A SYSTEMIC APPROACH TO THE DESIGN OF CELLULAR MANUFACTURING SYSTEMS

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Thesis Summary

Cellular manufacturing is widely acknowledged as one of the key approaches to achieving world-class performance in batch manufacturing operations. The design of cellular manufacturing systems (CMS) is therefore crucial in determining a company's competitiveness. This thesis postulated that, in order to be effective the design of CMS should not only be systematic but also systemic. A systemic design uses the concepts of the body of work known as the 'systems approach' to ensure that a truly effective CMS is defined.

The thesis examined the systems approach and created a systemic framework against which existing approaches to the design of CMS were evaluated. The most promising of these, Manufacturing Systems Engineering (MSE), was further investigated using a series of cross-sectional case-studies. Although, in practice, MSE proved to be less than systemic, it appeared to produce significant benefits. This seemed to suggest that CMS design did not need to be systemic to be effective. However, further longitudinal case-studies showed that the benefits claimed were at an operational level not at a business level and also that the performance of the whole system had not been evaluated.

The deficiencies identified in the existing approaches to designing CMS were then addressed by the development of a novel CMS design methodology that fully utilised systems concepts. A key aspect of the methodology was the use of the Whole Business Simulator (WBS), a modelling and simulation tool that enabled the evaluation of CMS at operational and business levels. The most contentious aspects of the methodology were tested on a significant and complex case-study. The results of the exercise indicated that the systemic methodology was feasible.

Keywords: Simulation, Cellular Manufacturing, Group Technology, Enterprise Modelling, Manufacturing Systems Design

Dedication

This project is dedicated to Naomi, Jed and Faye

Acknowledgements

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I would also like to acknowledge and thank my colleague, Jeff Barton, with whom the BroomCo model discussed in Chapter 8 was developed. Without the help and collaboration of Jeff, the model and experiments would never have been completed.

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Chapter 1

Introduction

1.1 Cellular Manufacturing System

Cellular manufacture is an approach to manufacturing that was originally based on Group Technology (GT) type principles. The main theme of GT when applied to component manufacture is the formation of parts families on the basis of either design or manufacturing similarities. Once these families are formed they are used to achieve efficiencies throughout a company, by exploiting these similarities. However, the main benefits usually arise from (Hyer, 1984) :

- Product Design, used for example to reduce product variety
- Manufacturing Engineering, to produce standardised routings to reduce effort required
- Cellular Manufacture

Cellular manufacture is the physical division of at least a portion of a manufacturing facility into cells. A cell may be defined as (Hyer & Wemmerlov, 1984):

> 'a collection of machine tools and materials -handling equipment grouped to process one or several part families'

There are two fundamental characteristics of cellular manufacture. Firstly, components are classified into different families and secondly, machines are arranged into groups. This compares to functional manufacture where machines which are similar in nature (e.g. lathes) are located next to one another and there is no dedication to the manufacture of particular parts families.

More recently, two generic types of cell have been developed. These are process cells and product cells. Process cells manufacture a family of parts that have been determined as having similar manufacturing (or process) requirements. Product cells manufacture all the parts for a particular product, despite the fact that they may not have similar manufacturing characteristics. Product type cells are therefore not necessarily based on GT families.

The use of cellular manufacturing principles is becoming widespread. Ingersoll Engineers (1990) undertook a survey that indicated that 65% of UK companies had used or were using cells. Of these approximately 58% were using process orientated (GT) cells and 77% product orientated (vertically integrated) cells. In another more recent survey, Fritz et al (1993) found that only 10% of companies that were in their sample were not considering the use of cells. In fact, Burbidge (1992) suggests that process (functional) based manufacturing is 'obsolete'. Drucker (1990) claims that by 1999 the successful plant will be based on modular (cellular) manufacturing principles.

Just-In- Time (or JIT) manufacture has gained widespread acceptance as a means of significantly improving performance in todays competitive market place. Cellular manufacture is one of the key building blocks required for the successful implementation of JIT (Schonberger 1982, 1986). In fact Wemmerlov & Hyer (1989) claim that it is difficult to imagine JIT systems that do not employ cellular manufacture. Cellular manufacture also plays a central role in the implementation of CIM. It is claimed that cellular manufacture overcomes the following disadvantages that have been noted for functional layouts (Burbidge, 1982):

- Very complicated material flow systems causing very long leadtimes, high stocks, high W.I.P. and very low stock turnovers

- Responsibility for the production of components cannot be fairly delegated to line managers. In a factory with a functional / process layout, line managers are only responsible for processes and not products. Therefore, it is impossible to delegate responsibility for due date compliance, quality conformance or cost.

In contrast, it is claimed that manufacturing cells reduce leadtimes (and thereby reduce inventory and improve market response times) and create teams of people that manufacture a complete family of parts often leading to superior motivation (Alford, 1994) and higher product quality. Typical benefits as reported by Wemmerlov & Hyer (1989) are:

45% reduction in throughput time
40% reduction in Work In Progress
30% reduction in space required
30 % improvement in product quality
30% reduction in finished goods inventory
25% reduction in labour cost

Ingersoll Engineers (1990) reported that approximately 50% of companies in their sample reported leadtime and work-in-progress reductions of at least 50%. However, there is not universal agreement on the benefits of cellular manufacture. Flynn and Jacobs (1987) for example, claimed that a well planned functional layout gave superior performance to an equivalent cellular layout.

It is proposed to focus this project on the design of cellular manufacturing systems because:

- they are particularly related to batch manufacture which is the dominant form of manufacturing environment.

- material flow patterns may be either similar to process layouts or flow layouts thus allowing the possibility of conclusions to be drawn for the manufacturing systems design process in general.

- they have demonstrated their ability to significantly improve manufacturing performance and are key to the successful implementation of JIT and CIM.

It should be noted that the use of the term 'design' does not only imply the creation of new greenfield facilities. Typically, as Fritz et al (1993) indicate, 'optimisation' or 'redesign' of an existing ('brownfield') facility is the main focus of design activity. This project deals with the design of cellular manufacturing systems in this inclusive context.

1.2 Project Thesis

The thesis of this project is that to be effective, cellular manufacturing systems must be designed not only *systematically* but also *systemically* (i.e. must be designed using a systems approach). It is important to distinguish between these two terms :

- Systematic: an orderly and well disciplined way of getting things done (Jenkins, 1969).

- Systemic: a form of thinking based on wholes and their properties which is used to tackle the problem of irreducible complexity and the concept of emergent properties. There should be a focus on holistic rather than reductionist thinking (Checkland, 1981).

Designing cellular manufacturing systems is not a trivial problem (Chryssolouris, 1992). There is increasing recognition that manufacturing needs to be considered in a holistic manner (Hitomi, 1979, 1990, Dale & Johnson, 1986, National Academy of Engineering, 1987, Heim & Compton, 1992). This is because manufacturing systems are dynamic with many interacting components and multiple performance requirements that may conflict. Companies are operating in a continually changing environment and there is an increasing need to (re)design manufacturing systems to improve productivity or to cope with a higher rate of new product introductions.

1.3 Project Overview

The project set out to examine the validity of the above proposition. The project began by reviewing the systems approach to create a framework for the evaluation of current ways of designing cellular manufacturing systems. The approaches to the design of cellular manufacturing systems were classified according to a taxonomy developed for the project. Each category was then reviewed against the systemic framework to establish its deficiencies in this respect. Chapters 2 and 3 document these activities.

Arguably the most systemic of these approaches, Manufacturing Systems Engineering (MSE), was then examined by a detailed cross-sectional analysis of a number of industrial implementations. The outcome of this analysis is detailed in Chapter 4. This investigation yielded an interesting dilemma. In its application MSE was shown to be less than systemic but still provided significant benefits. Therefore, two longitudinal studies were undertaken to establish if these benefits were both long-lasting and exhibited at a business level. This process is reported in Chapter 5. These studies supported the original contention.

The remainder of the project activities focussed on the development of a systemic design methodology to overcome the problems previously identified. The need for an appropriate simulation tool (Whole Business Simulation) was identified and this is discussed in Chapter 6. A methodology embedding the use of this tool was developed. The most contentious aspects of the methodology were investigated for feasibility by a series of laboratory and action research based experiments. Chapters 7 and 8 report these activities.The degree to which the project thesis has been supported is discussed in Chapter 9 and areas for future work identified.

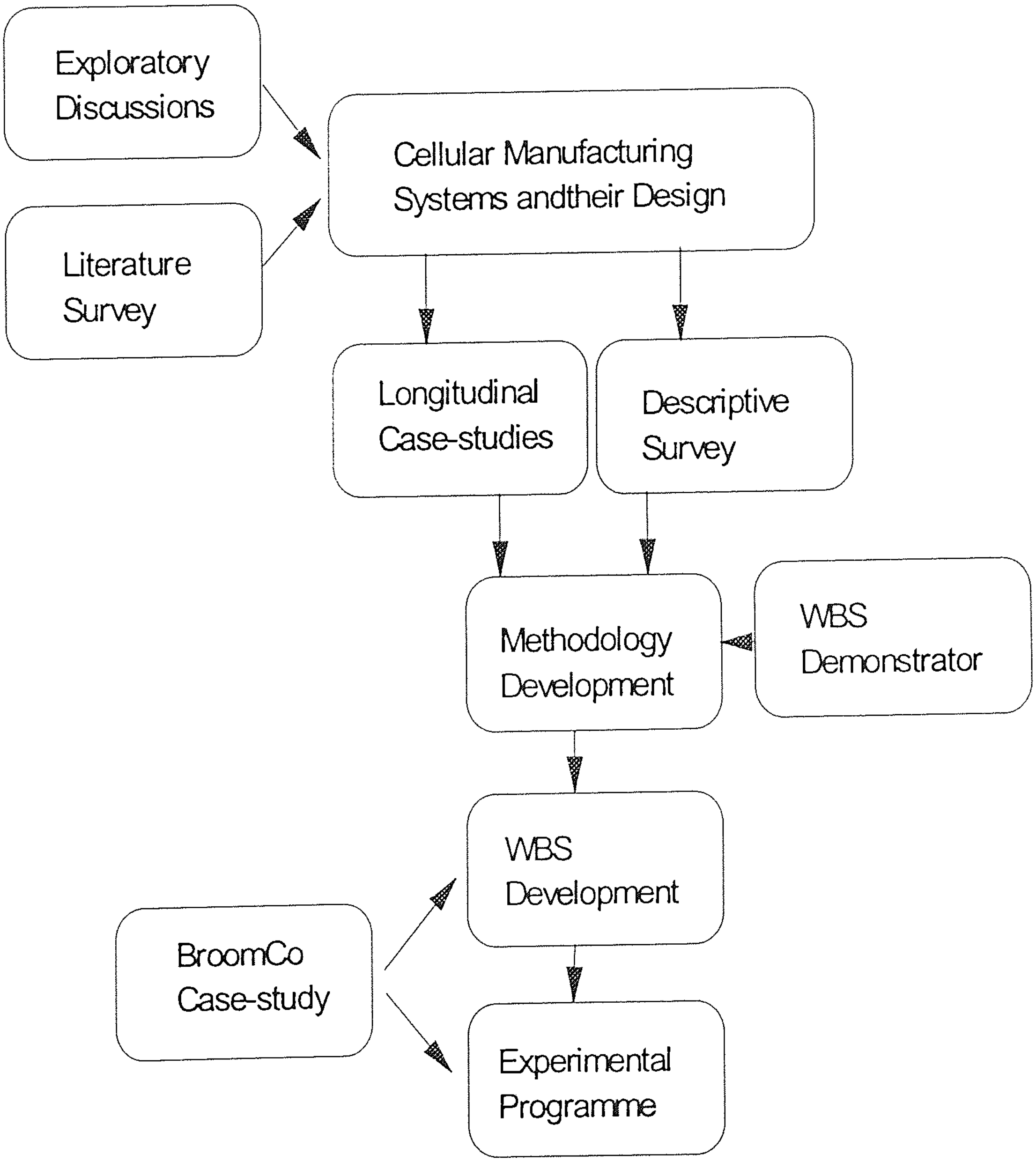
1.4 Overall Research Methodology

The overall research sequence that was followed closely mirrors the model proposed by Howard and Sharp (1983). A broad area of research was identified (cellular manufacturing). This area was identified as a consequence of its perceived importance to the improvement of manufacturing performance. A topic in this area was then selected. The process of selecting the topic involved undertaking a substantial literature survey to help identify the gaps in the current body of knowledge with regard to cellular manufacturing. Discussions were also held with academic and industrial practitioners in cellular manufacturing to aid this process. The survey and discussions resulted in the design of cellular manufacturing systems being selected as the topic to be investigated. This particular topic was selected as it was felt that it provided a substantial opportunity for making an original and useful contribution to the body of knowledge in the field of cellular manufacturing.

Following the detailed selection of the topic, the approach to the execution of the project was determined. It was recognised that the approach to the project would involve the use of a range of different research methods. For example, it was felt appropriate to use a descriptive survey for the collection of data concerning the application of Manufacturing Systems Engineering (Chapter 4). Longitudinal studies employing ethnographic research methods (see Gill and Johnson, 1991) were used to achieve the depth of insight that is given in Chapter 5. The development of the systemic methodology and its testing (detailed in Chapters 6 and 7) employed an action research type approach. The philosophical basis for these methodological choices are detailed in the relevant chapters. In addition, a review of the relevant literature (found predominantly in Chapters 2,3 and 6), was undertaken to provide a critical and insightful evaluation of the current state of the art with regard to the design of cellular manufacturing systems.

After the overall approach to the research project was determined, a plan was formulated and the necessary case-study data collected and analysed. This analysis provided the requirements definition statement for the systemic methodology that is detailed in Chapter 7. The key aspects of the proposed systemic methodology were tested on a model of a substantial business (BroomCo). These experiments were not 'true' or 'classical' experiments involving the use of experimental and control groups. This proved impractical (in terms of time and money) due to the nature of the work being undertaken. For instance, two teams of people would have had to undertake the design of a substantial manufacturing facility in parallel and unaware of each other. One team would have had to use the proposed systemic methodology and the other current best practice. The competing solutions would then both have had to be implemented and the performance compared after some time in operation. Instead, a number of 'quasi-experiments' were undertaken in the laboratory and field to demonstrate the feasibility of the proposed methodology. The superiority of the proposed methodology rests therefore, on a combination of its inherent systemic nature (compared to current approaches to the design of cellular manufacturing systems) and its feasibility. The overall research methodology is illustrated in Figure 1.1.

Figure 1.1 : Research Methodology



Chapter 2

Systems and Manufacturing

2.1 Introduction

Chapter 1 proposed that, to be effective, approaches to the design of cellular manufacturing systems, need to be not only systematic but also systemic. This chapter explores the concept of the systems approach further. By considering manufacturing systemically, this chapter provides a reference framework against which to judge current approaches to designing cellular manufacturing systems.

2.2 Systems and Their Properties

The systems movement was born in the middle of this century from such diverse parentage as biology and electro-mechanical engineering, as a consequence of (Checkland, 1981):

> '... the inability of reductionist science to cope with real-world complexity'.

Before going on to discuss the detail of the systems approach it will be useful to say what is meant by a 'system' and detail what are regarded as the important properties of systems. A typical definition of a system would read (see for example Kast & Rosenzweig (1970) or De Greene (1970)):

> 'A plan or scheme according to which things are connected into a whole'.

The key words in such a definition usually being plan (or organised), connected (or combination) and whole (sometimes unitary whole).

