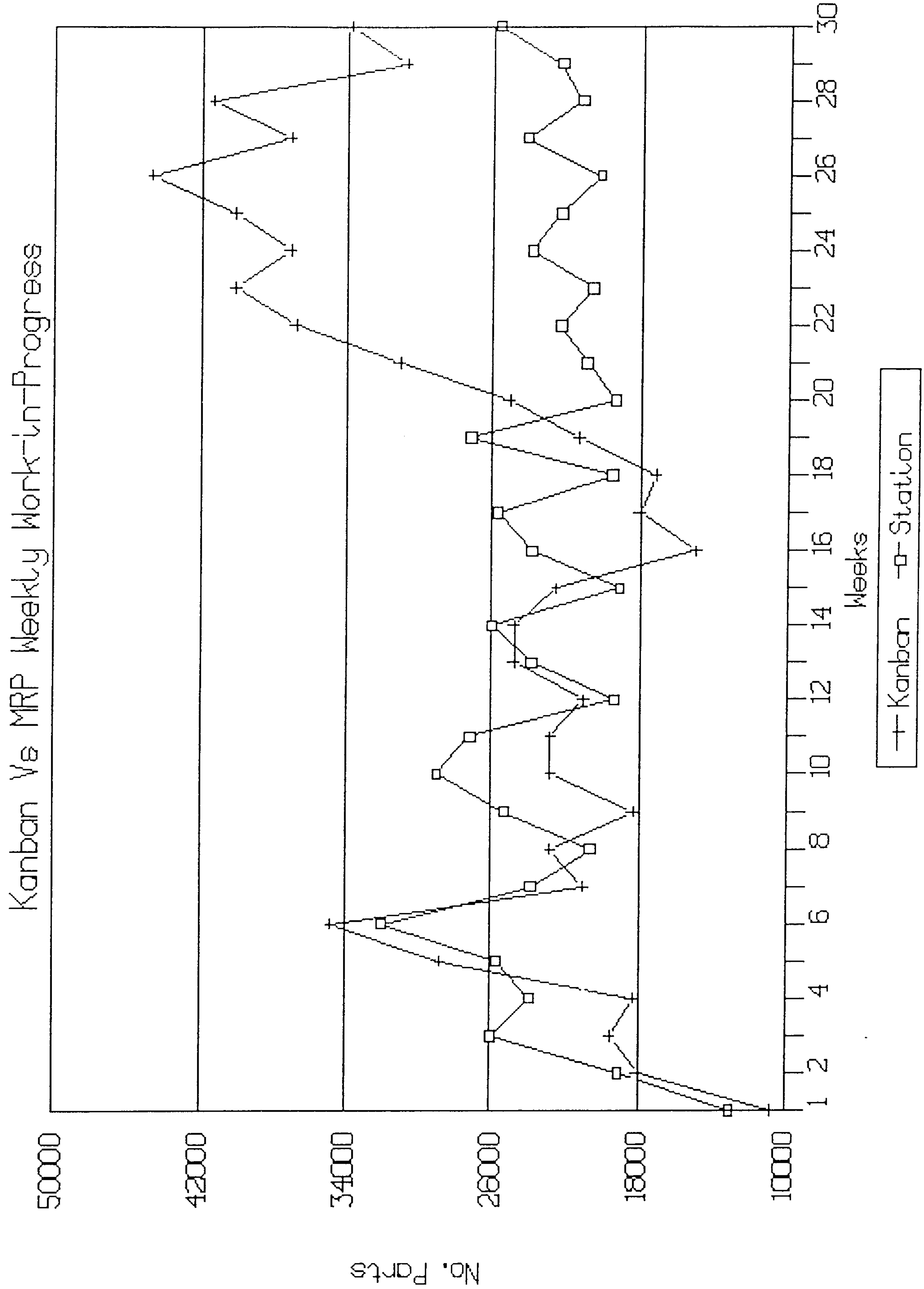


Figure 12.4 Kanban System Work-in-Progress

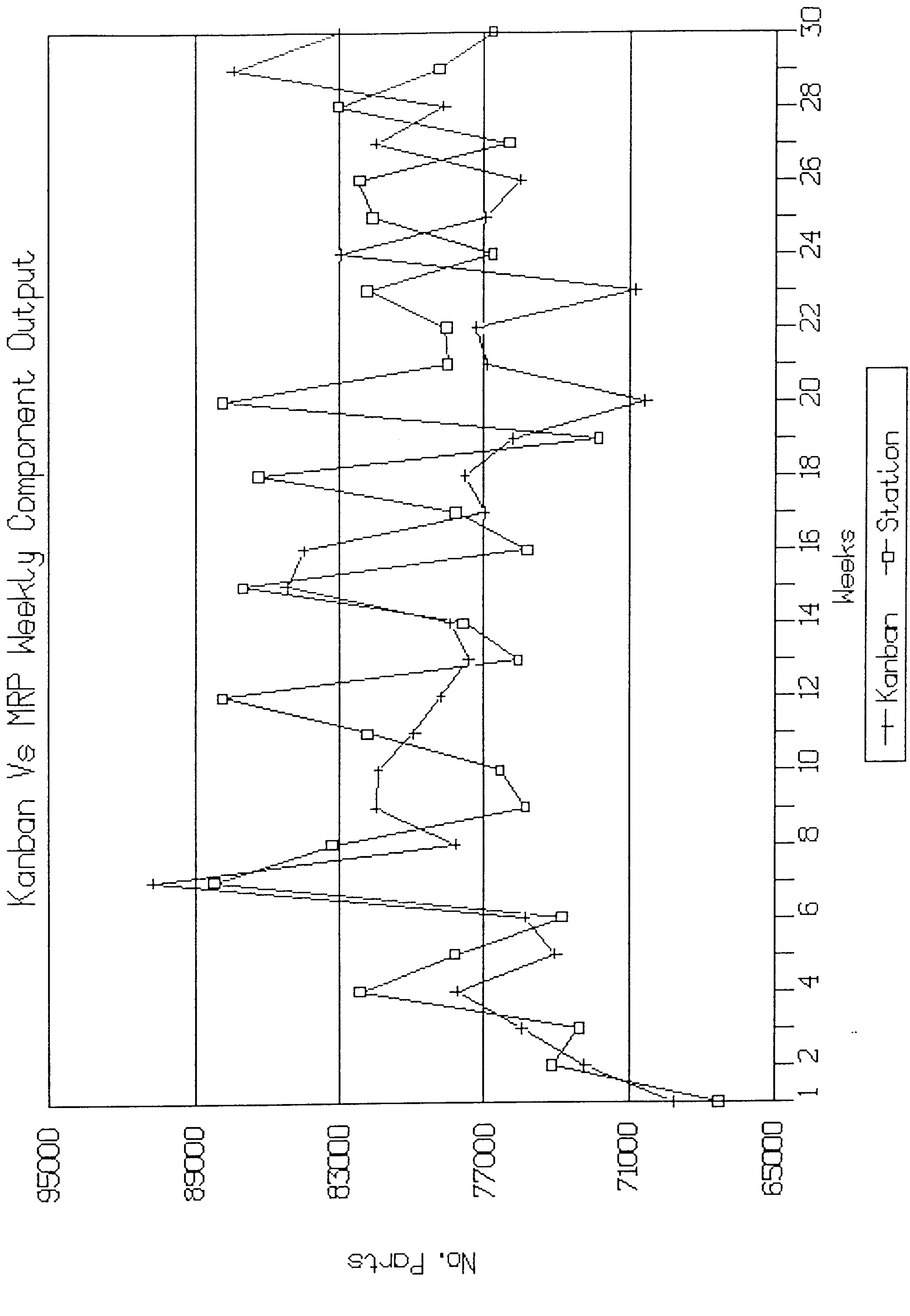


Figure 12.5 Kanban System Component Output

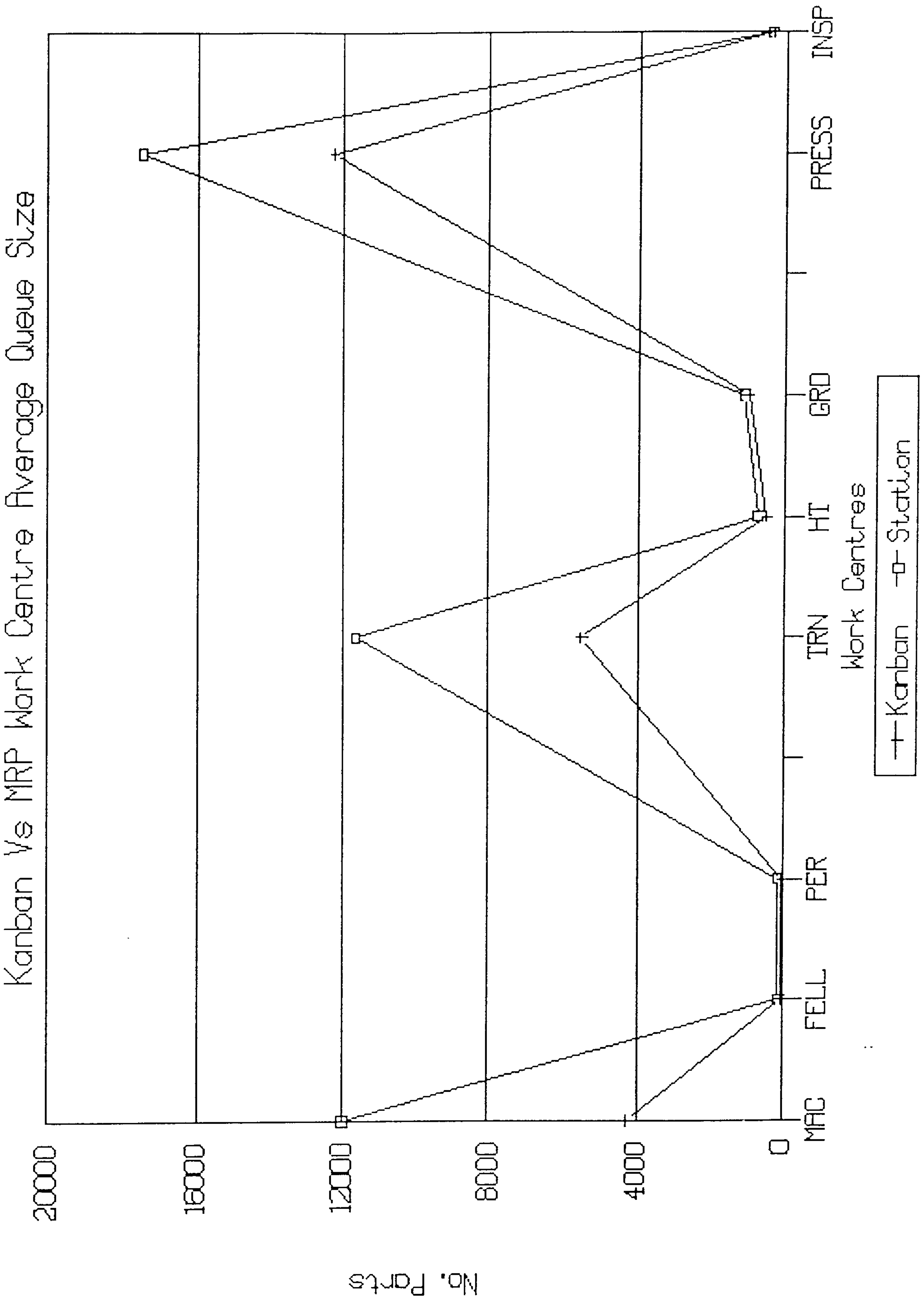


Figure 12.6 Kanban Average Work Centre Queue Size

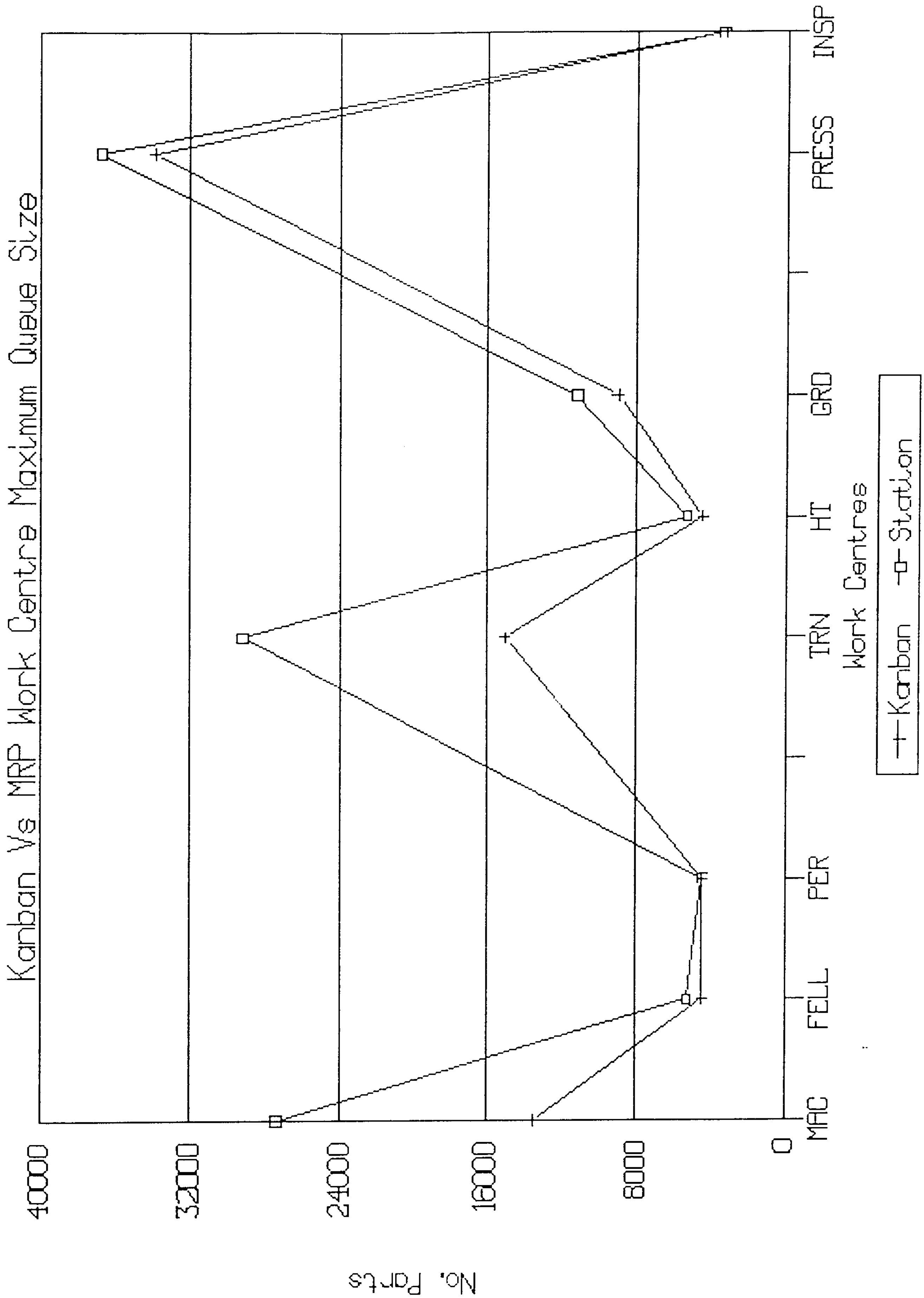


Figure 12.7 Kanban Maximum Work Centre Queue Size

significantly less under kanban than with the MRP system adopted in the station model. This is indicative of the approach, which so closely relates manufacture to both actual customer demand and current stock levels (i.e. a pull system). This differs from an MRP push system which generally issues work in chunks, accumulating batches and then simultaneously releasing them at a specific point in time (i.e. the start of a period). Additionally as the system determines new orders on the basis of both expected customer demand and the availability of stock, it tends to inflate order quantities because of the inevitable differences between actual and expected in such things as customer demand, scrap and rework.

Furthermore both the predicted average and maximum batch waiting times (figures 12.8 and 12.9) support the above results by suggesting that batches wait at first operation work centres far less under kanban than with MRP. However, it must be remembered that with kanban batches arrive into the system in much smaller quantities. Whilst due to the specification of transfer quantities all downstream operations in the station model under MRP control operate on batch sizes similar to those in the kanban system. Consequently in the station model, batch waiting time at first operation work centres is based upon larger quantities than in the kanban model. Though some of the differences can be contributed to the same reasons as those discussed with respect to centre queue sizes. That is with kanban the average total number of components ordered per week is smaller than under MRP control, therefore fewer components are being produced, and so less congestion.

The average batch waiting time predicted for the

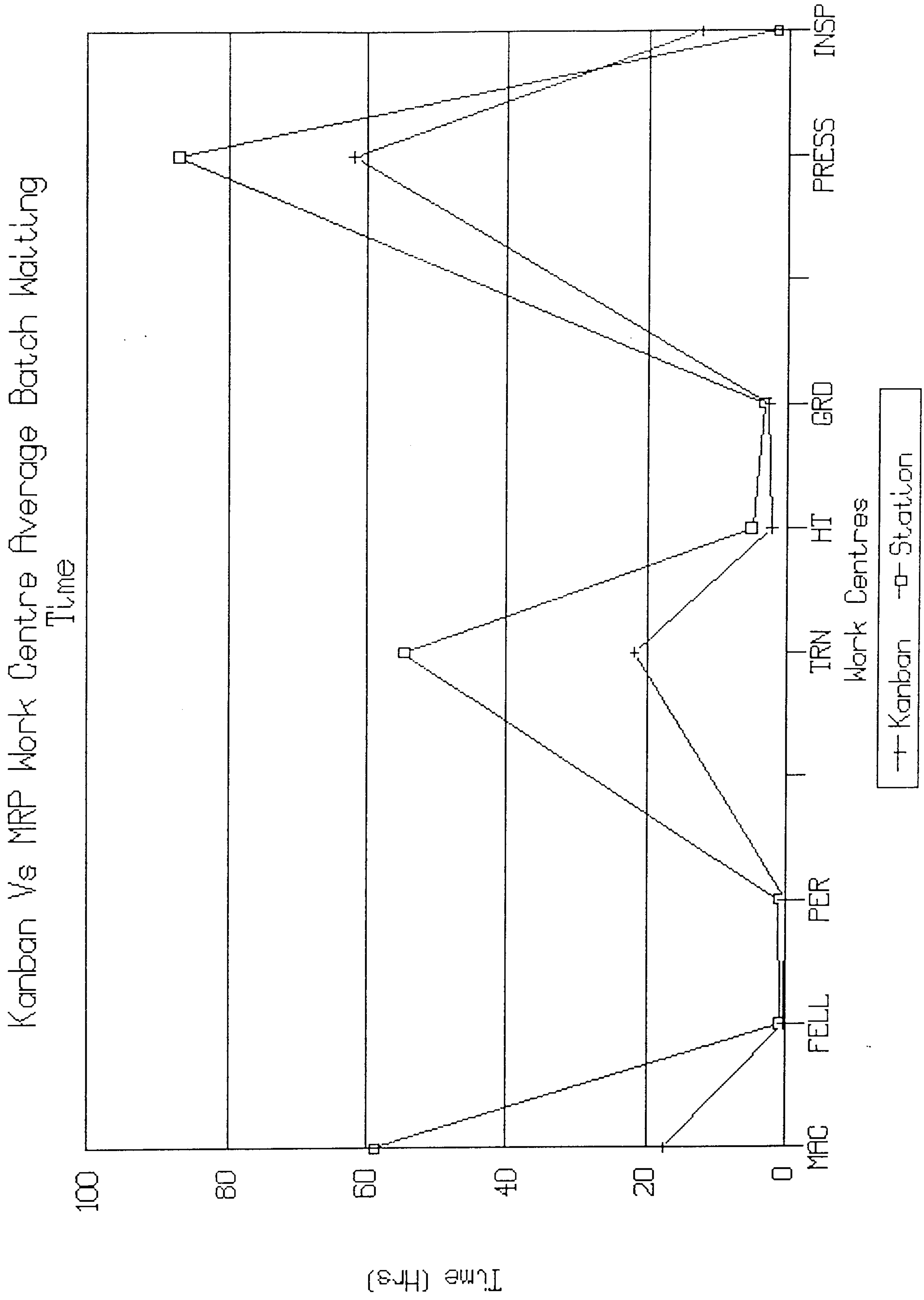


Figure 12.8 Kanban Average Work Centre Batch Waiting Time

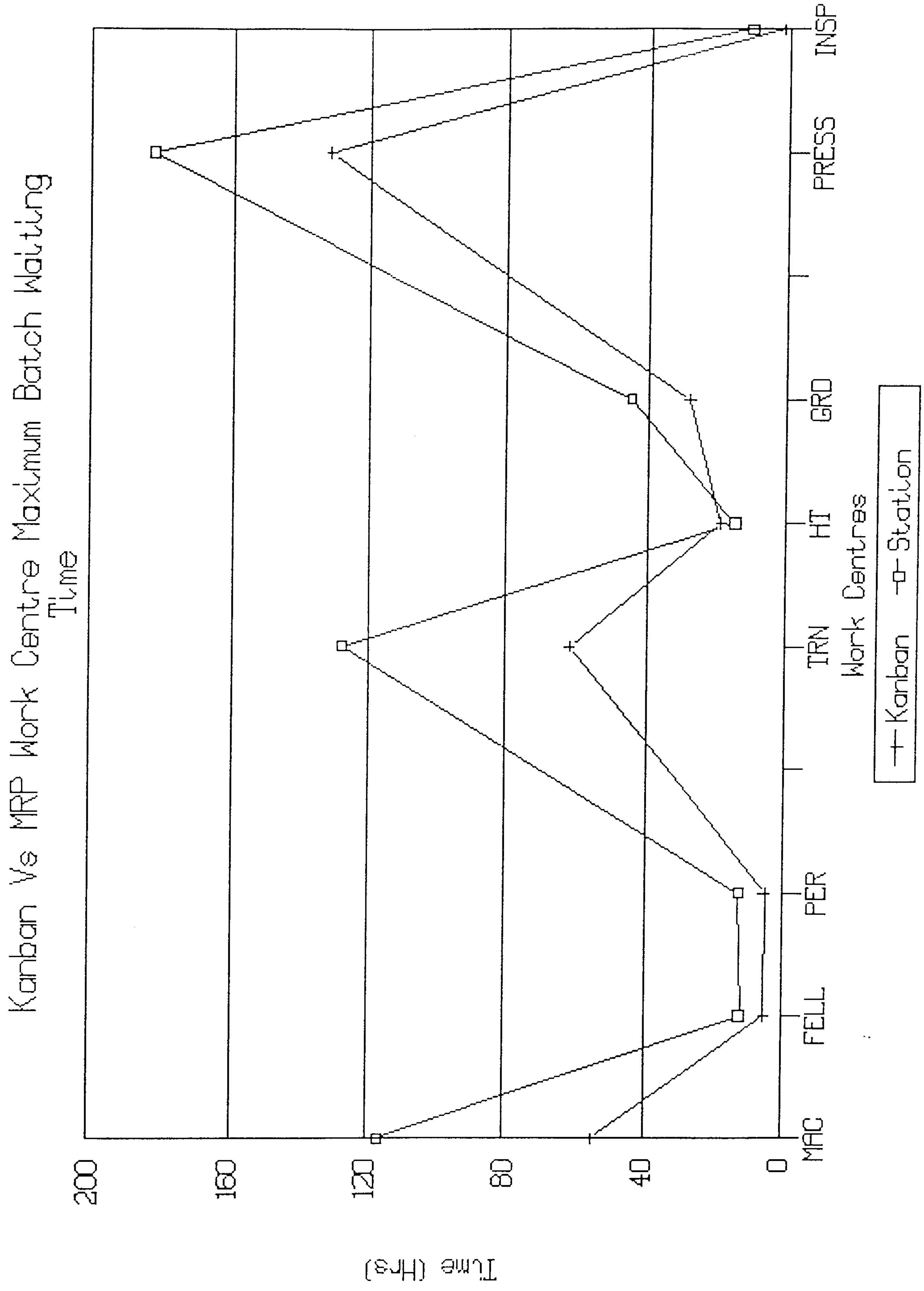


Figure 12.9 Kanban Maximum Work Centre Batch Waiting Time

INSPECTION work centre under kanban control again highlights the potential problems of introducing such a system. Due to the increased number of set-ups, batches are having to wait longer at the work centre before being processed.

Finally and perhaps most obviously the predicted batch lead-times are generally and quite significantly smaller with kanban (figures 12.10 to 12.12) because of the reduced batch sizes. Furthermore because of the reduced waiting time incurred at all first operation work centres (which have such a substantial effect on overall lead-times, section 11.4.4) and the uniform batch sizes, then generally component lead-times are approximately equivalent. Assembly batches, however, vary dramatically from component to component and are not necessarily better than those predicted under MRP control. This is largely attributable to the problem of component availability in order to perform the assembly operation (section 11.4.4), caused by poor batch flow through the kanban systems.

12.3 Concept Validity

To demonstrate that the ATOMS simulator was suitable for practical application and therefore relevant to real problems, it was used to evaluate and identify the implications of introducing new production scheduling techniques into two existing manufacturing systems. The two case studies are discussed below.

12.3.1 Production Control Design: Case Study No. 1

The first application of ATOMS to an existing manufacturing facility was concerned with the implementation