The above definition of a system is very wide and could include any system. Katz & Khan (1966) established that it is useful to distinguish between man-made or 'contrived' systems such as a large industrial company (called 'Human Activity Systems' by Checkland (1981)) and 'non contrived' systems such as living organisms.

There are a number of properties of systems, listed below, that are widely accepted (Kast & Rosenzweig, 1970, De Greene, 1970, Checkland, 1981, Jenkins, 1969, Waelchli, 1992, Hitchins, 1992) and are key to the concept of systems and the systems approach:

Emergence
Hierarchy
Communication
Control

2.2.1 System Emergence & Hierarchy

Emergence is concerned with properties that exist at certain levels in a hierarchy of a system that cannot be explained by the properties of lower levels in the hierarchy. They are properties which have no meaning in terms of the parts of the whole. Systems exhibit a hierarchical structural decomposition. A system is composed of sub-systems and it itself is a sub-system within a wider supra-system. This is true of both contrived and non-contrived systems. The general model of organised complexity is that there is a hierarchy of levels, with each level being more complex than the level below it, and displaying emergent properties that do not exist at the lower level.

2.2.2 System Communication & Control

All systems have boundaries which mark the extent of the domain of the system.

These boundaries may be 'open' or 'closed'. Open systems have permeable boundaries and interact with their environment by allowing the passage of inputs and outputs such as materials, energy and information. In a hierarchy of open systems, maintenance of the hierarchy will entail a set of processes in which there is communication of information for the purposes of regulation and control. Closed systems do not interact with their environment and hence allow no transaction across boundaries.

Open & closed systems will eventually reach a state of maximum entropy (disorder or death). However, open systems may overcome this tendency to a state of maximum entropy by interacting with their environment to maintain a state of 'negentropic' dynamic equilibrium (information is sometimes called negative entropy or negentropy). To remain negentropic, systems require a control mechanism to feedback (usually negative) deviations in performance and to provide adaptive mechanisms to adjust to this information. All control processes rely upon a flow of information in the form of instructions or constraints. The link between communication and control is therefore very close. In order for appropriate action to be taken by any adaptive mechanisms, deviations in performance must be viewed against overall objectives for the system.

One key concept associated with the need for system control is Ashby's 'Law of Requisite Variety' (Waelchli, 1992) which states that to control a complex system, the controlling system must generate at least as much variety as the system being controlled. As Beer (1959) characterised:

> 'Only variety in the control mechanism can deal successfully with variety in the system controlled'.

Jenkins (1969) has also identified the key role of control in a system context:

> 'A systems approach takes away the undue attention that is given to the mechanics of the control of local loops and focuses the attention on the wider questions of where control should be exercised and how sophisticated it should be'.

The above represents the ideas that constitute what is generally known as General Systems Theory (G.S.T.), a theory concerned with the generality of systems and providing useful concepts for the analysis of a systems behaviour.

2.2.3 The Formal System Model

Checkland (1981) has brought the above concepts together into a practical model that can be used to apply systems thinking. This model is called the Formal System Model. Figure 2.1 summarises the key points of the model. The ideas inherent in this model give an important baseline against which to judge the application of systems ideas.

2.3 System Methodologies

G.S.T has not been very concerned with the development of tools or methodologies for use in practical problems. It has primarily been concerned with obtaining an understanding of the fundamental nature of systems and their behaviour. Clearly, there is a large gap between the concepts provided by G.S.T. and the methodologies necessary to solve problems that involve real-world complexity. Methodologies that can be used to analyse the behaviour of a system and understand it to bring about improvements are lacking (Jenkins, 1983). The next section of this chapter discusses methodologies of the kind necessary to solve problems that involve 'real-world'

complexity - problems of the type that would be found in a factory. These methodologies have been classified (Checkland, 1981) into two broad areas, that of 'hard' systems and that of 'soft' systems.

2.3.1 Hard Systems and Soft Systems Methodologies

Hard systems methodologies are concerned with designing systems and using systems ideas to aid decision making. Typically, such situations are seen as well structured problems that are unitary in nature. Within this context 'unitary' refers to systems where there is a designated singularity of purpose. Jenkins (1969) has defined 'hard' systems approaches as being concerned with:

> '... the activity of planning, designing, constructing and operating complex systems'

Checkland (1981) summarises the fundamental ideas lying behind hard systems methodologies (often termed 'systems engineering') as follows:

- the world is systemic;
- its systems include organisations and their sub-divisions;
- organisations can be described adequately in the language of primary tasks, that is to say as logical machines set up to achieve objectives;
- on this basis, improvements may be engineered.

These ideas assume that a system's objectives may be stated unambiguously, thus allowing the system to be engineered to achieve them. Human behaviour is seen as goal seeking. However, there are many real-world problems which are seen as 'problems' because their is no agreement on objectives or measures of performance.

This lack of agreement may not be due simply to a lack of understanding or information : it may be fundamental because:

- there are different ways of looking at a problem.
- a goal seeking model imposes false structure on the problem.

Thus, soft systems methodologies (SSM) have been developed as an attempt to find a framework in what might seem, at first, an unstructured problem where (Checkland, 1981):

> '... objectives are hard to define, decision taking is uncertain, measures of performance are at best qualitative and human behaviour is irrational'.

Hard and soft system methodologies that purport to be based on the above concepts are outlined below.

2.3.2 Systems Engineering

Many methodologies for creating complex systems have been proposed over the last 40 years. For example, Hall (1962) described a methodology for turning scientific advances into applications for human use, his account deriving from the experience of Bell Telephone Laboratories. The account owed much to the methodology developed by the RAND corporation during the 1950's. The flavour of the RAND systems analysis approach is best described by Quade & Boucher (1968):

> 'One strives to look at the entire problem, as a whole, in context, and to compare alternative choices in the light of their possible outcomes. Three sorts of enquiry are required, any of which can modify the others as the work proceeds. There is a need, first of all, for a systematic investigation of the decision-makers objectives and of the relevant criteria for deciding among the alternatives that promise to achieve these objectives. Next, the alternatives need to be identified, examined for feasibility, and then compared in terms of their effectiveness and cost, taking time and risk into account. Finally, an

> attempt must be made to design better alternatives and select other goals if those previously examined are found wanting.'

There is thus a fairly large body of knowledge around hard systems methodologies which has allowed a generic methodology for systems engineering to be developed. The stages involved in 'engineering' a system have become known as the 'systems life cycle'. The specific stages involved in the life cycle vary in description but there are essentially four steps in the application of systems engineering (Jenkins, 1969, 1983, Checkland, 1981):

- Systems Analysis
- Systems Design
- Implementation
- Operation

These elements are discussed in more detail below and shown in Figure 2.2.

Systems Analysis : This stage of the methodology is concerned with analysing the problem situation, defining both the hierarchy of systems surrounding the problem area and the system (with boundaries) to be studied. This allows a very clear picture of the role which the system being studied plays. Objectives for the wider system and the system under study must also be defined. Overall economic criteria should also be defined so that objectives that are conflicting may be 'traded off'. This might typically be achieved through the use of a weighted objective function. The first stage of the systems engineering methodology is thus concerned with deriving the desired emergent properties of the system and understanding the hierarchy in which the system exists. Input / Output analysis is often used at this stage of the process to model the system under review and understand why the system behaves the way it does.

Systems Design (or Synthesis) : System design must be based on future requirements which are determined by forecasting both the expected values and estimates of the accuracy of this forecast. The forecasting stage is followed by a model building and simulation activity where the system design is tested against steady state (or average) and dynamic (or time varying) conditions. Control systems should be an integral part of the system design and not an afterthought as is often the case. Using a systems approach to design control mechanisms means a change in emphasis from concentration on localised control mechanisms to a consideration of control of the system as a whole and thus produces a more effective control mechanism.

System reliability should also be considered and the effects of uncertainty assessed. Once a model has been built, the design may be optimised utilising the overall economic criterion as the basis of judgement. Solutions should be examined in terms of their 'robustness' as well as how optimum (or otherwise) they are. In terms of the concepts explored in section 2.2 , the systems design phase is concerned with ensuring that adequate communication and control mechanisms are inherent in the system design.

Implementation : The systems study should lead to positive action which will be highlighted by a report and authorisation for implementation. Construction of the system should be well planned and the plan monitored against milestones.

Operation : It is very important that the initial operation of the plant is considered and the transient effects of startup understood. Once the system has been operating for sometime a retrospective appraisal (or audit) of the project should take place. Such an assessment allows a judgement on the success or otherwise of the system to be made and highlights opportunities for continuous improvement activity.

2.3.3 Soft Systems Methodologies

To tackle soft unstructured problems, it is claimed that what is required is a methodology which can provide practical guide-lines and yet which is vague enough to remain problem orientated and to avoid distorting the problem into a particular structure. Checkland (1981) has been responsible for much of the development that has taken place in the realm of soft systems methodologies (SSM). Checkland views the methodology as a means of using systems ideas to structure problem situations and to understand and improve 'human activity systems'. The basic steps of the methodology are detailed below (Checkland, 1981, Checkland & Scholes, 1990, Jenkins, 1983) and summarised in Figure 2.3.

Analysis : Checkland states that the analysis should NOT be in systems terms for an unstructured problem as this may well lead to the automatic identification of structural groupings as systems. Rather, the analysis should be stated in terms of structure (a static framework to support the process) and process (dynamic ongoing activities within the structure) as well as the relationship between them. This stage of the analysis is concerned with determining the system to be 'engineered' or designed.

Root Definition of Relevant System : Analysis may be taken as complete (at least for a first iteration), when it is possible to postulate a root definition (or number of root definitions) of the system thought to be relevant to the problem situation.

Conceptualisation : Conceptual Models are constructed of the various systems captured in the root definitions. This involves assembling the minimum activities, in correct sequence, necessary to meet the requirements of the system defined in the root definition.When a tentative sequence has been assembled it is useful to annotate it with major inputs and outputs. Information and controls necessary to fulfil the activities in the system should also be addressed. It is important at this stage that the

model building exercise does not start describing the current situation. In building up the conceptual model the idea of the formal system is used. The formal system model is a compilation of components which have to be present if a designed system is to be capable of 'purposeful' activity. Use of the model consists of asking, of the conceptual model, questions based on it.

Comparison & Definition of Possible Changes : The conceptual models are compared with what is perceived to exist in the real world. This comparison helps to structure a debate about possible change among individuals concerned with the problem situation.

Design and Implementation : Agreed changes are designed in detail and implemented.

Although SSM tries to overcome the fact that a system might not have an agreed objective, it does have some limitations. Because of the assertion that the analysis step should not take place in systems terms, it is difficult to compare a highly unstructured problem with a structured description as embodied by the conceptual model. Thus, it can be very difficult to postulate what changes are needed.

2.3.4 Comparison of Hard and Soft Systems Methodologies

It is clear that the two methodologies outlined above are suited to the solving of different problems. The systems engineering approach is suited to well defined problems and essentially looks at 'how to do it', when 'what to do' is already defined. The soft systems methodology is more suited to problems where the 'what to do' has not been decided. This difference forces SSM to include the comparison stage, which has no equivalent in systems engineering. It is at this stage that systems thinking may be used to structure a debate, a debate that does not usually take place when the systems engineering approach is used. Table 2.4 compares the two approaches. It could be argued that SSM may be seen as the general case and that systems engineering as a specific case in which 'conceptualisation' becomes (in a well defined case) system design. Improvement of the conceptual model in SSM would become 'optimisation' in a well defined problem. SSM could thus be seen (Checkland, 1981) as a general problem solving methodology adopting a 'softer' side in undefined problems and a 'harder' side in well defined problems.

This section has outlined methodologies which are suitable for solving 'hard' and 'soft' problem solving. There are other systems methodologies such as the Viable System Methodology which is based on cybernetics (Beer, 1959), which are more suitably used for problem solving.

2.4 Manufacturing as a System

The concept of a manufacturing system is not new (Hitomi, 1979, Parnaby, 1979). Parnaby (1986) defines a manufacturing system as:

> 'An integrated combination of processes, machine systems, people, organisational structures, information flows, control systems and computers whose purpose is to achieve economic product manufacture and internationally competitive performance. The system has defined but progressively changing objectives to meet, some of which can be quantified and others such as those relating to responsiveness, flexibility and quality of services, which whilst being extremely important are difficult to quantify. Nevertheless, the system must have integrated controls which systematically operate it to ensure that the competitiveness objectives are continually met and adapt to change.'

However, this definition does not fully utilise the concepts delineated in the Formal Systems Model (see Figure 2.1). In these terms manufacturing can be viewed as a purposeful human activity system possessing the following:

Table 2.4 : SSM & Systems Engineering Compared

Processes : The dynamic activities that link together to enable the transformation of raw materials into finished components.

Structure : The people, materials, money and methods (including information) required to perform the processes.

Emergence : These are not just operational in nature (e.g. leadtimes and inventories) but are also related to overall business performance (e.g. return on capital employed).

Hierarchy : There are a number of sub-systems associated with a factory. Traditionally, in a functional layout these have been associated with sections and departments. In a CMS, these may be cells and modules.

Communication : There is a flow of input and outputs from and to the wider company and external environment.

Control : Information is collected and control action taken to ensure that the right things are made in the right quantities at the right time and at the right cost. Such action takes place at all levels of the hierarchy.

In general, manufacturing may be seen as a system that is 'unitary' in nature with a single goal - to convert raw material into finished product as effectively and efficiently as possible. It is therefore contended that the use of a hard systems methodology is an appropriate approach for the design of cellular manufacturing systems. It is however recognised that SSM may have a role in ensuring successful implementation.

There is a need to distinguish between the total manufacturing supra-system and the manufacturing operation system (i.e.the domain to which cells are usually applied).

Manufacturing operation systems need to be evaluated, not only in terms of the emergent properties at their level, but in terms of the emergent properties of manufacturing as a whole. The implications of treating a CMS systemically, within the wider system of manufacturing, are detailed below:

a) The scope must be such that the complete design problem is addressed holistically. The whole system must be considered, not just those which are most amenable to cellularisation. All aspects of the system must be addressed, not just machines and parts. All aspects must be considered simultaneously not sequentially.

b) Evaluation must take place against the emergent properties of the manufacturing system as a whole, and not just the operational properties that pertain to the CMS.

2.5 Summary

This chapter has examined the application of the systems approach to the design of cellular manufacturing systems. Manufacturing has been considered as a system and the implications of this on the effective generation of cellular manufacturing systems have been delineated. The next chapter will examine existing approaches to the design of cellular manufacturing systems and assess their effectiveness against these systemic criteria.

Chapter 3

The Design of Cellular Manufacturing Systems - The State of the Science

3.1 Introduction

This chapter explores the current approaches to the design of cellular manufacturing systems, with a view to diagnosing their strengths and weaknesses, when compared with the criteria established at the end of Chapter 2. This activity was necessary in the overall schema of the investigation in order to establish if truly systemic design methodologies currently exist. Their existence would eliminate the need to create a systemic cellular manufacturing systems design methodology from 'scratch'. Formal approaches to the design of cellular manufacturing systems can be categorised into four groups (Lewis & Love, 1993a).

Design Techniques and Procedures : The first category consists of nothing more than specialised techniques for the forming of part families and machine groupings. There is usually no consideration of machine loading and never any consideration of manufacturing planning and control systems and the dynamic behaviour of the manufacturing system.

Systematic Design Approaches : The second category of approach, usually outlined as the result of an industrial case-study, is the systematic decomposition of a manufacturing facility into manufacturing cells with some consideration of steady state loading and, occasionally, reference to dynamic behaviour as a result of simulation.

Integrated Modeling : The third category involves the use of computer modelling tools for the successive analysis of manufacturing models. There is, however, no clear design methodology associated with the use of these tools.

Design Methodologies : The fourth category, based, to some extent or other on the systems approach detailed in Chapter 2, are methodologies for the design of manufacturing systems.

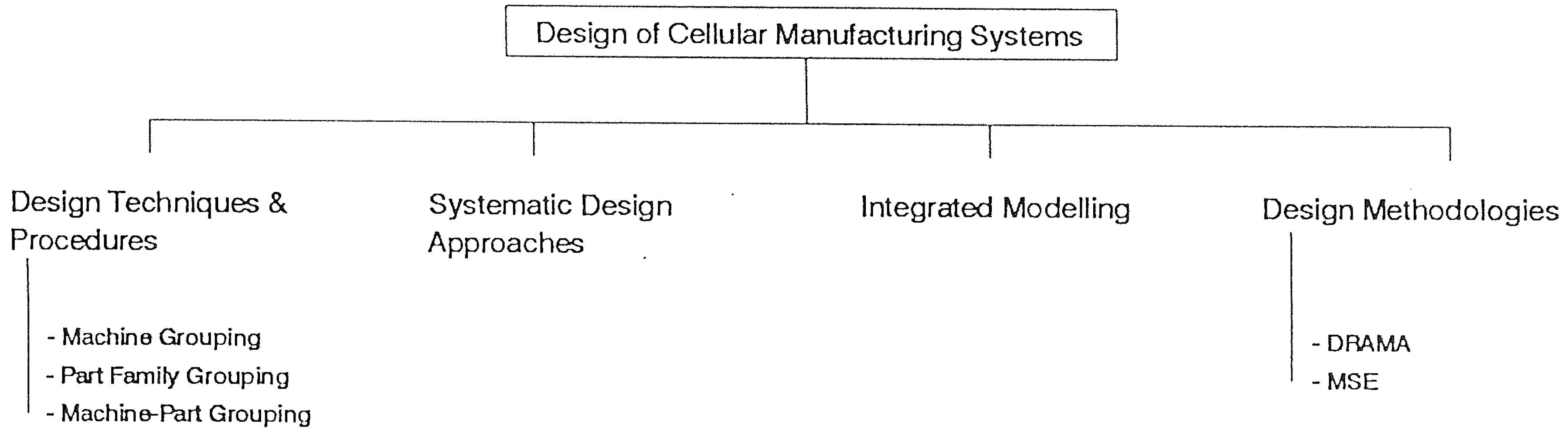
This taxonomy is shown in Figure 3.1. Although there are these fairly well recognised techniques available for the design of cellular manufacturing systems (CMS), one should not get the impression that their use is widespread. For example, Wemmerlov & Hyer (1989), in a survey of U.S. manufacturing industry found:

> '... a lack of sophistication and preplanning before making an often radical change to the factory floor'.

Devereux et al (1994) in a U.K. survey found that only just over 50% of respondents used a formal approach to the design of CMS. Of these 50%, 60% used an 'in house' approach, leaving only 40% of respondents using an approach that had some wider recognition. Therefore, it is reasonable to conclude that perhaps only 20% of the sample used a recognised formal approach. This is consistent with the larger sample analysed by Fritz et al (1993), where 20% to 30% of respondents utilised a formal approach to CMS design. The above survey results tend to confirm Chryssolouris' (1992) contention that a 'Trial and Error' or 'Rule of Thumb' approach to the design of manufacturing systems constitutes much industrial practice. This approach essentially consists of 'guessing' a suitable manufacturing system design, evaluating performance measures of the system, stopping the process if they are satisfactory, or repeating it if they are not. It is not proposed to examine such design approaches as they do not constitute best practice and each approach used would be very specific.

This analysis specifically excludes those manufacturing systems analysis and design techniques that are predominantly used in the design of information systems and computer architectures. This includes, for example, techniques such as SADT / $IDEF_0$ (Structured Analysis and Design Technique and the ICAM Definition Technique, essentially the same technique) (Ross, 1977, Ross 1985, U.S. Airforce, 1981), GRAI (Graphe a Resultats et Activities Interlies) (Pun et al, 1985,

Figure 3.1 A Taxonomy of the Approaches to the Design of CMS



Doumeingts, 1985) which is concerned with the modelling and design of 'managerial systems' (Wu, 1994) and Petri Nets (Peterson, 1981). Such methodologies are often used for the analysis of Computer Integrated Manufacturing systems. Their relevance to the domain of this project is tangential and they are usually applied at a level of aggregation above that required in the design of a CMS. A full review may be found in Colquhoun et al (1993).

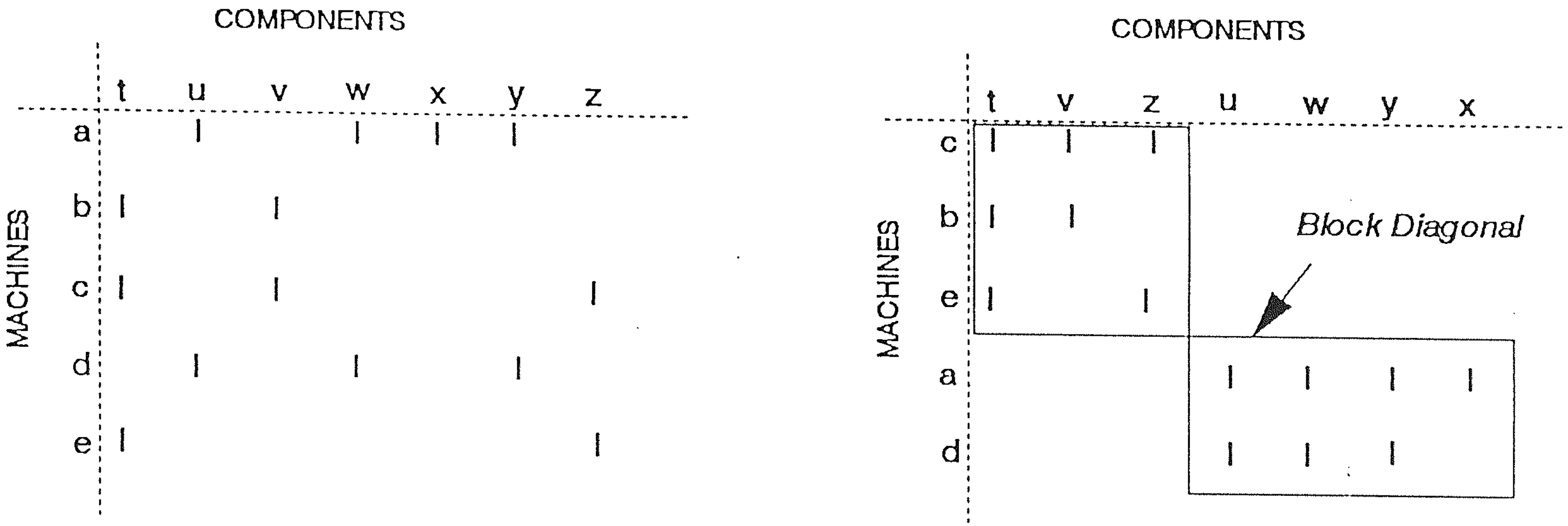
3.2 Category 1 : Design Techniques and Procedures

Considerable research has been undertaken in the area of manufacturing cell formation (e.g. Srinivasan & Narendran (1991)). The process of defining cells involves determining what separate facility groups are required to manufacture a specific range of components or products. This problem is often referred to as the machine - component problem. When viewed as a matrix the problem may be thought of as the block-diagonalisation of the machine-component matrix. Before cells are formed the matrix appears as a haphazard pattern of entries (i.e. it is unordered). After cells have been defined, the unordered matrix will have been converted from a haphazard pattern of entries into a form where the entries are contained in mutually exclusive groups, arranged along the diagonal of the matrix (called a Block Diagonal Form or BDF). Such an arrangement indicates that certain families of parts are being manufactured on certain groups of machines. This is shown in Figure 3.2. The techniques and procedures for the formation of cells may be classified into different types as shown in Figure 3.3 and detailed below.

3.2.1 Machine Grouping Techniques

These techniques group machines together into cells. Parts then have to be assigned to the machine groups that have been defined. The techniques that fall into this type

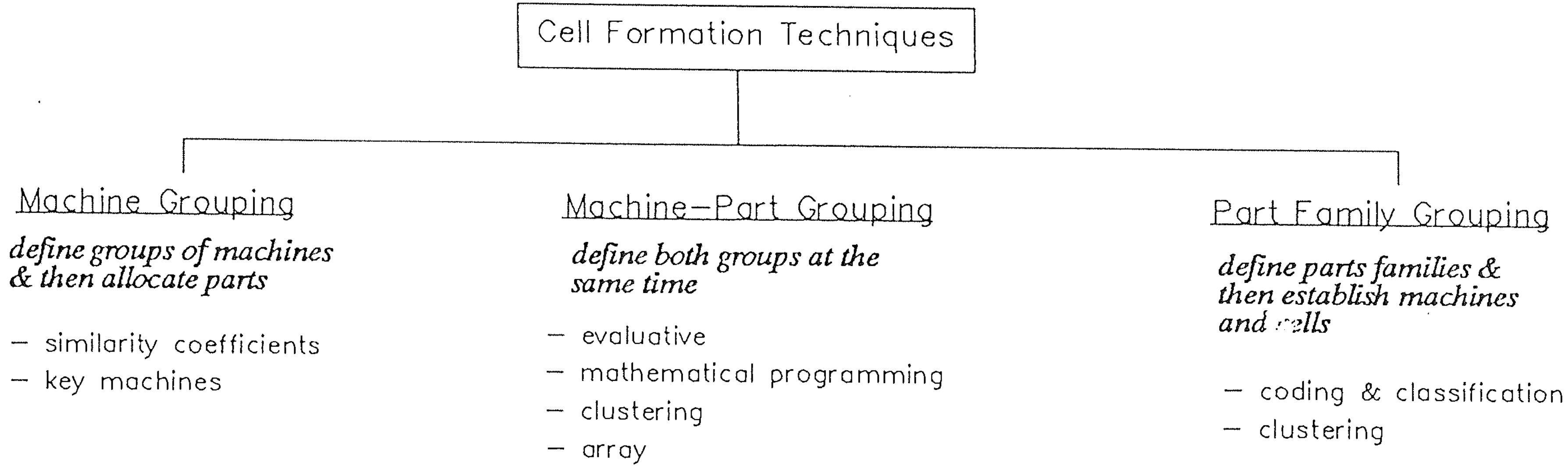
Figure 3.2 The Machine-Component Matrix



Haphazard Matrix

Ordered (BDF) Matrix

Figure 3.3 Classification of Cell Formation Techniques



are typically based on the use of Similarity Coefficients. The use of the similarity coefficient approach to forming cells usually has two distinct phases.

Phase 1 Calculate Similarity Coefficients : This involves calculating how similar or 'alike' machines are to one another, based on what parts are processed by each machine. An example of such a coefficient is:

$SC_{ij} = NCC_{ij} / (TNC_i + TNC_j - NCC_{ij})$

where :

SC_{ij} = Value of similarity coefficient
NCC_{ij} = Number of common components using machines i and j
TNC_i = Total number of components using machine i
TNC_j = Total number of components using machine j

Such coefficients have values between 0 and 1 and must be calculated for every pair of machines.

Phase 2 Cluster Machines To Form Cells : Various algorithms are used to 'cluster' or group together like machines (as measured by the similarity coefficient) into machine cells. The first iteration of cluster formation is straight-forward : all that is required is to bring the two entities with the highest level of association (SC_{ij} in this case) together in one cluster. All subsequent iterations however require some sort of methodology. An example of such a methodology is the Single Linkage (SLINK) clustering algorithm. SLINK defines the similarity linking two clusters together as the maximum of the machine similarities between machine pairs where one machine is in the one cluster and the other machine in the other. When clustering is terminated, the results are often shown in the form of a dendogram and the analyst is able to subjectively decide when to stop the clustering. Figure 3.4 shows an example of a dendogram.

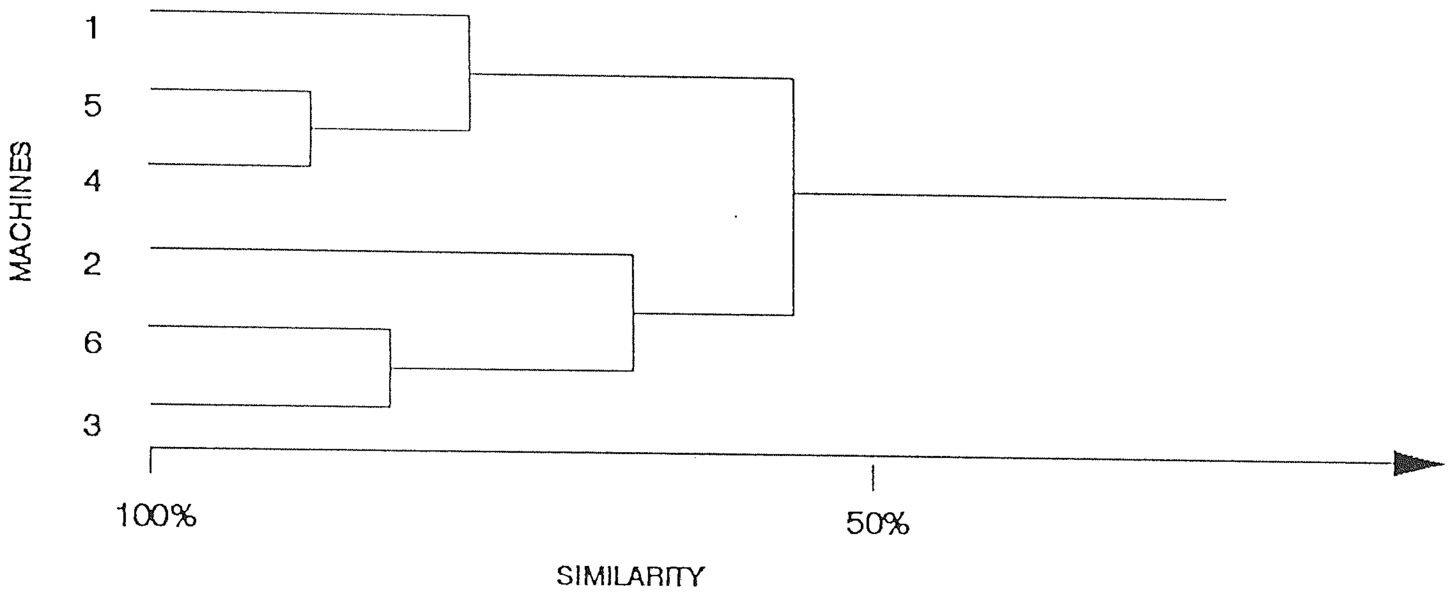
The use of similarity coefficients was pioneered by McAuley (1972), in an effort to put some mathematics into the cell formation process, using an additive similarity coefficient and the single linkage cluster analysis technique as detailed above. Significant research has been published in this area developing either new similarity coefficients (such as a product type by Waghodekar & Sahu (1984)) or different approaches for clustering similar machines together. The focus of this research has generally been limited to the mathematics of utilising the approach to form cells rather than the complete design of manufacturing facilities. Examples of this research may be found in Rajagopalan & Batra (1975), De Witte (1980), Waghodekar & Sahu (1984) and Mosier (1989). An alternative approach utilises the concept of key machines. Key machines, identified as requiring a high utilisation are used as 'seeds' or 'nuclei' for the formation of machine groups. Parts are then allocated to these groups to form cells.