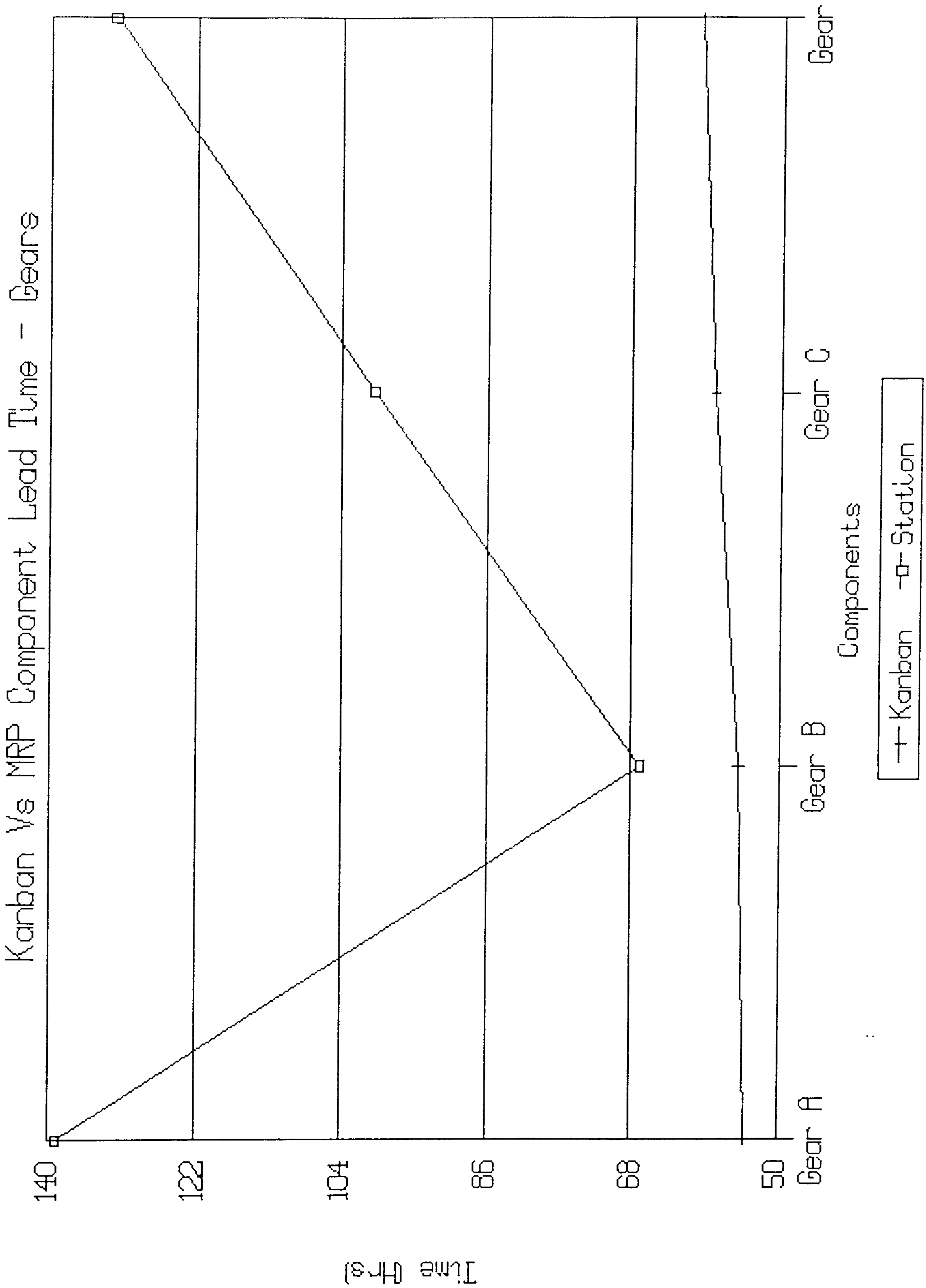


Figure 12.10 Kanban Component Lead-Time - Gears

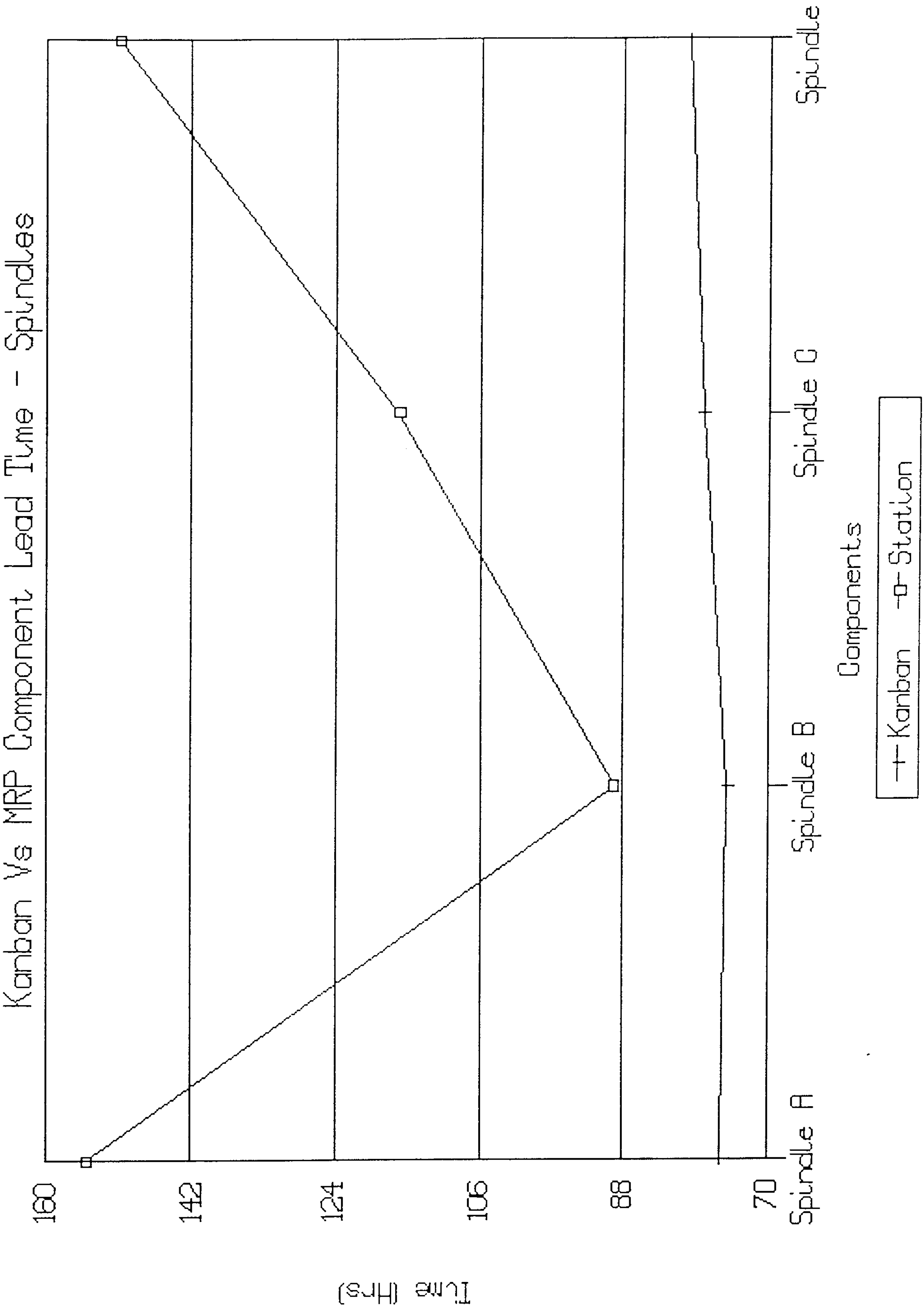


Figure 12.11 Kanban Component Lead-Time - Spindles

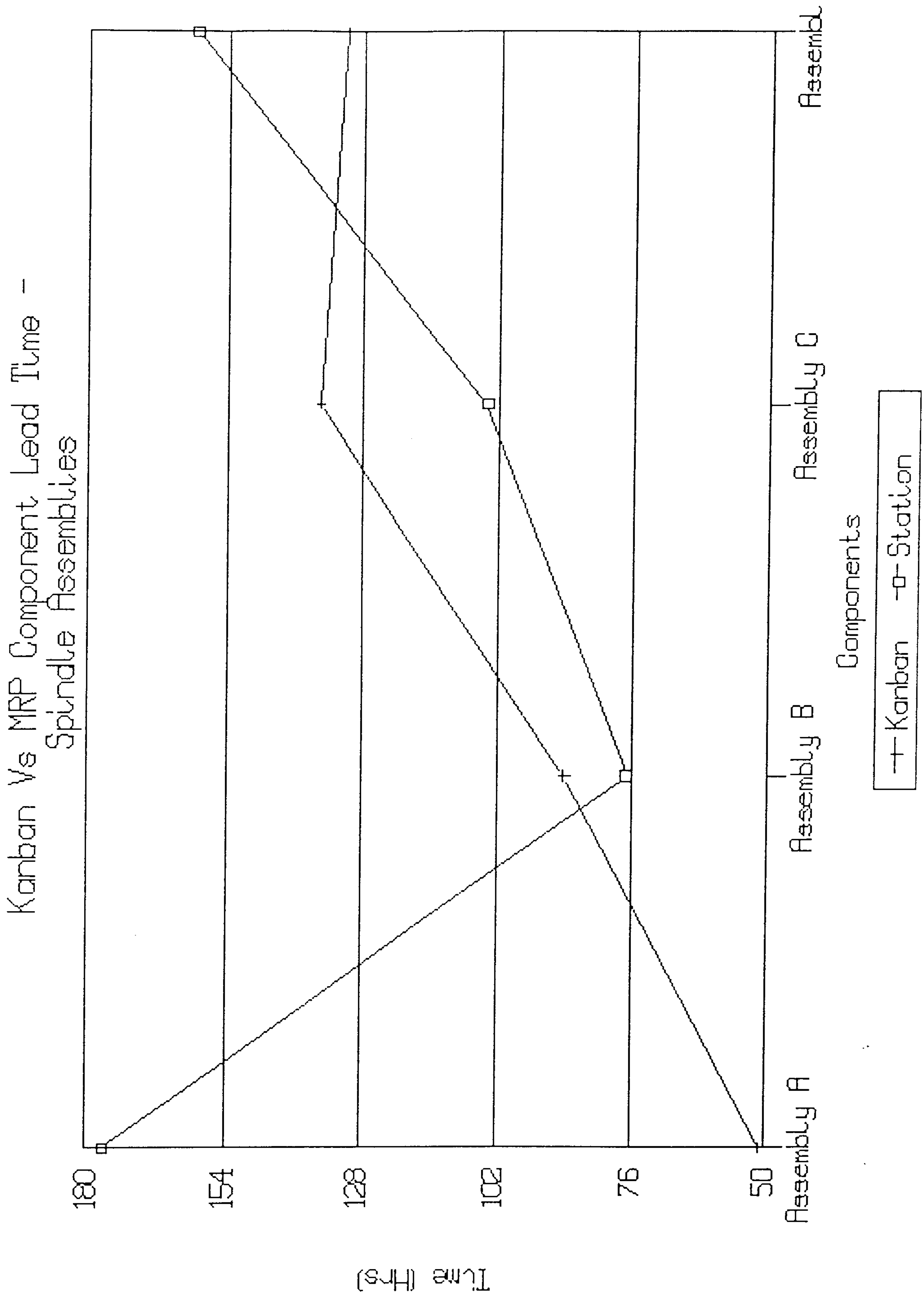


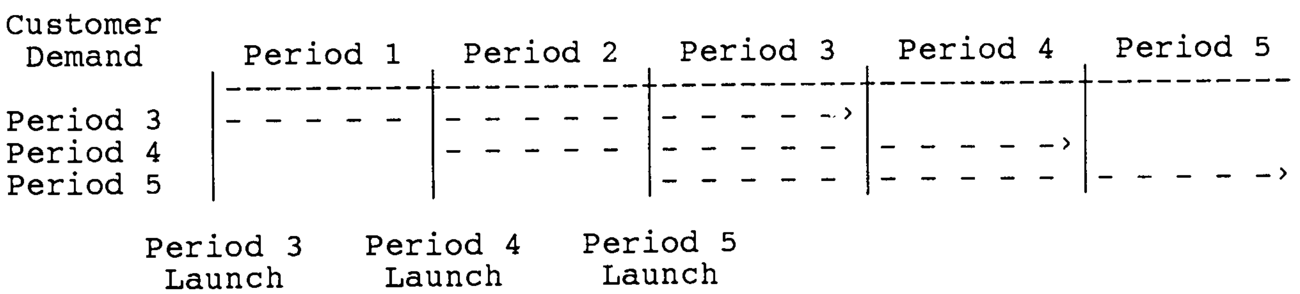
Figure 12.12 Kanban Component Lead-Time - Assemblies

of a period flow control (PFC) system to manage component manufacture. Ultimately PFC is the manufacture, within a given period, of all customer requirements for that particular time interval. Where a period generally reflects the frequency of customer demand and so can be any length of time from a day, week, month or year, which ever is the most appropriate. PFC assuming that all work is available at the start of the period and customer requirements are due at the end. Consequently the system determines component lead-time (i.e. one period) and system inventory and implies the apportioning of manufacturing capacity between all components.

When component lead-times are actually greater than one period the aim is to manufacture the customer requirements for one period over several periods. Implying that the requirements for more than one period are being processed at any time. For example:

customer requirements = 50 units/period,

lead-time = 3 periods.