3.2.2 Part Family Grouping Techniques

These techniques are concerned with grouping parts into families. Machines then have to be allocated to the manufacture of particular families of parts. There are two mechanisms that have been identified in the literature for the grouping of parts together to form families. These are classification and coding and cluster analysis.

Classification & Coding : A classification and coding (C & C) scheme allows parts to be sorted into different classes based on certain part characteristics (e.g. diameter, length). These classes may then be used as the basis of part families. C & C schemes are usually one of three types (Gallagher & Knight, 1986) :

Figure 3.4 An Example Dendogram



i) monocodes which are hierarchical in nature and where the classification is obtained by proceeding step by step down through a hierarchy.

ii) polycodes where a certain digit value always indicates that a certain feature is present.

iii) hybrid system where some digits are arrange hierarchically and others have a fixed significance.

Gallagher & Knight (*op cit*) identified over 31 C & C systems available for use by industry.

Cluster Analysis : In the same way that machines may be clustered together into groups, so may parts into families, using the same principles as above. An example of this is given in Carrie (1973). More recently, Shtub (1989) treated the problem as a Generalised Assignment Problem (GAP), managing to solve a five part, four machine problem !

3.2.3 Machine - Part Grouping Techniques

The group of techniques that fall into this category attempt to form groups of machines and families of parts simultaneously. There are four different types of techniques that fall into this category, evaluative or manual methods, mathematical programming procedures, cluster techniques and the use of arrays.

Evaluative : The main technique that falls into this group is Production Flow Analysis (PFA) developed by Burbidge (1963, 1977, 1982, 1989, 1992, 1993, 1994) and probably the first attempt at trying to arrive at machine groupings and part families simultaneously. It was developed in response to the inability of C & C methods to form machine groups on which to manufacture parts families. The aim of the technique is stated as (Burbidge, 1977):

> '...finding the families of components and associated groups of machines for group layout ... by a progressive analysis of the information contained in route cards'

The main feature of the technique is that it involves systematic manual listing of components in various ways, in the expectation that groups of components and machines may be found by careful inspection. A similar technique, called Component Flow Analysis (CFA), has been proposed by El- Essawy & Torrance (1972). In fact, it is so similar that many (e.g. Rajagopalan & Batra, 1975) have been unable to see the difference between CFA & PFA.

Mathematical Programming : Integer programming formulations have also been used to try and solve the machine - part grouping problem. Kusiak (1987) assigns machines and parts using a model which maximises the sum of similarity coefficients for a fixed number of groups under the constraint that each part may be assigned to one cell only. Purcheck (1985) utilised a linear programming routine in association with a lattice theoretic method in an attempt to maximise scheduling flexibility and minimise the total cost of establishing cells.

Clustering : Direct clustering involves solving the machine - component grouping problem without first calculating a similarity type coefficient. These approaches (e.g. Chandrasekharan & Rajagopalan, 1986a, 1987) tend to treat components and machines as vectors which are clustered using a non-hierarchical method until a natural structure emerges. This process is achieved through the use of 'seeds' which are used to form initial clusters on the basis of a metric. The process is then repeated using cluster centroids as seeds until column and row clusters are equal in number. Other developments include GRAFICS (Srinivasan & Narendran, 1991) which is an attempt to utilise a nonhierarchical clustering algorithm. More recently the clustering problem has been addressed by the use of neural networks (Kaparth & Suresh, 1992, Chu,1993).

Array : These methods treat the rows and columns of the machine - part matrix as binary words and sort them to obtain the block diagonal form outlined above. The earliest work undertaken in this area was by King (1980) who developed the Rank Order Clustering (ROC) procedure which was later extended to ROC2 (King & Nakornchai, 1982). The ROC procedure firstly ranks rows in binary order and then columns. This ranking procedure is continued until no further re-arranging is possible, at which point the BDF will be produced if one exists. The ROC2 procedure has itself been extended to overcome some of its shortcomings. Examples of this include Chandrasekharan & Rajagopalan (1986) with MODROC, where the ROC procedure is combined with a form of clustering and Askin & Subramanian (1987) who combine ROC with a cost based heuristic.

3.2.4 Commentary on Design Techniques and Procedures

The use of design techniques and procedures for cell formation has received a significant amount attention as detailed above. The key point to note, however, is that the attention is of a specialised narrow nature, despite the titles used on published papers in the area. For example, Choobineh (1988) proposes a two stage cell formation algorithm in a paper titled:

> ' A framework for the design of cellular manufacturing systems'

Clearly, all the algorithm does is form part families and group machines into cells. There is no consideration of static loading, dynamic loading and manufacturing control systems. This is despite the fact that Choobineh (1988) claims that :

> '... the proposed procedure is a logical and systematic approach to the design of cellular manufacturing systems.'

Similarly, Rajamani et al (1990) in a paper titled :

> 'Integrated design of cellular manufacturing systems in the presence of alternative process plans'

proposed solving the cell formation problem through the use of three integer programming formulations, with no consideration of anything other than the assignment of machines and parts. This again is far from what may be considered an approach to designing complete cellular manufacturing systems. As a final more recent example, Cheng (1993), in a paper titled :

> ' A tree search algorithm for designing a cellular manufacturing system'

merely proposes a 0-1 integer programming model for cell formation, stopping well short of what might be described as an attempt to address the design of cellular manufacturing systems. It is also very unusual for cell formation algorithms to take any account of production volume.

Although such techniques do have a place in the design of cellular manufacturing systems, they are only a means to the design of such systems and not an end in themselves, as many of the authors detailed above appeared to regard them.

3.3 Category 2 : Application of Systematic Design Approaches

Recognising that the techniques discussed above are not in themselves an adequate approach to the design of cellular manufacturing systems, some authors have published approaches that attempt to be more complete. One of the earliest papers outlining a systematic approach to the design of cellular manufacturing systems was by Thornley (1972). This paper outlined an approach that started with data collection, followed by the formation of manufacturing cells, which were then analysed for load. The layout of the facility was then determined and an assessment of economic savings and other benefits made. The approach was extended by Kruse et al (1975) with a view to improving production control systems as part of the approach. More recently, others (e.g. Prickett & Coleman, 1992, Afzulpurkar et al, 1993, Prickett, 1994) have proposed systematic design approaches that include some analysis of manufacturing planning and control systems.

Chryssolouris (1992) gives this approach the title of 'Systematic Functional Problem Solving' and characterises it in four steps. Resource requirements are first calculated using a steady state calculation. Resources are then layed out (typically on a trial and error basis), material flow is then examined and finally buffer capacities are determined.

Although the approaches published are systematic, they are deficient in a number of ways. For example, design involving the use of static load calculations only is the norm, with limited study of dynamic behaviour. Control systems are usually only treated in a tangential manner rather than being treated an integral part of the design process. In addition, none of the approaches examined are, or profess to be, general methodologies appropriate for the design of cellular manufacturing systems.

3.4 Category 3 : Integrated Modelling

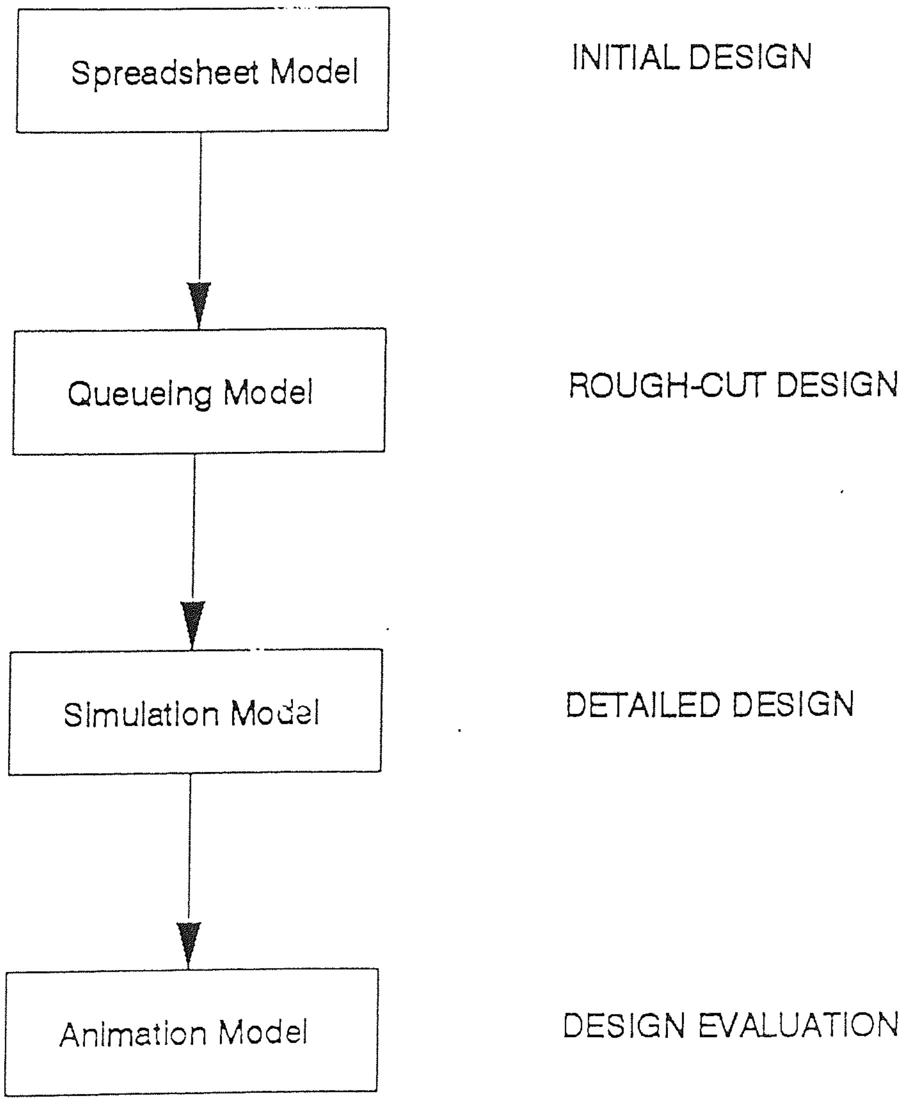
This approach to the design of cellular manufacturing systems is based on the integration of four types of computer modelling that, it is suggested, should be used sequentially for manufacturing systems modelling. It does not include the use of any cell formation algorithms. Suri & Diehl (1985) and Suri & Tomsicek (1988) have identified Lotus 1-2-3 (spreadsheet), Manuplan II (analytical modelling), Siman (discrete event simulation) and Cinema (animation) as a linked set of computer tools for the modelling and analysis of manufacturing systems. Although much effort appears to have been spent on ensuring that data can be passed from one modelling tool to another (e.g. the development of 'Simstarter' to allow the conversion of analytical models into simulation code), the tools have not been integrated into a design methodology for manufacturing systems. Little indication of the manufacturing system design methodology necessary to effectively utilise these computer tools is explored. With the exception of the use of superficial terms such as 'rapid analysis' and 'detailed analysis' - there has been no analysis of the process of manufacturing systems design. Huettner & Steudel (1992) have also investigated this approach utilising Lotus 1-2-3, Manuplan II and Starcell instead of Siman.

Shimizu & Van Zoest (1988), as well as Shimizu (1991) have to some extent tried to remedy the lack of an explicit documented design methodology, by specifying design activities that might be undertaken when using each computer tool in sequence. So for example, Lotus 1-2-3 is specified for use in the 'Initial Design' phase (basic system parameter design) and Manuplan II for 'Rough Cut Design' (initial analysis of system dynamics). Figure 3.5 illustrates the approach of Shimizu.

This approach has the strength of providing a means for both a static and dynamic analysis of a manufacturing system, and providing some guidance as to how computer modelling tools may be used in the design of manufacturing systems. However, a number of weaknesses can be identified. The application of the approach is acknowledged as being limited in the context of manufacturing systems design, focussing on (Shimizu 1991) :

> '... the selection and layout of the direct production equipment together

Figure 3.5 Integrated Modelling



(After Shimizu (1991))

with its associated operating parameters.'

In addition, the design methodology that is specified is limited in its detail and application. Both Shimizu (1991) and Huettner & Steudel (1992) are only able to discuss the application of the modelling tools to individual manufacturing cells rather than complete manufacturing facilities. Finally, the objectives against which manufacturing systems are judged are somewhat limited when viewed in a business context. For instance, Shimizu (1991) 'optimises' with respect to a minimum implementation cost, maximum machine utilisation and a maximum leadtime - there is no consideration of either profitability or return on capital employed. Wang & Bell (1992) have developed a knowledge based approach to integrated modelling. However, it has been specially designed for flexible manufacturing facilities, limiting its usefulness for the more general problem of CMS design.

3.5 A Summary of the Limitations of Approaches for The Design Of Cellular Manufacturing Systems in Categories 1 - 3

Given that the use of systems thinking and systems methodologies is useful and offers the possibility of generating 'good' design solutions, it is necessary to evaluate how current approaches to the design of cellular manufacturing systems in categories 1 - 3 compare with such concepts.

3.5.1 Scope of Approaches To Cellular Manufacturing Systems Design

From the approaches detailed above, it is clear that most work has been directed towards solving the cell formation problem rather than focussing on the total design of manufacturing systems. There has been an over-emphasis on techniques that are used to define cell structures rather than methodologies for the design of whole systems. This point has been emphasised by Parnaby (1986) who defines two types of systems design problem :

- The macro problem : Concerned with large systems, integrating machines, processes, information flows and control systems.

- The micro problem : Concerned with, for example, small electro - mechanical mechanisms.

His point is that much of the work has treated the manufacturing system design problem as a 'micro' problem rather than a 'macro' problem. Burbidge (1993) has also commented on this trend, indicating the publication of 100 papers on various cell formation algorithms in the Journal of Manufacturing Systems between 1987 and 1993. His concern is that the algorithms seem to have:

> '...lost touch with the basic need to design methods that can be used in industry.'

Thus, the scope of much work has been narrow and anything but 'holistic'. This point is emphasised if one examines the titles of papers in journals and compares this with the content, as demonstrated in Section 3.2.4. Most of the algorithms that have been developed have also been based and tested on limited, synthesised data that is not representative of likely industrial scenarios. For example, Srinivasan & Narendran (1991) deal with a 24 machine, 40 component problem, Chu (1993) an 8 machine 20 component problem and Shtub (1989) a 4 machine, 5 component problem. Finally, many of the authors have a very blinkered view of what constitutes a manufacturing system. Arvindh & Irani (1994) for example indicate that :

> 'A manufacturing system can be represented by machine-part matrices'

Thus, the scope of many approaches to the design of cellular manufacturing systems can be said to be limited, not addressing the complete design problem.

3.5.2 System Objectives & Evaluation

Cellular manufacturing systems are neither designed or evaluated in terms of the overall emergent properties that are required of them. When a manufacturing systems design is undertaken it should start with objectives that are related to business goals such as improved return on capital employed. However, most procedures identified for the cell formation process such as ROC (King & Nakornchai, 1982) and MACE (Waghodekar & Sahu, 1984) do not, on the whole, generate solutions with consideration to any stated business objectives. Often one, or at best, a few performance variables are used when generating manufacturing systems design solutions (Wemmerlov & Hyer, 1987). For example, cells are generated with respect to the minimisation of inter-cell moves. As a result, cell assessment or evaluation, with respect to the desired emergent properties, must take place independently of cell formation. Heim & Compton (1992), indicate that:

> '...metrics used to evaluate the performance of the manufacturing enterprise seldom address system performance.'

Usually, the evaluation that takes place, does so in local terms, not system terms and the evaluation is not linked to overall business objectives. For example, Morris & Tersine (1990) evaluate cell formations in terms of mean throughput time and mean level of work-in-process (WIP) inventory. Ghosh (1990) specifies the use of measures such as queue lengths, throughput rate and utilisation. Sassani (1990) suggests that maximum throughput time, percentage of jobs late, accumulated machine hours utilised and accumulated set-up time penalties are used as performance measures. Prickett (1993) on the other hand, suggests evaluation through the implementation of a pilot cell.

The models that are used for the evaluation of cellular manufacturing systems are often inadequate. The whole system or 'synergistic' benefits that often result as a consequence of cellular manufacture are not considered. For example, some simulation studies indicate better performance for process layouts rather than cellular layouts (Flynn & Jacobs, 1986, 1987, Morris & Tersine, 1990) (albeit on the basis of synthetic data) supporting a controversial view first proposed by Leonard & Rathmill (1977). Such quantative analytical evaluation does not reflect much of the actual physical evidence that has been obtained (Wemmerlov & Hyer, 1989). Possible explanations include the fact that, for example, Flynn & Jacobs (1986, 1987) compared process layouts and cellular layouts on the basis of first-in first-out despatch rules at work stations, ignoring the fact that a cellular layout facilitates the introduction of JIT (Dale & Willey, 1980, Wemmerlov & Hyer, 1989). In addition, the 'cells' used in the evaluation had significant inter-cell part movement indicating that they were not very well specified. This issue has been further investigated by Suresh and Meredith (1994) who have suggested the action that is required to extract the potential benefits of cellular manufacture.

In summary, the techniques and methodologies that are suggested for the design of manufacturing systems do not evaluate alternatives with respect to the criteria that most senior executives in industry would expect (for example, effect on net profit and return on capital employed) and the models used for the evaluation are often less than systemic. Typically, the form of computer evaluation used takes only a 'parochial' view, with a system view of the effects on desired emergent properties not considered. There is an implicit assumption that improvement in operational metrics will be reflected in business metrics. It is not demonstrated that the use of operational metrics, as proxies for business metrics, is valid.

3.5.3 Manufacturing Systems Boundaries

It is common practice not to consider the performance of the whole manufacturing system when introducing cellular manufacture. With most cellular implementations, either a temporary or permanent 'residual' or 'remainder' uncellularised machine shop is operated in conjunction with the newly created cells. A temporary residual is created by cellular implementations taking place in small steps (Mosier & Taube, 1985) or in a time phased manner (i.e. cells are implemented over a number of months or even years). A permanent residual is created when it is decided that certain components or machine-tools are not suited to operation in a cellular structure (Wemmerlov & Hyer (1987, 1989), Co & Araar (1988)).

Typically, the effect of cellularisation on this residual, which could be quite large, is not investigated and improvements demonstrated for cells might be obtained at the expense of the remaining (residual) manufacturing system. Many manufacturing systems are seen as too large to treat as one entity and interactions are ignored. This is an example of local optimisation, with boundaries not being adequately addressed rather than system optimisation. An evaluation of this situation could be very important for a business considering the move to cellular manufacturing. For example, it has been claimed that a process based batch environment can give superior performance than a hybrid arrangement of cells and a residual process based manufacturing facility (Christy & Nandkeolyar, 1986). Thus, if a system boundary is drawn around the manufacturing cell in question rather than the whole manufacturing system, for the purposes of evaluation, a misleading conclusion might be arrived at. Although this is very serious when the residual is permanent in nature, it is equally serious when it is temporary. If the transient behaviour (performance during the period from starting cellularisation to completing it) of the system is not understood, implementation might be abandoned because of poor performance. On the other hand, implementation could be continued because of local benefits, when a system wide evaluation might indicate an inadequate cost-benefit equation.

It was indicated in Chapter 2 that approaches to the design of cellular manufacturing systems should have the following characteristics:

a) The whole system must be considered, not just those areas which are most amenable to cellularisation. All aspects of the system must be addressed, not just machines and parts. All aspects must be consider simultaneously not sequentially.

b) Evaluation must take place against the emergent properties of the manufacturing system as a whole, and not just the operational properties that pertain to the CMS.

The approaches to the design of manufacturing systems discussed above might claim to be systematic but they are by no means systemic, not fully meeting any of the above criteria.

3.6 Category 4 : Design Methodologies

The approaches detailed in this section should not be susceptible (or as susceptible) to the criticisms discussed in Section 3.5. Both the 'design methodologies' that are presented are more 'complete' and claim to be based on the use of a systems approach. Essentially, they are methodologies, comprising of (Bennett and Forrester, 1993) :

> ' a structured collection of techniques and tools that assist the designer in the development of new processes.'

They both meet Checkland's (1981) requirement of a methodology, in that they both guide the system designer to an approach and solution that is appropriate to their context.

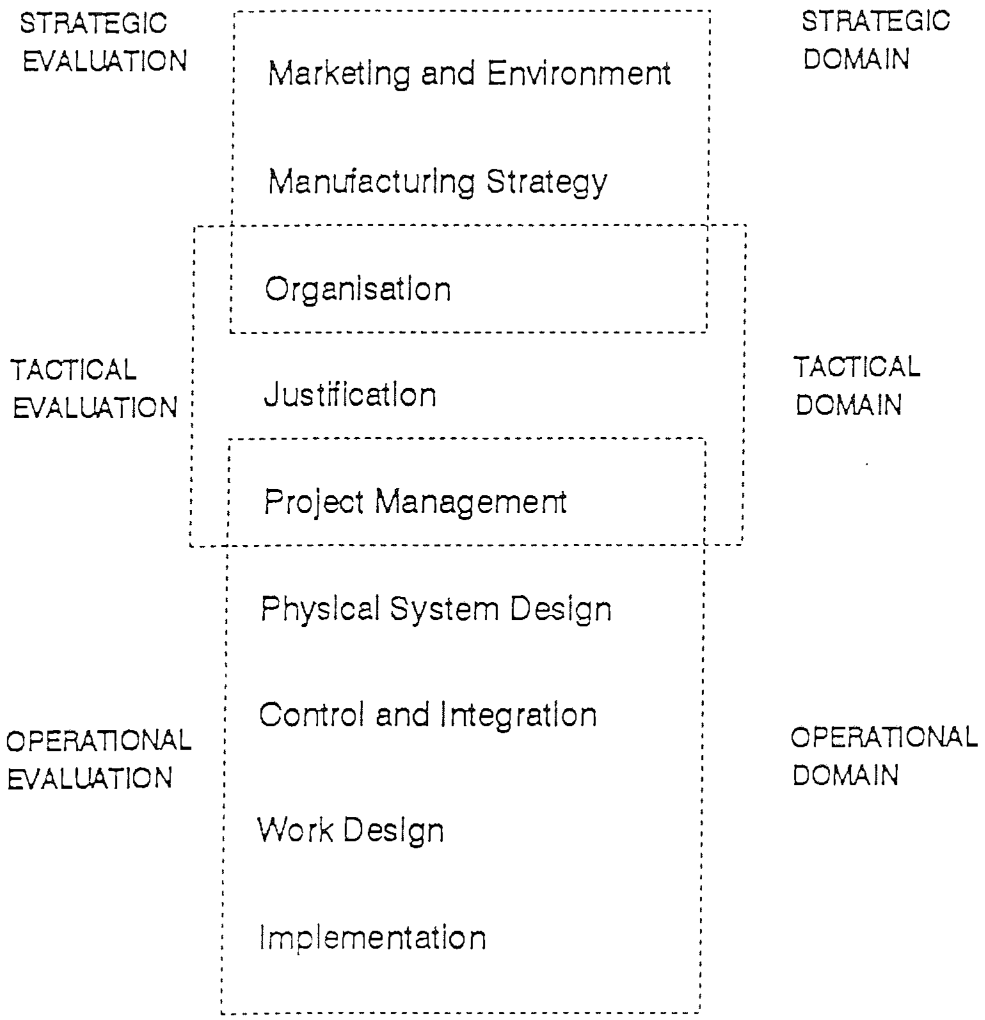
3.6.1 Decision Rules for Analysing Manufacturing Activities (DRAMA II)

The DRAMA II (Decision Rules for Analysing Manufacturing Activities) methodology (Bennett & Forrester, 1993), has been developed from an approach used by ICL to introduce a manufacturing system architecture termed the 'Modular Assembly Cascade'. This methodology, DRAMA (Design Routine for Adopting Modular Assembly) was essentially aimed at designing 'market focused' manufacturing systems which are typically cellular (or modular in ICL terms) in nature and utilise world class manufacturing techniques such as just-in-time (JIT).

The DRAMA II methodology consists of ten elements operating in three domains, as illustrated in Figure 3.6. For each of the ten elements, the key parameters to be considered are identified and analysed. These are then utilised in 'design option guides' (DOGs) which have been developed to help users make choices from alternatives based on an assessment of strengths and weaknesses. Finally, for each element of the methodology, a generalised methodology flowchart is available showing the broad sequence of analysis and decision.

The DRAMA II methodology has a number of strengths. Firstly, it gives a view of the manufacturing systems design process that is multi-perspective in nature. It covers the strategic issues through to the operational issues. It attempts to link the design of a manufacturing system to its overall strategic context. It also encourages the evaluation of design decisions throughout the design process (at a strategic, tactical and operational level). The methodology encourages the use of best practice at all stages, allowing users to select their own approach based on an analysis of their

Figure 3.6 The DRAMA Methodology



(After Bennet and Forrester (1993))

situational context. In many ways, DRAMA II might be termed a 'meta-methodology' in the sense that it puts the use of many other, significant methodologies into an overall perspective.

However, from the view of the detailed design of manufacturing systems the DRAMA II methodology appears to have a number of weaknesses. For example, nowhere in the methodology is explicit reference made to the need for detailed static and dynamic capacity and load calculations. Although it is claimed that DRAMA II can be used as (Bennett & Forrester, 1993) :

> '...an analytical tool for generic production systems design'

the emphasis is clearly on assembly operations. Bennett & Forrester (1993) quite clearly focus the methodology on 'downstream' activities such as:

> '...(the) configuration of finished products'

rather than so-called 'upstream' activities such as component part manufacture. This perspective is not surprising since the focus of the DRAMA II methodology is 'market focused' manufacturing systems. It is reflected for example, in the 'Physical System Design' component of the methodology. Considerable prominence is given to the storage and transportation aspects of manufacturing systems design, both of which are of much more importance to assembly operations rather than component part production operations.

The strengths of the DRAMA II methodology lie in the conceptual design issues of manufacturing systems design rather than in the detail design aspects. Additionally, the methodology is more appropriate to market focused manufacturing operations whose emphasis is product assembly rather than piece part production. This is not surprising given the domain that the methodology was originally developed for.

3.6.2 Manufacturing Systems Engineering

Manufacturing Systems Engineering (MSE) has been defined, by one of its originators and acknowledged global authorities (Hitomi, 1979, 1990, 1994) as :

> '... a unified approach to manufacturing technology and production management.'

It may perhaps be described as a philosophy, with Hitomi (1990) emphasising the following four aspects:

- The clarification of the concepts of manufacturing systems and their basic functions and structures; including the problem of manufacturing systems design, particularly, their material flow;
- The optimisation of the manufacturing system;
- The control of manufacturing systems;
- The processing of production information.

It claims to be based on an understanding of systems ideas and on the recognition of the complexity of manufacturing and the need to view it in its entirety. The main focus is the simplification of manufacturing, particularly material flow as this helps in the simplification of the other aspects of the manufacturing system. In the U.K. and U.S.A., it is clear that the term 'Manufacturing Systems Engineering' has been used by many to describe their own work in fairly specialised areas, such as merely linking computers together (see for example, Judd et al (1991)). On a face validity basis they by no means consider manufacturing as a system.

However, one form of the MSE approach that has been extensively applied to the design of CMS and has been widely reported is based on a 5 step design methodology (Parnaby (1979, 1986, 1987, 1988, 1991), Dale & Johnson (1986)).

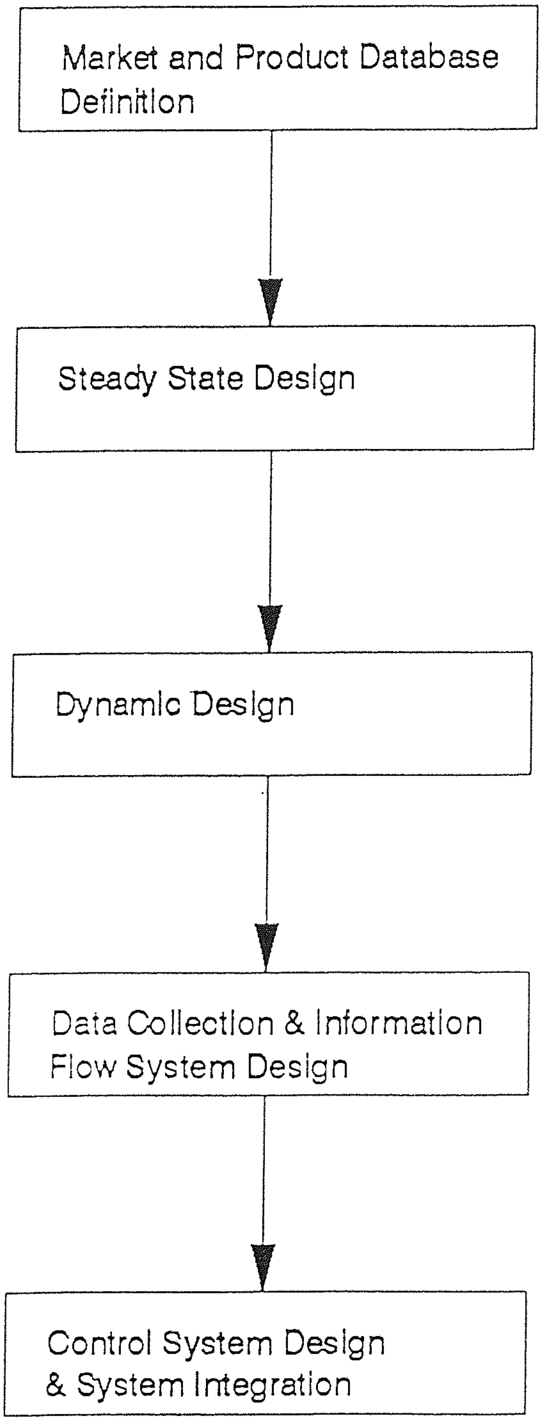
MSE, in this context, is regarded as a detailed approach to problem solving. The approach takes the form, at its most basic, as illustrated in Figure 3.7 and is detailed below.

Market and Product Database Definition : Data concerning markets, volume and variety of products, factory processes and component routings is collected. Usually techniques such as input-output analysis, process flow analysis, pareto analysis and cell formation techniques such as PFA (Burbidge, 1989) are used to help structure the data. In addition, it is important that business and manufacturing strategies are examined and understood at this stage. This is so that decisions to be taken further into the design process are placed within the wider context of the overall direction in which the business is heading. Component data is sorted into families which are used as the basis of a cellular manufacturing system. This stage may be regarded as a system specification and simplification activity.

Steady State Design : This stage of the approach is concerned with designing the system to meet average requirements. The number and types of operators and machines required is determined. These calculations are based on average performance for machines and operators. Average demand volume and mix are used as are average work content figures. Capacity and load are considered and likely bottlenecks identified. All the machine, operator and materials resources required for the operation of the manufacturing system are quantified in detail. Steady state is used to indicate that nothing changes with time. Average theoretical inventory is calculated. A figure for overall average performance is obtained.