Therefore whilst manufacturing one period's worth of customer requirements, due in the third period, two further batches of components have to be released (i.e. in periods two and three) in order to fulfil demand in the fourth and fifth periods, respectively. Consequently at any time there are three periods worth of components being processed, amongst which available manufacturing capacity has to be divided. Hence capacity is divided into "time buckets", which specifies the amount of processing time any batch can have done during a particular period. Hence:

$$\text{Time bucket (hrs/period)} = \frac{\text{Manufacturing Capacity (hrs/period)}}{\text{Number of Batches In System}}$$

and

$$\text{Average Lead-time (periods)} = \frac{\text{Total Batch Processing Time (hrs)}}{\text{Time Bucket (hrs/period)}}$$

It was clearly understood that the introduction of PFC does not directly create any system improvements, in terms of inventory, lead-times or stock turns, but does, however, maintain any benefits once they had been achieved [McKibbin, 1989]. The problem here therefore, as reported by Mckibbin, related to the introduction of PFC into a system currently containing, on average 300 batches WIP, and concerned three interrelated system elements:

- capacity,
- inventory (i.e. number of WIP batches), and
- lead-times.

Capacity was labour constrained and fixed at 2200 hrs per period with approximately 300 batches live in the system at any time.

Therefore:

$$\text{time bucket} = \frac{2200}{300} = 7.3 \text{ hrs per period}$$

and with each batch on average requiring 54 hours of work

$$\text{average lead-time} = \frac{54.0}{7.3} = 7.4 \text{ periods.}$$

This was felt excessive especially when lead-times were, for several components, already substantially less than 7.4 periods. Though other components were significantly higher. PFC would therefore ensure a more consistent lead-time overall components. However, 7.4 periods was unsatisfactory. The above identified that capacity was fixed and lead-times were a function of both capacity and the number of batches in the system. Therefore an investigation, using ATOMS was undertaken to evaluate what effect the reduction in WIP (i.e. number of batches) would have on predicted batch lead-times, resource utilization, component output and the average WIP level. The system under investigation contained:

- 240 individual part numbers,
- 2600 total operations,
- 40 machines,
- 17 operators on day shift,
- 4 operators on night shift,
- 70 work orders per month.

The main advantages of using ATOMS for the investigation being that:

- the exercise would not involve any model formulation, translation or verification,
- evaluation could switch quickly and easily between MRP and PFC material management systems,
- component routing information could be used directly from an existing computer database, and
- actual MRP generated works orders could be fed directly into ATOMS.

The ability to use existing data directly from either a mainframe or PC database, being provided by ATOMS through its capability to automatically generate models from text files (figure 12.13). Together with its built-in calendar allowing the input of "real" works orders with actual release and due dates (i.e. DD/MM/YY), which ATOMS automatically converted into simulation time (i.e. minutes from the start of execution). Consequently there were no lengthy data input activities. The modelling exercise therefore was characterized by:

- quick and simple model configuration,
- model amendments easily incorporated,
- fast execution, and
- extensive investigation, through numerous iterations, made possible by the previous features.

The data for individual models was specified within a PC database and down loaded into ATOMS through ASCII text files; ATOMS taking approximately five minutes to generate new models. The results from each simulation exercise then being imported into a PC spreadsheet package for analysis.

The computer models developed for the investigation were all deterministic, with the core data (i.e. set-up and standard time for all operations) being obtained directly from a computer engineering database in which established operation times were stored. The impracticalities of establishing statistical distributions for all 2600 set-up and standard operation times, precluding the generation of a stochastic model. Having estimated that it would take a minimum of three months to gather sufficient data on which to produce the

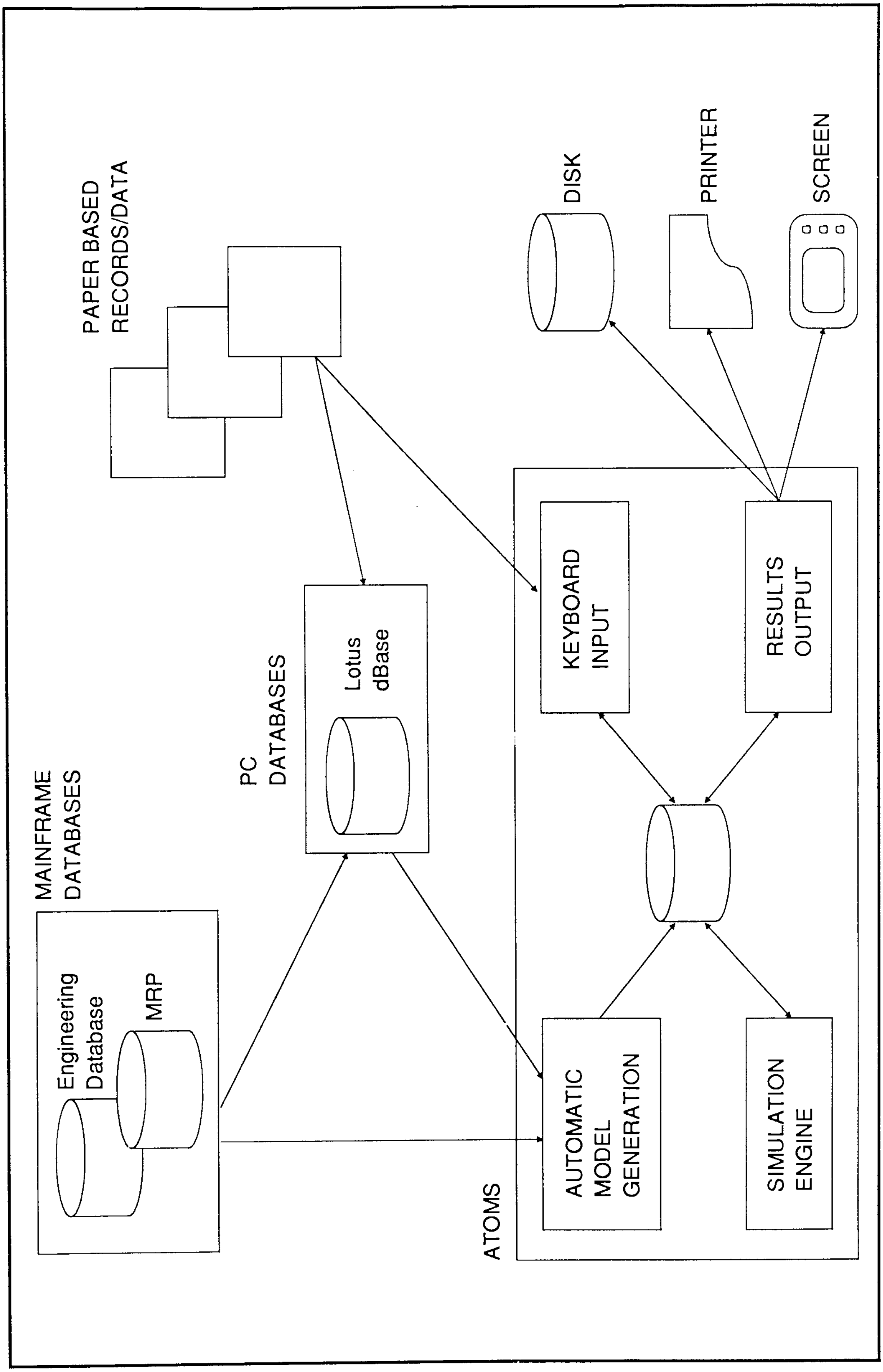


Figure 12.13 ATOMS Application Model

distribution, because of the frequency of operations and the size of the task. There being no information currently available with regards to variation of actual operation times. Furthermore such a data gathering exercise would, in this case be superfluous, as operation times were predominantly machine based and therefore relatively deterministic, with only slight variation due to operator involvement. In addition machine breakdowns were irrelevant, having negligible effect on resource availability and the completion of operations.

The investigation commenced by establishing the validity of the simulation model upon which subsequent analysis of the implementation of PFC would be based. Consequently ATOMS was configured to reflect current operational procedures. A statement of current WIP in the system being used to set initial starting conditions, with works orders, generated in accordance with the actual MRP system, being released on a daily basis. The model was evaluated over a 52 week period, with results being recorded at weekly intervals and then compared with actual system performance measures for the pervious 18 months, in terms of:

- overall average component lead-time,
- average resource utilization,
- average component output, and
- average WIP.

Furthermore operational managers examined the results in order to confirm that the model was a sufficiently accurate representation of reality, and therefore credible.

Having gained confidence in the accuracy of the model, PFC was introduced with works orders now being release on a monthly basis. The model again being simulated for 52 weeks, with the same initial starting conditions as before. To assess the effect of reduced inventory on the performance of PFC, the initial WIP was then reduced by 20 batches and re-evaluated against the same monthly input of works orders. This process was repeated until there was no initial inventory and the four measures of performance (i.e. lead-time, utilization, output and WIP) from each model were then compared (figures 12.14 to 12.17).

Analysis of the results indicated that a 50% reduction in the number of batches in the system would reduce batch lead-time by approximately 45%, with minimal effect on both component output and resource utilization. PFC was therefore introduced into the existing manufacturing system with such a reduction in WIP. Six months later actual results were very comparable to those predicted by ATOMS, with a 55% reduction in WIP and an average reduction in lead-times of 54%.

12.3.2 Production Control Design: Case Study No. 2

The second application of ATOMS, like the first was concerned with the implementation of a period flow control (PFC) material management system. However, unlike the previous example, this implementation was based upon fixed partitions. A problem with the earlier, time bucket approach being the fact that it ignored congestion in the system and therefore queuing time at individual operations. This phenomenon though could have a significant effect on whether individual batches actually achieved the required amount of processing time for a given period.