Dynamic Design : The design established at the steady state stage of the methodology is tested against potential variations from the average values assumed above. Consideration is given to the dynamic effects of controllable and uncontrollable variables. Both the requirements on the manufacturing system in terms

Figure 3.7 The MSE Approach to the Design of Manufacturing Systems



(After Parnaby (1979), (1986), (1993))

of product volume and variety and internal performance parameters such as breakdowns are varied. Their effect is assessed to determine whether any changes to the design should be made to make its performance more robust. Consideration is given to issues such as maintenance, overtime policies, inter-stage buffer inventories and sub-contract policies

Data Collection and Information Flow System Design : Details of system information requirements and data requirements are generated. Actual data sampling points and the required sampling intervals are determined. Essentially, information relating to the states of materials, machines, methods and operators is collected at appropriate intervals.

Control Systems Design and System Integration : Planning and control systems are defined at this stage. Particular emphasis is placed on material planning, with shop-floor material control systems such as Kanban or Period Batch Control (PBC) being designed, along with mechanisms to put in place a robust production plan. This includes the careful definition of procedures for providing and changing control set-points or plans. This is an important stage in the process that is often ignored as Passler et al (1983) have found :

> 'It is still widespread design practice to develop the production control procedures after implementing the engineering technological project'

The consequences of this can be very severe. For example, Mosier & Taube (1985) found that most difficulties with the implementation of cellular manufacturing systems have been because of the poor design of the production planning and control systems used. The approach taken has often been to first re-organise the shop layout and then use the existing control system. These findings support Passler et al (1983), who concluded that it is difficult to change control systems after physical system designs have been implemented if system behaviour does not meet expectations.

This stage also includes organisation and job structure definitions. All tasks necessary for the new manufacturing system to function adequately are determined through an analysis of the redesigned manufacturing system. These tasks are grouped together into jobs that are usually significantly different from the traditional jobs that people are used to undertaking. For example, a cell leader's job will be a combination of not only man management tasks but will also include material planning and scheduling, which may constitute a major difference from the role undertaken by foreman.

The above five activities are often preceded by the pre-design consideration of determining the overall system objectives.

The five step methodology detailed above has a number of underlying principles which guide its application. These include decentralisation into smaller units with each unit viewed as a customer or contractor to other units. The concept of 'levels of control' is used to determine data requirements, information flows and response times. Typically, the higher levels are involved in planning (with long sampling intervals) and the lower levels with real-time control (with short sampling intervals). The approach also utilises the concept of 'Top Down' and 'Bottom Up' design approaches. A 'Top Down' approach is a prescribed solution that is general purpose in nature. A 'Bottom Up' solution is defined as a tailored solution that is specific to local needs. A 'Top Down' solution might be implemented in terms of a budgeting systems and a 'Bottom Up' solution might be implemented in terms of a shop-flooor material control system. Finally, the use of world class manufacturing approaches such as just-in-time (JIT) may be considered as an inherent element of MSE. Buchanan and Preston (1991) identify a not dissimilar group of dimensions to characterise MSE. These include group technology, product autonomy, local control and simplified scheduling, JIT and multiskilled teamwork.

Wu (1994) presents a similar view of MSE, with a slightly different methodology for the design of manufacturing systems. The methodology commences with an analysis of the current situation and the setting of objectives. From these, a conceptual model of the proposed manufacturing system is generated. These steps may be seen as broadly similar to the first step (market and product database definition) in the methodology detailed above (Parnaby 1979, 1986). A detailed design phase follows, dealing with the steady state, dynamic and control system issues. In addition, the methodology does have an explicit evaluation step after the conceptual modelling and detail design stages, a feature noticeably missing from the above MSE methodology (although it does take place implicitly).

Considerable benefit has been ascribed to the adoption of MSE. Butler (1992), indicates a reduction in work-in-progress to 10% of its current level and a near doubling in output. Heim and Compton (1992) have also reported considerable benefit from the use of MSE in the U.S.. Buchanan and Preston (1991, 1992) quote some impressive benefits including a reduction of between 30% and 40% in manufacturing costs, 75% reductions in leadtime and 50% - 60% reductions in work in progress.

3.6.3 Commentary on Design Methodologies

The methodologies presented in this section are clearly more 'complete' than those approaches to the design of CMS that fall in categories 1 - 3. However, the issue is how they perform against the criteria for a systematic and systemic methodology detailed in Chapter 2. From the analysis that it is possible to carry out from a review of the literature, the methodologies presented are certainly systematic. With regard to the criteria identified in Chapter 2, the following initial comments can made.

- Both approaches give consideration to the whole manufacturing system and the wider system of which it is part. DRAMA II is the more explicit of the two approaches in this area. Two components of the methodology ('Market and Environment' and 'Manufacturing Strategy') deal in reasonable detail with this issue. In MSE, the first step of the methodology ('Market and Product Database Definition') implicitly examines business and manufacturing strategies for their wider implications.

- DRAMA and MSE include consideration of overall objectives.

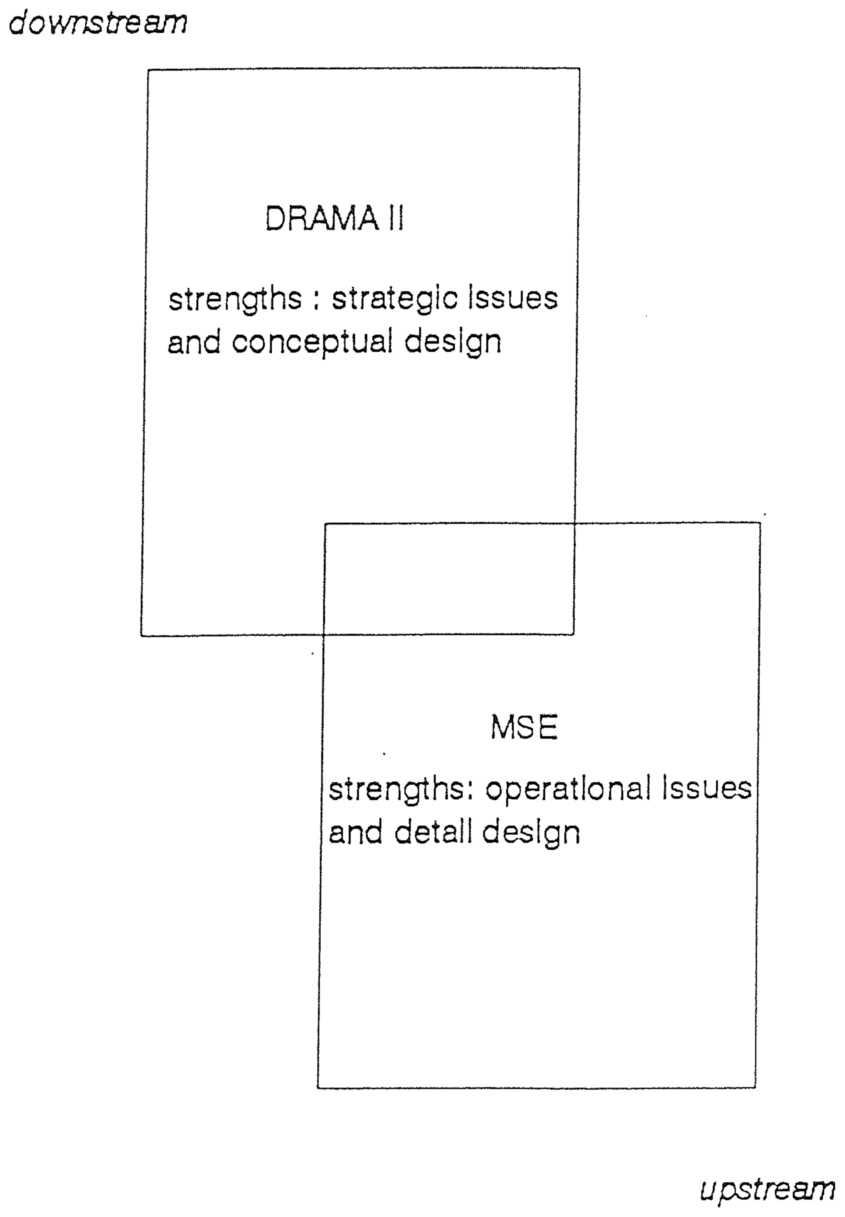
- Both methodologies have a systems design stage, with different perspectives as detailed above.

- DRAMA II and MSE place considerable emphasis on control systems specification, not just considering the mechanics of local control loops but considering the wider issues. MSE has a number of philosophical principles to be considered when designing control systems.

- Evaluation takes place at a number of levels in DRAMA (strategic, tactical and operational). The evaluation therefore includes a consideration of business metrics as well as operational metrics. In MSE, static and dynamic evaluation is undertaken, although it is not clear whether this analysis extends to business metrics or considers operational metrics only.

In theory therefore, the methodologies discussed can be interpreted as systemic by substantially meeting the requirements laid down in Chapter 2. In many ways DRAMA II and MSE may be seen as complementary to one another, rather than as alternatives to one another (see Figure 3.8). DRAMA II is focused on downstream assembly activities and has strengths in the strategic domain. MSE is strong in the design and analysis of upstream activities and has a focus on the detail design issues.

Figure 3.8 DRAMA II and MSE : Complementary Methodologies ?



It is proposed to focus this investigation on MSE. This can be justified on the following grounds.

- The domain of this work is primarily concerned with component part production rather than assembly operations.

- The strategic issues that DRAMA pulls together are reasonably well documented. This does not mean that the investigation will focus on the 'micro' problem as defined by Parnaby (1986) but rather the 'macro' problem that may be conceptualised as falling between the strategic issues and the 'micro' problem.

- MSE has been widely applied, and there is therefore an established base of applications in different environments to examine and guide future developments. DRAMA, on the other hand, was developed specifically for the electronics industry and has been tested in only thirteen organisations (Bennett & Forrester, 1993, p98)

3.7 Summary

In order to create an effective CMS design methodology, it has been argued that this methodology must be systemic. This chapter has presented a taxonomy for approaches to the design of cellular manufacturing systems. The approaches that fall into the first three categories of the taxonomy can clearly be seen not to meet the criteria of a systems approach to the design of cellular manufacturing systems. The approaches in the fourth category ('design methodologies') in particular, seem more promising. The next stage in the project investigation was to undertake a detailed examination of the practical use of MSE to :

a) Ensure that it was systemic in practice as well as in theory.

b) Identify any opportunities for improvement (be they of a systemic nature or not).

The next chapter will therefore examine Manufacturing Systems Engineering in practice, reviewing a range of applications, across a number of different industry sectors.

Chapter 4

Manufacturing Systems Engineering Revisited : Practical Applications

4.1 Introduction

Chapter 3 established that Manufacturing Systems Engineering (MSE) was the most complete of the current approaches to the design, at a detail level, of manufacturing systems. The purpose of this chapter is to explore MSE through a survey and examination of its application in a number of businesses involved in a range of industrial sectors. The purpose of the investigation was to understand and analyse, in detail, the strengths and weaknesses of MSE and its systemic nature as applied by experienced and well respected practitioners.

4.2 Survey Research Methodology

The survey was undertaken by working with Lucas Engineering & Systems Limited, an acknowledged leader in the application of MSE methodologies. Data on the application of the methodologies was collected by using four different, but complementary approaches. These approaches included:

- Interviewing formally and informally Lucas Engineering & Systems staff about previous and current MSE projects.
- Interviewing formally and informally clients of Lucas Engineering & Systems.
- Consulting documentary sources such as Lucas Engineering & Systems project reports, archives and internal training material.
- Extended participant observation, a form of ethnography and giving a significant depth to the research (Gill & Johnson, 1991).

The use of the four approaches described above aligned well with the aims of the research and were possible with the resources available. The use of this range of research methodologies enabled a rich picture of the application of MSE to be built up from a number of projects. The survey was descriptive and exploratory in nature rather than analytical. In other words, it focused on the phenomena whose variance I wished to describe (the application of MSE) rather than the identification of independent, dependent and extraneous variables. The use of a descriptive rather than analytical survey can be justified on the basis that the survey was concerned more with generality rather than precision and that the intention was to be unobtrusive rather than obtrusive.

The possible population from which a representative sample of MSE applications had to be determined, was defined as those manufacturing systems design projects that had resulted in the implementation of a cellular manufacturing system. This potential population was reduced by the need to obtain access to the clients, the site and individual consultants involved with the project. The size of the potential population was in excess of 50 projects. A representative sample (of 14 projects of various size) was selected in order to cover a range of company sizes, industry types, manufacturing technology and volumes. In addition, care was taken to ensure that a wide range of individual Lucas Engineering & Systems consultants were involved in the projects examined. This was to ensure that an unbiased view of the application of MSE (in terms of the individuals involved) was obtained. Over 40 different individual consultants were involved in the projects investigated. The careful selection of the sample ensured that a representative view on the implementation of MSE by Lucas Engineering & Systems was derived.

Table 4.1a gives the projects and companies that formed the basis for this investigation. Table 4.1b and Table 4.1c indicate the key characteristics of the companies where the application of MSE was investigated.

Table 4.1a : Lucas Engineering & Systems Client Sites Used as Basis for the Investigation into MSE

Lucas Aerospace, Power Systems Division, Hemel Hempstead, UK (Hemel)
Lucas Aerospace, Power Systems Division, Netherton, UK (Netherton)
Lucas Aerospace, Power Equipment Corporation, Cleveland, USA (LAPEC)
Lucas Aerospace, Actuation Division, Wolverhampton, UK (Fordhouses)
Lucas Aerospace, Defence Fabrications, Burnley, UK (LADF)
Lucas Aerospace, Engine Fabrications (now owned by Hurel Dubois), Burnley, UK (LAEF)
Lucas Automotive, Diesel Systems Division (formerly Lucas CAV), Sudbury, UK (Sudbury)
Lucas Automotive, Diesel Systems Division, (formerly Lucas CAV), Gillingham, UK (Gillingham)
Lucas Automotive, Body Systems Division, (formerly Lucas RISTS), Newcastle-under-Lyme, UK (Rists)
Lucas Automotive, Body Systems Division, (formerly Lucas RISTS), Ystradgynlais, UK (Ystrad)
Lucas Applied Technology, CEL, Hitchin, UK (CEL)
Rolls Royce, Fabrications, Hucknall, UK (Hucknall)
GEC EEV, Chelmsford, UK (EEV)
Westland Helicopters Limited, Yeovil, UK (WHL)

Table 4.1 (b) Characteristics of Sample Companies

SITE	SIZE	INDUSTRY	PRODUCTS	VOLUMES	CONSULTANTS
Hemel	~1000	Aerospace	Power genertn. system	Low	6
Sudbury	~600	Automotive	Diesel injectors	Very high	3
Rists	>2000	Aerospace	Wiring systems	Very high	2
Ystrad	~600	Automotive	Wiring systems	Very high	2
CEL	~100	Industrial	Sound level	Medium	1
RR	~500	Aerospace	Fabrications	Low	1
EEV	~200	Defence	Microwave Emitters	Low	3

Table 4.1(c) Characteristics of Sample Companies

SITE	SIZE	INDUSTRY	PRODUCTS	VOLUME	CONSULTANTS
Netherton	~200	Aerospace	Gearboxes	Medium	3
LAEF	~200	Aerospace	Engine Fabrications	Low	1
LADF	~200	Defence	Missile fabs.	Medium	3
Gillingham	>1500	Automotive	Diesel pumps	Very high	6
WHL	>3000	Aerospace	Gears	Low	2
Fordhouses	~1200	Aerospace	Actuation	Low	7
LAPEC	~750	Aerospace	Power gen. & Actuation	Medium	5

4.3 Lucas Engineering & Systems Limited

Lucas Engineering & Systems Limited (LE & S) is a wholly owned subsidiary of Lucas Industries plc, a supplier of mechanical and electrical systems and components to the automotive, aerospace and other selected markets. Lucas Engineering and Systems Limited was formed in 1984 with 12 people under the leadership of Dr John Parnaby, who was appointed Manufacturing Technology Director of Lucas Industries. He is now Managing Director of Lucas Applied Technology, one of three main sectors of Lucas with Lucas Aerospace and Lucas Automotive. He was the first Lucas executive not to have spent their career within the company (Levi, 1990). Dr Parnaby was recruited to implement manufacturing systems engineering within Lucas Industries (from the University of Bradford, where he was Professor of Manufacturing Systems), after it suffered its first financial loss (of £22 million) in 1981. Competitive Achievement Plans (CAPs) were drawn up for every business at a strategic level, indicating performance against world's best practice and indicating action necessary to close any competitive gap. MSE was regarded as the key operational formula to close the gap in manufacturing (Loveridge and Pitt, 1990). Lucas Industries are now regarded as one of the key British emulators of Japanese manufacturing systems engineering principles (Oliver & Wilkinson, 1992).