At bottleneck operations, by definition, batches will

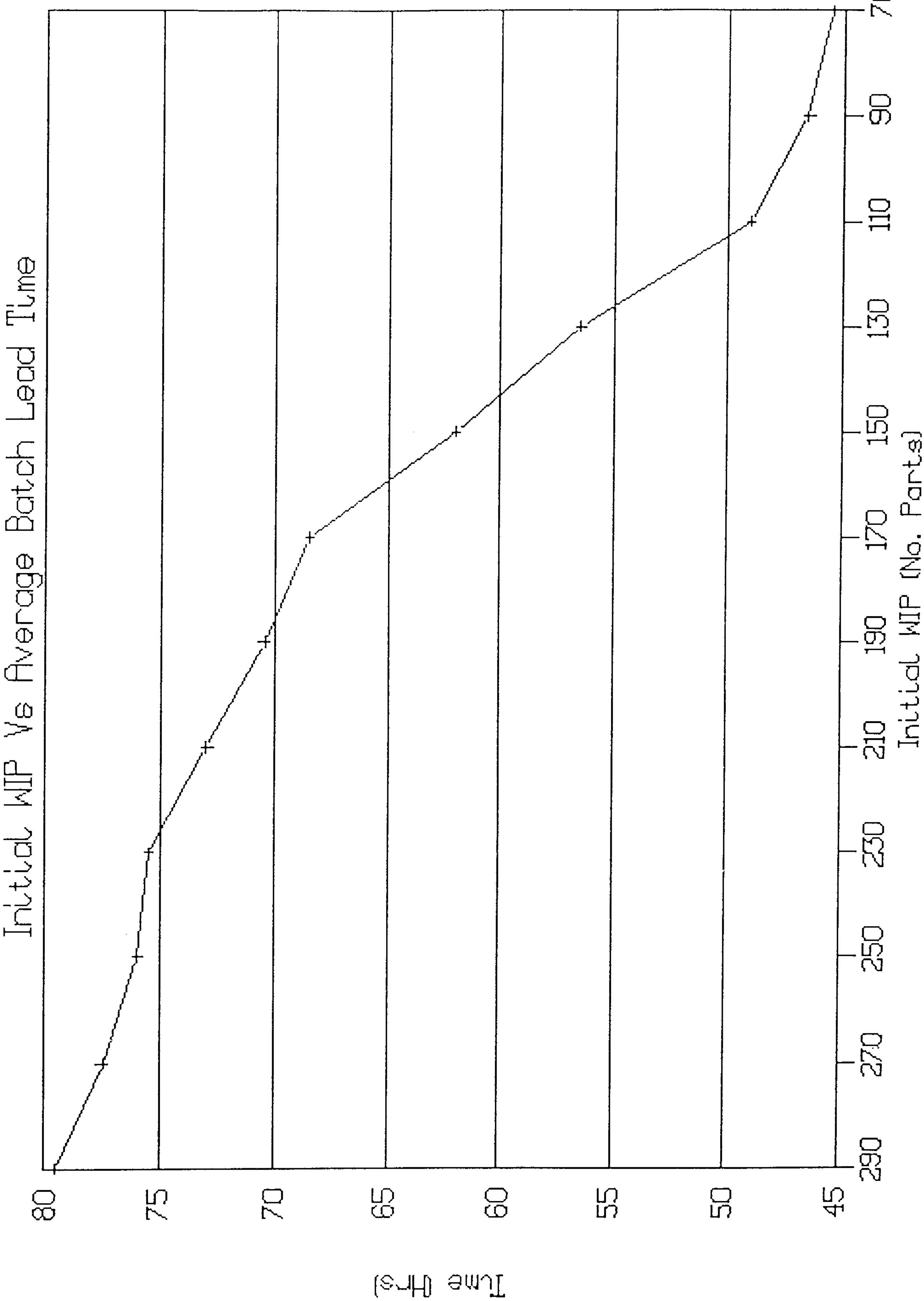


Figure 12.14 Case 1 - Initial WIP vs Batch Lead Time

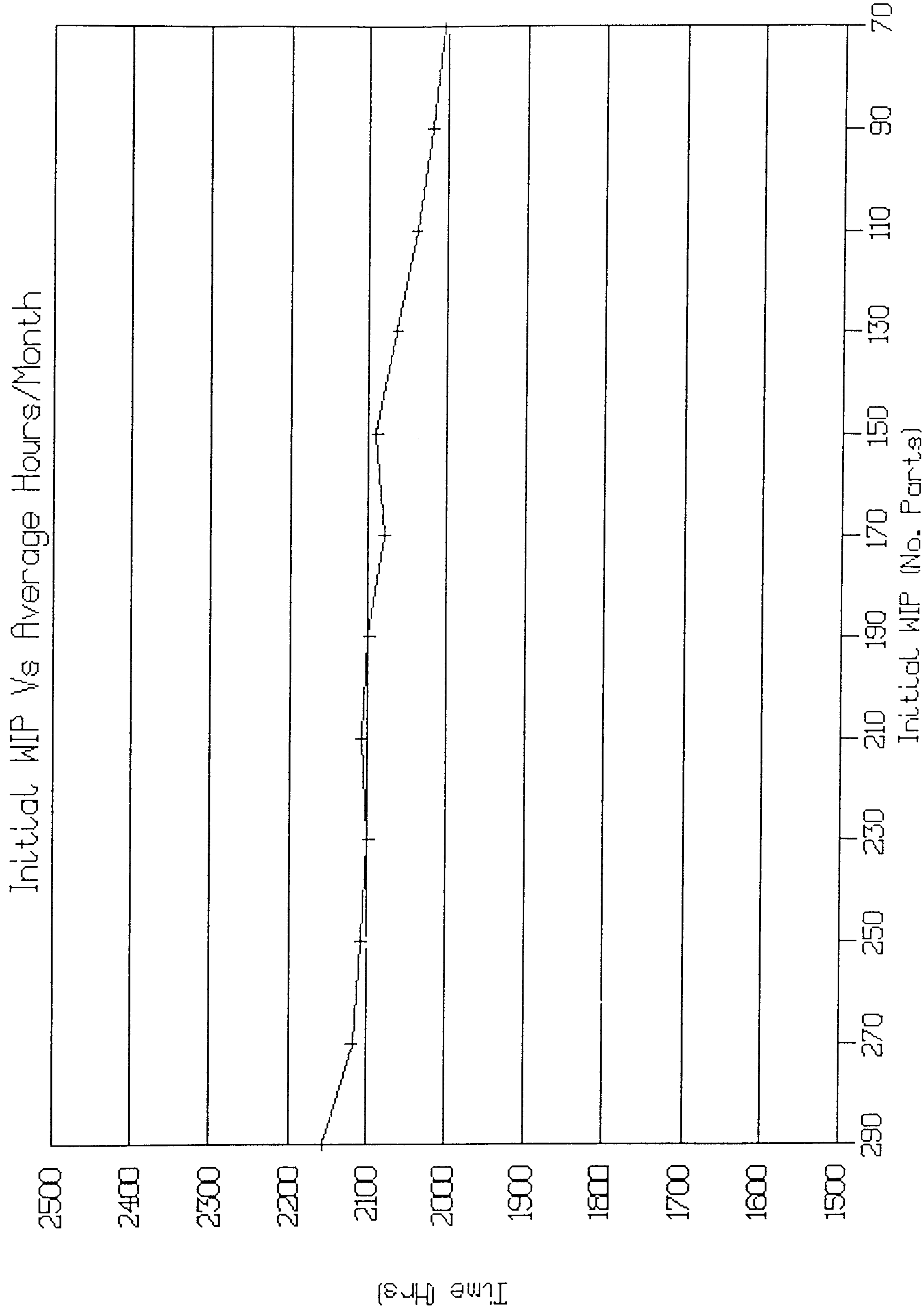


Figure 12.15 Case 1 - Initial WIP vs Standard Hours

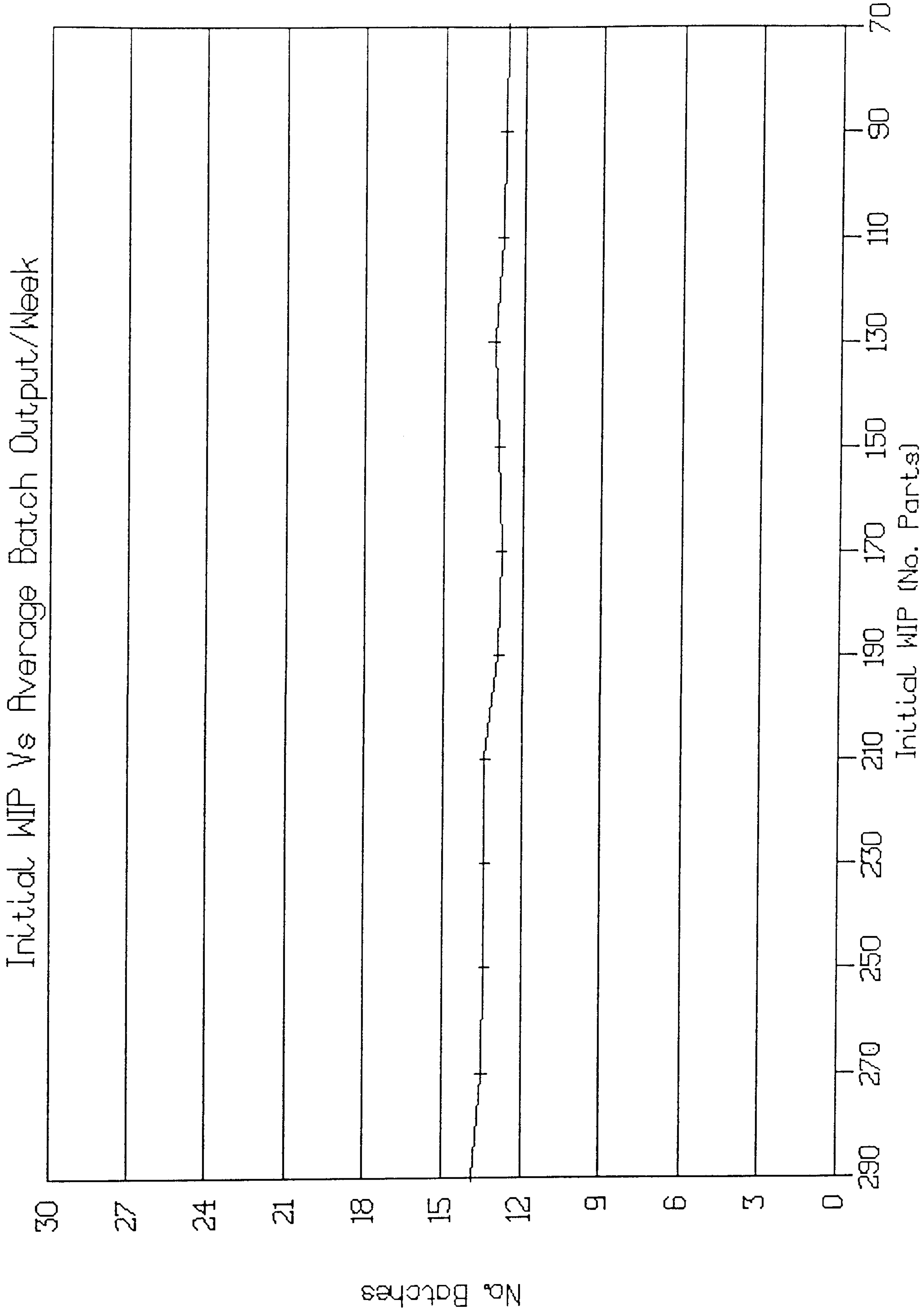


Figure 12.16 Case 1 - Initial WIP vs Batch Output

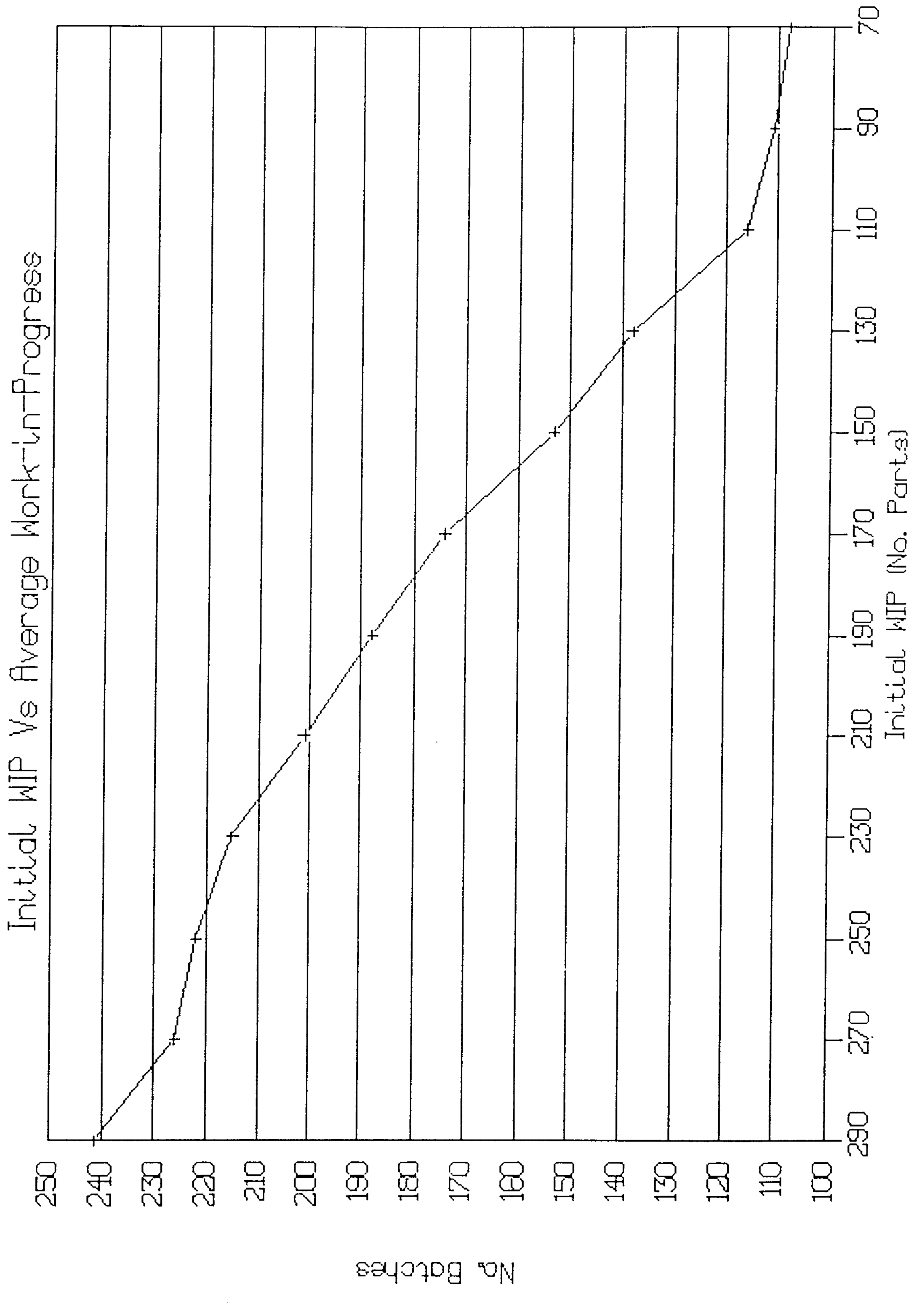


Figure 12.17 Case 1 - Initial WIP vs Work-in-Progress

have to wait before being processed. Consequently the longer they wait, the longer they take to pass through the operation and the less time there is available for other operations to be performed within the period. Hence the more congested an operation, the greater the waiting time and this obviously varies over a given period. To redress this problem therefore, the routing for each component is divided into fixed partitions (where one partition represents one period's worth of operations) taking into account bottlenecks. As a result a partition may contain a small or large number of operations to be performed in a period. Due to the nature and size of the task therefore, ATOMS was used to help divide component routes into appropriate and achievable partitions.

The system under investigation contained:

- 80 individual part numbers,
- 1090 total operations,
- 60 machines,
- 25 operators,
- both runner and repeater components [Parnaby, 1988b],
- an operator skills matrix,
  (i.e. which operators work which machines).

Again ATOMS' capability to automatically generate models from text files was used, with model data being stored, configured and down loaded from a PC spreadsheet. This also included works orders, generated directly from the MRP system, for the next 50 weeks, with release dates every two weeks.

The manufacturing operations consisted primarily of two types, those performed by the resources under consideration and those completed either by other areas of the factory or external suppliers. The latter operations therefore being modelled as subcontract work with a standard lead-time (as apposed to a set-up and standard time) and represented at the centre level, whilst all other operations were defined at the detailed, station level. The underlying models being deterministic in nature, principally due to the same reasons as given in the previous case study.

The investigation commenced by establishing the validity of the simulation model upon which subsequent analysis would be based. Unfortunately the manufacturing system had been newly re-designed and consequently there was no historical data available on which to base model validity. Furthermore the initial starting conditions within the model could not be realistically set to represent typical WIP levels, because of the lack of data. Model evaluation therefore started with an empty system and waited to reach a steady-state situation before results were taken. Hence model validation involved comparison of the predicted steady-state performance with rough-cut capacity calculations (performed on a spreadsheet), hypothesis validation (by stepping through each event) and some face validation by operational managers with experience of the manufacturing system before the system re-design. Together with a data validation exercise to assess the accuracy of set-up and standard operation times.

Having confirmed the accuracy of the model, it was first evaluated without PFC, in order to identify bottleneck operations, in terms of machine utilization and average and maximum batch waiting time. Once the bottlenecks had been established, the component routes could be partitioned and a two week PFC system introduced. The model was then evaluated, with attention focusing predominantly on those batches which failed any given partition. Partitions were then reassessed and the evaluation process repeated. This continued until the partitions were correct and the model predicted no batches failing any partitions.