L E & S was started to enable the process of implementing MSE and has been the major influence within Lucas Industries. It has the following objectives:

- to increase the stock of Lucas engineers with manufacturing systems engineering skills.

- to transfer manufacturing systems engineering skills to Lucas manufacturing businesses.

- to improve the performance of Lucas manufacturing businesses.

At the same time the company is expected to meet the same financial criteria (in terms of profitability etc.) as other Lucas businesses. LE & S achieves this by charging for its services to Lucas clients at a small percentage above cost and by charging 'commercial rates' to its external clients.

Lucas Engineering & Systems has grown significantly since 1984 and is now a £22 million business with over 400 well qualified consulting and specialist staff. The company claims to have successfully completed over 600 company site based projects in the aerospace, automotive and general industrial sectors world-wide. Table 4.2 indicates some of Lucas Engineering & Systems recent larger customers. Lucas Engineering & Systems also claim to have up-to-date experience of implementing manufacturing systems engineering in small and medium sized enterprises. The company has also established links with many other bodies such as universities (Lucas sponsors 15 UK university Chairs and 1 Chair at Trinity College, Dublin), the Department of Trade & Industry and various Training and Enterprise Councils.

Lucas Engineering & Systems Limited may therefore be regarded as an appropriate organisation to work with in an investigation into MSE. They have wide experience both in terms of the volume and the range of work (in terms of different types of businesses) that they have undertaken. They are led by an acknowledged leader in the field of MSE (Dr John Parnaby) and they have many links with the established academic community in MSE. They have also shown that their application of MSE is valued by many blue chip companies. With ten years work in the area, they are also one of the most well established practitioners.

Table 4.2 Recent Lucas Engineering & Systems Customers

Lucas Industries (Site based projects across all sectors world-wide)
Westland Helicopters
BTR
Rolls Royce
Hindustan Motors (India)
TI Industries
Bruel & Kjaer (Denmark)
Royal Ordnance
GEC

4.4 Overview of the MSE Methodology in Practice

This section gives an overview of the interpretation of the approach used to implement MSE by LE & S. The methodology used in MSE design and redesign projects by LE & S is slightly different from that which has been published (for example, Parnaby 1979, 1986, 1991). Figure 4.3 indicates the main stages of the methodology adopted by LE & S and Figure 4.4 shows how this maps onto the methodology proposed by Parnaby (1979, 1986, 1991). The key stages in the LE & S application of MSE are :

Data Collection and Analysis - This stage is concerned with collecting the data that is required for design purposes. Typically, data is collected concerning demand, products, processes and performance. This data is usually analysed using a number of different techniques such as Pareto analysis, Process Flowcharting and SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. In addition, business and manufacturing strategies are examined and understood.

Manufacturing Architecture Definition - A manufacturing architecture is defined, utilising cellular manufacture. The focus is usually on defining a product orientated structure that gives a team of people responsibility for a whole product. What is in effect a three level reference architecture is utilised, consisting of Product Units,

Figure 4.3 LE&S MSE Methodology

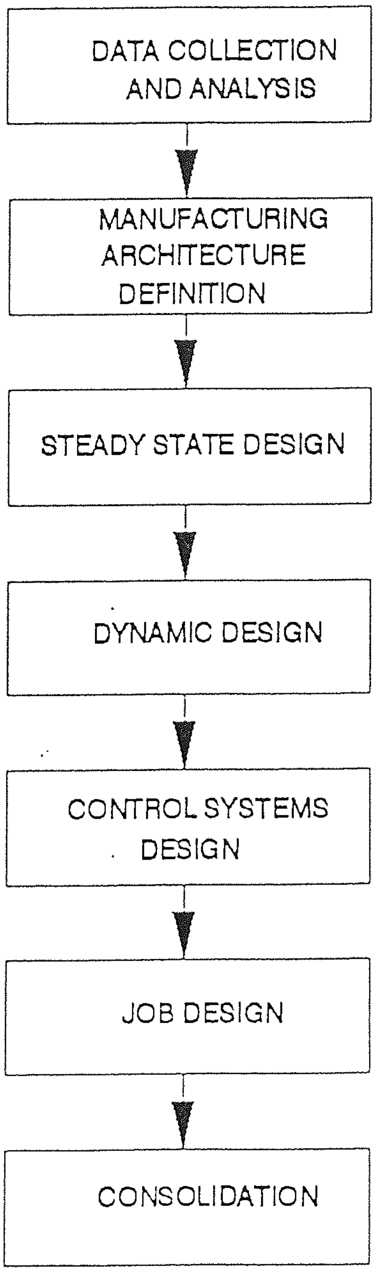
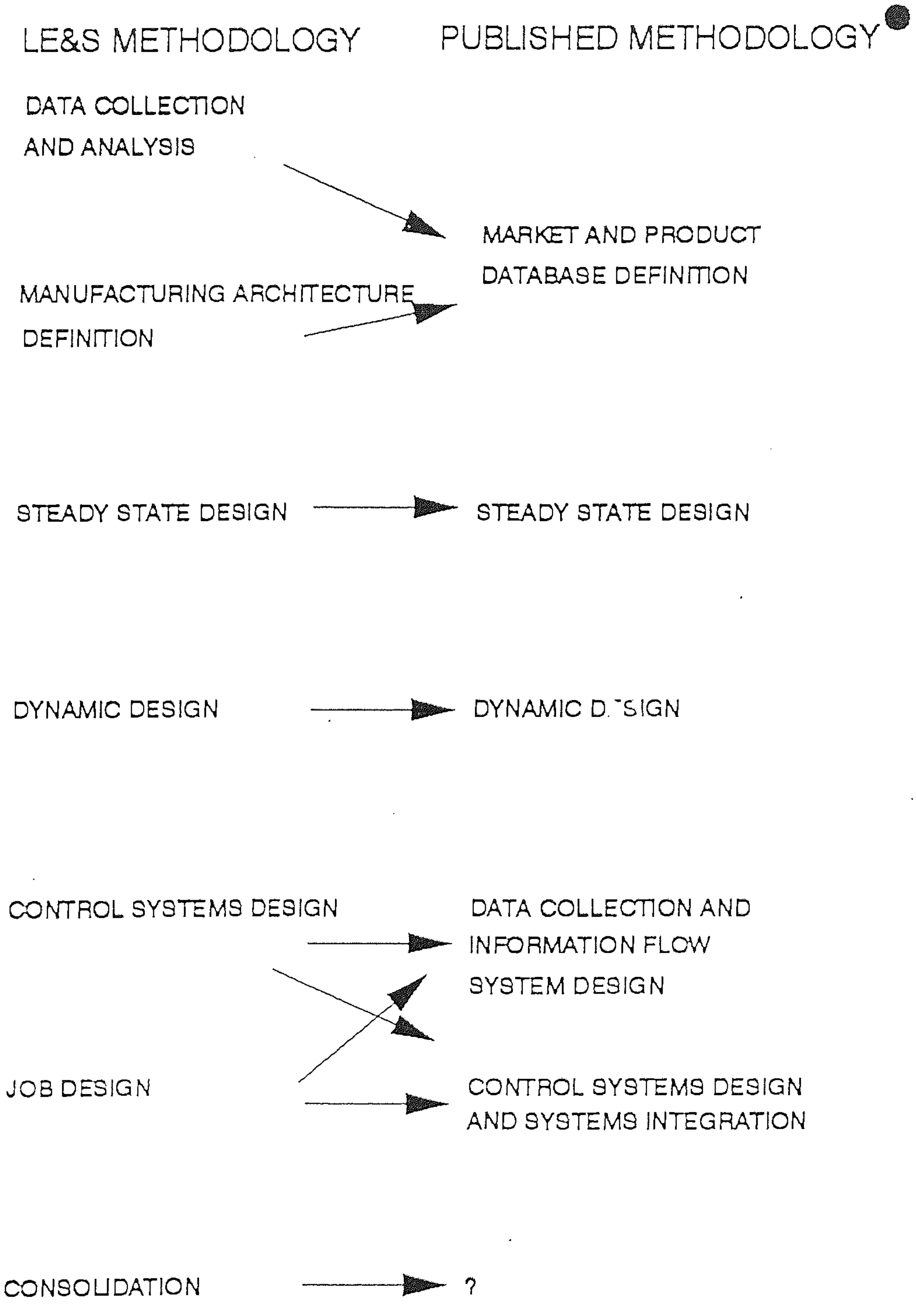


Figure 4.4 Mapping of Published MSE Methodology Against LE & S Methodology



● - e.g. Parnaby (1979), (1986), (1991)

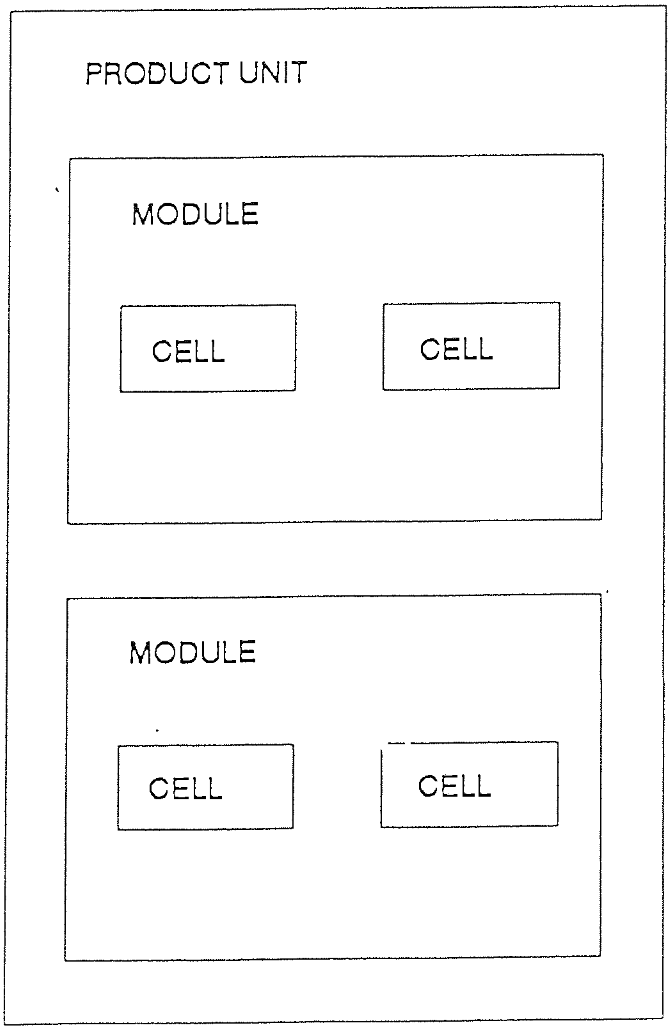
Modules and Cells. Figure 4.5 illustrates the relationships between each of these building blocks. Product Units are usually organisational units with responsibility for the manufacture of complete products. Modules are essentially a collection of manufacturing cells related in some fashion (e.g. assembly cells). Cells are the lowest organisational building block and are usually subject to the most detailed analysis. In the situation where a product unit consists of one module (i.e. there are two levels in the architecture rather than three), the terms product unit and module are often used interchangeably.

Steady State Design - The operational design of the manufacturing system is undertaken at this stage. The design is based on the use of average operating parameters (such as demand and performance) and ideal conditions (i.e. ignoring possible constraints). The focus is on machines (including processes and equipment), people (numbers and skills) and the physical layout. World Class Manufacturing principles are adopted in its design (e.g. 'U' shaped layouts).

Dynamic Design - This stage is concerned with the design of the manufacturing system using so-called 'real world' conditions. Typically, 'what-if' analysis is undertaken on spreadsheets (to discover the effect of demand variations and performance variations for example) and cause and effect analysis to try and discover key areas for consideration. Rarely, is any dynamic analysis in the sense of analysing performance over time either deterministically or stochastically undertaken.

Control Systems Design - At this stage in the methodology, consideration is given to various control systems such as tool control, quality control and material control. The focus is very much on material flow control at the shopfloor level, with attention given to the design of work control boards for example. Little attention is paid to the interfaces with top down material planning systems such as MRP.

Figure 4.5 Manufacturing Reference Architecture



Job Design - At this stage activities are grouped into jobs, organisational structures determined and training requirements diagnosed.

Consolidation - This stage is concerned with the submission for approval of the manufacturing system design. Usually, implementation plans with resource and timescales are submitted with a financial assessment and an associated risk analysis.

The activity of designing or redesigning manufacturing systems by LE & S is undertaken by a multi-disciplinary task-force. This task-force is staffed by a number of full-time members, supported as appropriate by a part-time input. The task-force includes knowledgeable site personnel and experienced LE & S manufacturing systems engineers. The task-force has a terms of reference and a set of objectives. Typically, the task-force is charged with generating a 'step change' in performance. The objective is to raise performance above the level of competitors and create an environment where continuous improvement (or kaizen) can flourish.

The stages will now be considered in detail, with reference to actual practise. Particular emphasis will be given to the Manufacturing Architecture Definition, Steady State Design, Dynamic Design, Control Systems Design and Consolidation stages of the methodology. The samples used to illustrate the approach in each stage have been chosen to be representative of both good and bad practice.

4.5 Manufacturing Architecture Definition

The LE & S methodology recognises the significance of defining a manufacturing architecture. LE & S defines manufacturing architecture as:

> '...a manufacturing organisation structure designed to meet business objectives.'