In addition this particular exercise provided the opportunity to evaluate the ATOMS manufacturing simulator approach against conventional methods, by comparing it with the commercial Witness simulation package. At the same time as the above exercise was being performed, Witness was being used to evaluate another part of the manufacturing system. The two facilities under investigation being very comparable, in terms of both size and complexity. The two exercises started at the same time, with each being allocated a site engineer to undertake the actual simulation modelling. The comparison identified the benefits of the ATOMS approach to include:

- a substantially shorter exercise, being completed in two weeks, as apposed to eight, and
- faster model execution, approximately four times as quick.

The benefits arising from:

- no requirement for simulation expertise,
- no model programming involved,
- no program debugging i.e. verification,
- standard ASCII text file data input facilities,
- efficient modelling, using both centre and station representation.

12.4 Conclusions

The objectives of these experiments was to demonstrate that a computer simulator can be applicable to a range of conventional discrete batch manufacturing systems. The experiments have clearly illustrated that a simulator can contain sufficient flexibility to accommodate the major elements and issues regarding manufacturing systems, without undertaking any form of computer programming. In addition it has been established that such a simulator is a practical and valuable tool, being highly relevant to existing systems. In general the benefits gained through these experiments are indicative of configurable, manufacturing system simulators.

The potential benefits of a computer simulator approach to dynamic system evaluation, as apposed to conventional techniques, having been demonstrated, in terms of:

- no required computer or simulation expertise,
- exceptionally quick model configuration and execution,
- comprehensive design investigation, by allowing model changes and amendments to be incorporated simply and easily.

Additionally the significance of the multi-level approach has been further highlighted by its relevance in modelling both essential and supporting operations efficiently. The principal operations being considered in detailed through the station representation. Whilst other operations, though not directly relevant but which have an influence on overall performance, were approximated by modelling at the centre level.

In order to undertake the PFC experiments, the mechanism had first to be incorporated into ATOMS. This recognises the fact that there may be instances were a simulator needs to be further developed, due to the introduction of new technology or operational procedures. These, however, represent minor modifications, whilst the principle of a manufacturing system simulator remains valid, as has been proven here.

Chapter 13 Conclusions and Future Work.

13.1 Multi-level Manufacturing System Modelling and a Computer Simulator Implementation

The complexity and interrelationships inherent within manufacturing systems means that the successful design of such facilities is dependent upon the coherent and opportune application of suitable individual design tools and techniques. Hence the necessity for a formal mechanism to monitor system development in order to ensure the effective and efficient use of available design techniques. To apply appropriate control to any given system design, it is important that development is assessed in respect of the initial manufacturing objectives, generally specified in terms of overall system performance measures. The only practical way of achieving this is through the application of dynamic computer modelling techniques, as all other design tools tend to be highly specific, achieving only local design optimization.

A survey of the application of computer modelling in manufacturing system re-design exercises established that very little use is made of the technique. Furthermore where modelling is applied it is generally only to check or verify a final design proposal and is not used to aid or support the original development. The lack of use is attributed to the excessive time and expertise required to implement such a technique. Hence resulting in a design process in which development is not effectively monitored, alternative system configurations are not thoroughly considered or investigated and final design proposals therefore are not necessarily the best or most appropriate.

Current design methodologies do provide a very structured and appropriate approach to manufacturing system design, but by failing to utilize the full potential of computer modelling techniques (as suggested by the survey), the overall procedure tends to be rather inefficient. Ignoring the opportunities for thorough design investigation early in the process when changes can be incorporated easily and cheaply. Instead restricting design opportunities by attempting to identify the final system configuration early in the process (when only limited data and information is available) and allowing progress to be made without assessing the full implications of design decisions with respect to the required performance objectives. A multi-level modelling strategy has therefore been proposed, which is intended to complement and support design methodologies by providing an effective means of monitoring progress, so making design more efficient. The main objectives of the modelling procedure being to allow:

- thorough and appropriate investigation of all possible design alternatives,
- evaluation throughout design with respect to required performance measures,
- progressive development of computer models in line with corresponding system designs,
- attention to focus on critical/bottleneck areas,
- continual evaluation to reduce possible errors.

The modelling strategy describes a procedure for applying the appropriate level of computer modelling support at each phase of design, so ensuring that system evaluation is efficient in terms of data requirements and speed of evaluation. Experimentation (chapter 11) showing that there are no advantages (in terms of improvements in the prediction of a system's performance) in representing non-critical or non-bottleneck areas in a detailed manner. Evaluation of cell 12 demonstrating that by representing non-critical areas in a more aggregated fashion reduces both the data requirements and time involved in producing and executing a computer model, without affecting the accuracy of the results. A fully detailed model of cell 12 taking 102 minutes to execute, as a opposed to a combined multi-level representation which took only 80 minutes, 20% quicker and reduced data requirements by 30%. Whilst the output results did not differ by more than 3-5% and both demonstrated similar trends.

An underlying assumption of the multi-level modelling strategy, without which it cannot work, is that computer modelling techniques are quick and easy to implement, allowing models to be progressively extended overtime. However, as previously indicated, current methods of implementing a model are ineffective and therefore inappropriate to support the proposed modelling strategy. Present methods requiring a high degree of expertise and incurring an excessive amount of time in both the creation and further modification of a computer model. An alternative approach is to adopt a computer simulator. A simulator being a specific application model with sufficient inherent flexibility to represent a pre-defined range of system configurations. The advantage of such a system being that it allows users, with no specialist expertise to apply computer modelling techniques quickly and easily.

Use of computer simulators has in the past been very restricted as they have tended to be too specific, only applicable to either the operational or physical evaluation of manufacturing systems, very rarely applying to both. Therefore lacking any generality which would make them relevant to a far more broader range of applications.

In order to implement and demonstrate the benefits of a multi-level modelling procedure, the ATOMS manufacturing simulator has been developed. ATOMS incorporates the proposed modelling procedure and is in tended as a practical evaluation tool, generally applicable to a broad range of less highly automated manufacturing systems. Over a variety of applications, including the cell 12 evaluation and two actual system re-design projects (chapters 11 and 12), ATOMS has proven its capability to represent a variety of different "real" system configurations. All the applications exhibiting similar characteristics:

- no requirement for computer or simulation expertise,
- fast model configuration and execution,
- model modifications incorporated quickly and easily.

The actual application of ATOMS to a real problem demonstrated that, in comparison with a conventional approach to computer simulation, modelling can be completed in approximately a quarter of the time, whilst individual models executed four times quicker. In addition the relevance of the multi-level modelling approach has also been established. Extraneous or subcontract operations, (those outside the bounds of investigation but having an impact on the behaviour of a system under evaluation) being represented at the centre level, whilst operations internal to the system were considered in absolute terms at the detailed, station level.

13.2 Mathematical Modelling

The implementation of the factory level evaluation in ATOMS was achieved through the use of the CAN-Q mathematical model, based upon close-loop queuing network theory. The implied benefits of such an approach being:

- fast evaluation, in terms of minutes, and
- minimum data requirements.

Experimentation, however, has identified certain circumstances where CAN-Q is not efficient. The use and benefit of a department level evaluation at times making a factory representation superfluous. Certain department models executing just as quick, if not faster than the corresponding CAN-Q model, with the added advantage of:

- the results being easier to understand and interpret,
- models contain more realistic assumptions, and
- links into lower or more detailed levels of evaluation.

Further work is therefore necessary to identify the appropriate areas of application for CAN-Q, where is does offer potential benefits over a department evaluation.

13.3 Multi-level Modelling in Manufacturing System Design

The multi-level modelling strategy, as proposed has demonstrated potential benefits in industrial applications. However, its full implementation in manufacturing system design has not been thoroughly validated. Such an investigation requiring the application of ATOMS to be studied throughout the major phases of a design project, taking a minimum of 4-6 months. The objective of this original work, however, has been concerned with developing and implementing the new manufacturing system modelling approach. Further work is therefore required to fully investigate the adoption and implementation of multi-level modelling procedures within manufacturing system design.

13.4 Implementation of a Manufacturing Simulator

Development of the ATOMS manufacturing simulator has demonstrated that model simulators can contain enough flexibility to model a wide and varying range of manufacturing systems and are therefore a practical and efficient means of implementing computer modelling techniques. However, it is recognized that new features will, in the future have to be incorporated into ATOMS. This is not to suggest that the original design considerations were not sufficiently comprehensive. The statement simply acknowledges that in the future new technology and/or methods of operation will be developed and generally introduced into manufacturing systems. Subsequently these new techniques would then have to be incorporated into an existing simulator. Hence model simulators require continuous modification/maintenance during their life. It is therefore recommended that manufacturing simulators are implemented through an object-orientated programming language, especially as tools are now becoming available, which allow such techniques to be applied on IBM compatible personal computers. The affinity between object-orientated programming and simulation having already been identified [O'Keefe, 1986; Zeigler, 1987; section 5.3.7]. The advantages of object-orientated programming being:

- that it provides an effective, well structured environment for modular programming,
- resources can be represented as autonomous objects,
- new objects can be easily created or modified, without affecting overall system behaviour.

13.5 Computer Graphics

An objective of the ATOMS manufacturing simulator was to validate the use of model simulators as generic manufacturing system evaluation tools. This is concerned with the flexibility of a simulator, and directly relates to its functionality. Computer graphics do not add too a simulator's modelling functionality or ability to emulate a given manufacturing system, therefore no time was spent on developing such a facility. However, graphics are necessary for two reasons. Firstly to allow a user to communicate easily, to someone unfamiliar with the project, both the results of the evaluation and of the underlying model. Secondly, to allow users to gain confidence in the evaluation procedure within a simulator. This includes data verification (e.g. a user has correctly defined component routes, operator/machine allocations, etc.) as opposed to model verification, the latter having been performed during the original system development. Without computer graphics it is difficult for users to validate the evaluation process, graphics providing a vivid picture of the current state of a model, making it easy to understand what is happening and see why certain things are occurring

13.6 Batch Scheduling

The range of potentially different types of resources and methods of production control found in most manufacturing systems is finite, and an objective in the development of a generic simulator is to incorporate all possible variation. However, in terms of work or batch sequencing there is in effect an infinite range of possible algorithms. In practice it is impossible to provide sufficient standard routines to coupe with all potential variations. All manufacturing simulators therefore simply provide a number of standard algorithms, which in the case of ATOMS are FIFO, LIFO, fixed schedule, shortest set-up and least slack. The restricted availability of alternative sequencing rules could potentially limit the use of a simulator especially when one of the major uses of computer simulation techniques is to develop and evaluate alternative methods of operation. It is important therefore that within a manufacturing simulator, sequencing rules/algorithms can be "user-defined", (in terms of both model data variables and mathematical and logic operators) in such a way that did not require any computer programming.

13.7 Operational Application

In addition to supporting the design of manufacturing systems, computer models are used to develop feasible production schedules. The production scheduling task involving a complex assessment of available resources, inventories and operations. Computer simulation can therefore be used to assess the appropriate work load to be placed on a system by predicting system performance under alternative production schedules. Hence the benefits of a model simulator apply just as well to the operation, as they do the design of a manufacturing system, in terms of:

- generally accessible by non-experts and experts alike,
- applicable to a wide range of manufacturing systems,
- allow total user influence over model features,
- involve short, minimal model development lead-times,
- necessitate minimum system training requirements.

However, for operational use a simulator requires good financial modelling and reporting facilities. Furthermore the system needs to allow simple manual interaction with the specification of a production schedule, as ultimately this is what a user is attempting to optimize. Hence for operational use, further work is necessary to develop the financial modelling facilities and to investigate the coupling of a computerised planning board with interactive graphics to a manufacturing simulator.

13.8 Training

The potential for misusing a manufacturing simulator is an area of great concern when such a system is adopted. Although the implementation of a model through a manufacturing simulator removes the necessity for both simulation and computing expertise, there are additional issues to be resolved in order to undertake a successful simulation exercise. Model validation and experimentation are both qualitative activities which ultimately determine the foundation and accuracy of future decision making. However, by simplifying the implementation of a computer model the fear is that it will encourage inexperienced users to undertake simulation exercises quickly, without appreciating the necessity for either model validation or experimentation. Resulting in poor and inappropriate decision making. Users of manufacturing simulators cannot therefore be allowed to utilize such packages without first clearly understanding the potential "pit-falls". However, the simplicity of a manufacturing simulator allows more time and effort to be spent on teaching model validation and experimentation techniques. In addition, to reduce the potential errors incurred by inexperienced users of simulators, further work is required into the development of expert systems to support the implementation of successful computer simulation exercises.

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