The general philosophy that underpins the process of defining a manufacturing architecture is characterised by the following statement made by an LE & S Consultant :

> '...unless there are overwhelming reasons to the contrary, vertically integrated product unit definitions are to be preferred'

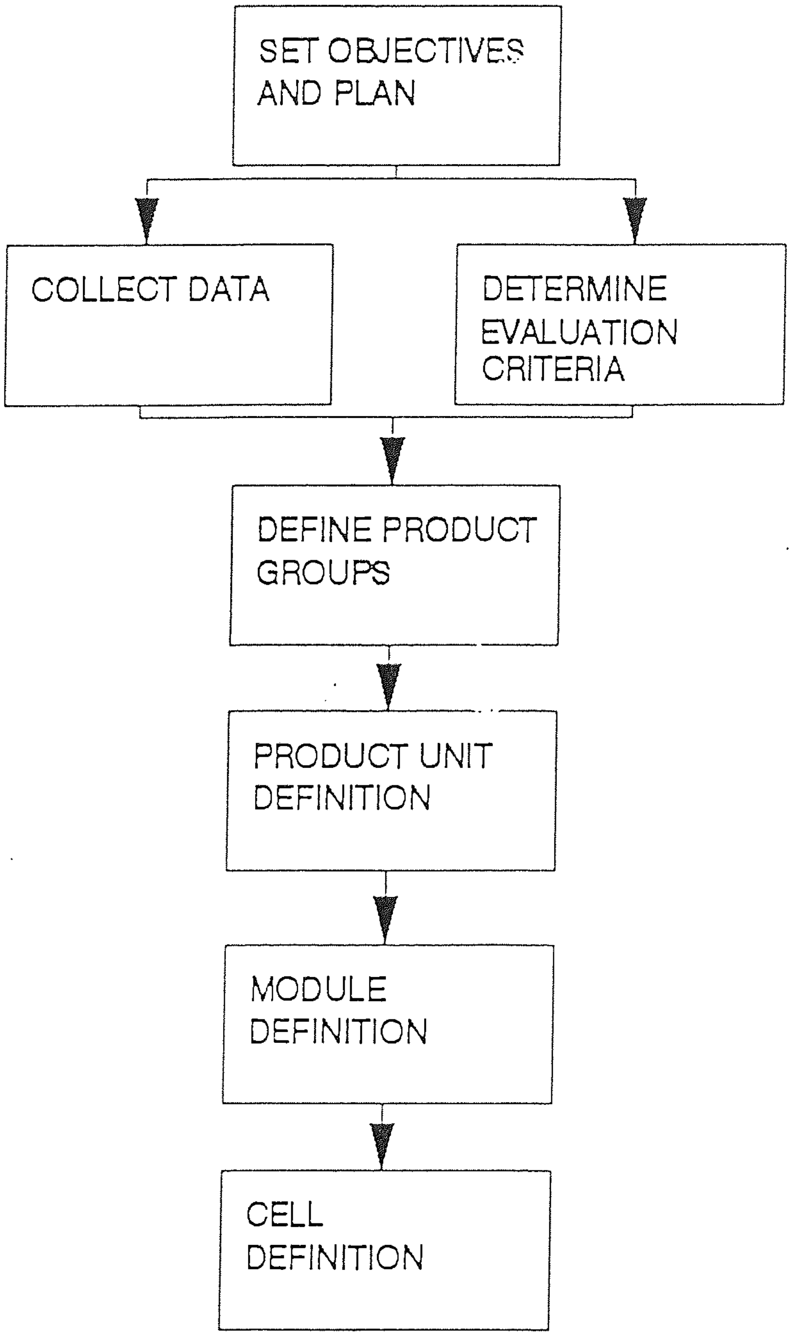
The justifications given for this position included the assertions that such product units focus on customer needs, promote low complexity through high 'ownership' (defined as product hours in cell / total product hours) and foster teamwork. The general methodology adopted in this phase of a manufacturing systems engineering design project is illustrated in Figure 4.6.

The process starts with the setting of objectives and the planning of the manufacturing architecture definition process. Data is collected (on products and processes) and evaluation criteria decided. These criteria are usually proxies for operational metrics and usually qualitative in nature and rarely quantitative (in fact no case of a quantitative metric being used was found). Typical criteria include 'ownership', training requirements, communication and so on. Product groups are then defined on the basis of some similarity, such as product type. Product Units and Modules may then be defined. Product Unit and Module Definition are undertaken with little quantitative analysis. Cell Definition follows Module Definition, and quite often utilises reasonably sophisticated tools such as Rank Order Clustering (ROC) (King & Nakornchai, 1982).

Often the process of defining a manufacturing architecture will initiate a 'Make v Buy' exercise. This activity is usually taken at a very 'tactical level' and focuses on parts that (in the words of one LE & S Consultant) :

> '...do not fit easily into the scheme of things'

Figure 4.6 Manufacturing Architecture Definiiton Process



(Product Unit Definition and Module Definition may not both be undertaken, depending on the number of levels in the architecture.)

That is to say parts which do not fit into the manufacturing architecture that has been defined, or are 'C-items' when parts are classified by an ABC analysis.

4.5.1 Product Unit Definition at EEV

This case deals with the product unit definition process at EEV, a subsidiary of GEC involved in the production of travelling wave tubes for the defence industry. LE & S were involved in this project as external consultants for a period of approximately one year. The approach used for the process of module and cell definition at EEV included the collection of data on the market and the current manufacturing system. Options for both product units and cells were then defined and the 'most appropriate' option selected.

The evaluation process included generating a cause and effect analysis of poor performance and from this determining what product unit characteristics should be incorporated into the manufacturing systems design. Each characteristic was given a weighting. Each alternative product unit definition (existing,product orientated or some hybrid) was marked out of ten for each characteristic and a weighted score calculated. This is shown in Table 4.7. The existing functional structure scored 283, the product based structure 434 and a hybrid structure 436. As a product orientation was 'preferred' the vertically orientated structure was chosen as there was little difference between it and the hybrid solution. This process led to the definition of two vertically orientated product units, one for Coupled Cavity products (2 cells) and one for Helix products (3 cells). The cells were defined on the basis of volume and frequency of demand characteristics. 'Runner' (a product for which a regular demand exists) cells was defined as were cells for irregular runners (repeaters) and strangers (unpredictable frequency of demand) (Parnaby (1988) introduces the terms runner and stranger).

Clearly, in this case the product unit definition was evaluated in a very subjective way and there were a distinct lack of alternatives considered. All the alternatives considered

Table 4.7 : Product Unit Definition Evaluation Matrix used at EEV

Evaluation Criteria	Weight	Score Functional	Score Product	Score Hybrid
Ownership	5	15	50	45
Controls	5	20	50	45
Robustness to variation	5	30	25	30
Current mix, volume split	5	20	40	40
Product travelling time	5	20	50	40
Impact on morale	5	10	35	35
Running costs	4	20	20	24
Cost of implementation	4	32	8	24
Teamwork	4	32	36	32
Response time	4	12	32	28
Training Requirements	3	24	12	18
Skills flexibility	3	12	24	24
Implementation disruption	2	8	12	16
Ease of tracking product	2	8	18	14
Support requirements	1	6	8	7
Ergonomics	1	6	8	7
Environment	1	8	6	7
Score		283	434	436

(Source: Interviews and EEV Travelling Wave Tubes project reviews) were generated as a consequence of some broad top-down analysis rather than the detailed examination of relevant data. The preference for vertically product units is also clear.

4.5.2 Product Orientated Cells at Lucas Body Systems (Rists)

This case-study is concerned with the cell definition process (rather than product unit or module definition) at Lucas Body Systems, formerly known as Lucas Rists. The company supplies three different market segments; specialist (e.g. military), commercial (e.g. housewiring) and automotive. The specialist segment accounts for 15% of capacity usage, commercial 32% and automotive 53%. The manufacturing architecture definition process adopted included the following steps:

i) Define the current problems : Poor quality and 68% schedule adherence.
ii) Determine the causes : Large department, difficult to control with high volume and high variety.
iii) Consider desirable cell characteristics and rank 1 - 3.
iv) Brain-storm different types of cell split (or cell definition).
v) Mark each type of split out of 10, against each characteristic.
vi) Draw up matrix, and calculate scores.
vii) Pick the highest scoring cell split.

Table 4.8. shows the matrix that was generated as a result of the above process. As a consequence of the analysis shown in Table 4.8 the task-force proposed six manufacturing cells based around a product or vertical focus. Clearly, the comment regarding subjective evaluation in Section 4.4.1 is relevant here. In this case a reasonable number of alternative solutions were proposed.

A couple of years after the exercise detailed above was carried out, the company contracted another firm of consultants (Booz, Allen & Hamilton Inc) to review their

Table 4..8 : Cell Evaluation at Rists

Good Cell Characteristics	Rank	Cable	Cust.	Plant	Vols	Lead	Prod	Exist
Accountability	3	6	10	6	8	4	10	5
Delivery	3	4	10	4	8	4	10	4
Ownership	3	4	10	2	8	2	10	3
Quality	3	7	10	7	8	7	10	5
Communication	2	4	10	2	7	1	10	3
Low WIP	2	5	7	4	7	4	8	1
Changeovers	2	6	4	2	6	4	4	8
Raw Mat Flow	2	8	6	3	7	3	5	3
Response Time	2	6	9	4	5	4	10	4
Simple Control	2	5	8	3	7	4	9	2
Teamwork	2	7	9	7	7	7	5	3
Product Costing	1	5	9	4	5	4	10	3
Handling	1	2	8	2	4	2	9	5
Highlight Problems	1	6	10	6	6	6	10	1
Set up cost	1	9	4	6	7	4	3	10
Tooling Cost	1	7	5	5	8	4	6	4
Rank Total		174	262	130	218	125	262	122
Sum Total		91	129	67	108	64	129	64

(Source : Interview with LE & S Consultant) manufacturing strategy. The analysis carried out by this team suggested that Rist's enthusiasm for a completely product orientated structure was a little mis-placed (it should be noted that the business environment was felt to be substantially the same). They concluded that the business had a significant problem delivering to small order customers on time. They determined that the best definition for cells was on the basis of demand characteristics. Their proposed solution proposed a number of 'runner' cells charged with maximising output, productivity and quality. It also proposed a number of repeater cells, charged with minimising set-up costs and ensuring a fast response. These definitions would allow direct labour to be used more effectively (multi-machine manning) and make best use of fast changeover technologies. In the view of the Booz, Allen & Hamilton Inc team the architecture implemented along vertically integrated product principles (interview with a team member) :

> '...clearly missed opportunities.'

4.5.3 An Analytical Approach to Cell Formation at Westland Helicopters Limited

This short case-study describes the cell definition process which took place at Westland Helicopters for the design of their 'Gears Operation' manufacturing system. The site had already been split into a number of Product Units, of which the 'Gears Operation' was one. The 'Gears Operation' manufactures a range of high precision, high technology parallel axis and spiral bevel gears, all with ground flanks. It utilises a range of manufacturing processes including shaping, hobbing, spur grinding, spiral bevel gear cutting and grinding and heat treatment (nitriding and carburising). There are approximately 100 machine tools in the facility. Batchsizes of 20 - 25 and changeover times of up to 24 hours are common. Average process time for a gear is in the region of 30 hours and the average planned leadtime of around 8.5 months compares with the actual leadtimes of about 13 months. The 'Gears Operation' is a £13 million business contributing significantly to company profitability with 220 employees of whom 120 were 'direct' labour. Figure 4.9 shows the process that was adopted for the definition of the manufacturing architecture, each step of which is detailed below.

i) Preparation and Initial Analysis : A routing database, market demand database, parts family database and a machine classification database were all established in this phase. An initial ROC matrix was produced, indicating complexity. The matrix was very dense and no block diagonal form was present. The total routing file used initially had 9555 part-number operations. This was reduced to 365 part-number operations by eliminating all operations other than those performed by key machine groups. Key machines were defined as gear manufacturing machines. This was justified on the basis that the facility was gear manufacturing operation, they represented over 50% of the load hours, and were the most highly valued machines. The intention was to use MODROC (Chandrasekharan and Rajagopalan, 1986) on the key machines and build up cells through the addition of required support machines (such as lathes). In effect, the key machines were used as seeds for the formation of manufacturing cells.

ii) Primary Cell Configuration : A MODROC analysis was applied to the part-machine group matrix. This resulted in a number of potential manufacturing architectures being defined. These initial architectures were evaluated in a fashion similar to that described in Sections 4.4.1 and 4.4.2.

iii) Assignment of Key Machines : The primary cell configuration was expanded at this stage by assigning particular machines (from the key machine groups) to each cell.

iv) Assignment of Support Machines : In this phase machines such as lathes, mills and drills were included in cell definitions.

v) Support Cell Configuration : An early decision was made that processes such as heat treatment, NDT, anodic processes and surface treatments (such as nital - etch) would

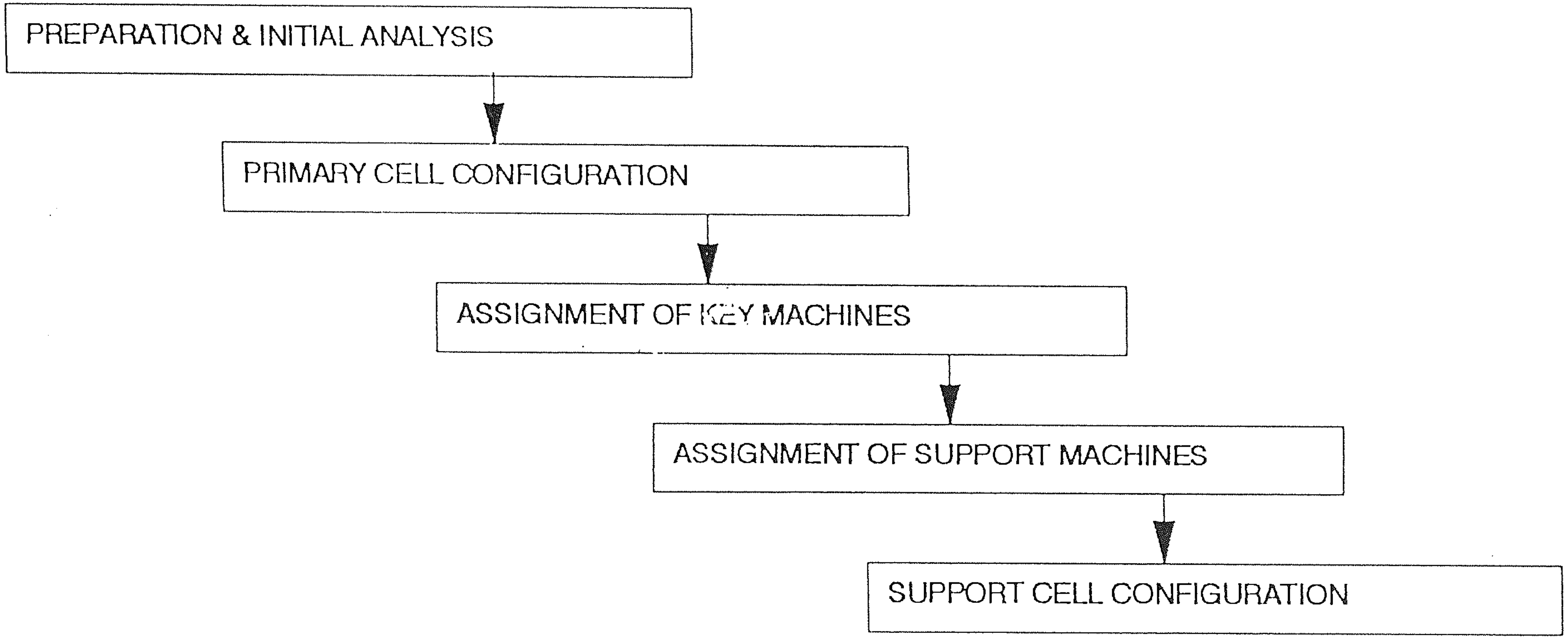


Figure 4.9 Cell Definition Summary Flowchart

be placed in central process orientated cells. This was a consequence of the potential capital cost and health and safety considerations.

The process of cell formation discussed above is fairly sophisticated from an analytical point of view and is less driven by product considerations. However, it still suffers from a very subjective evaluation process. The adoption of manufacturing systems engineering at Westland Helicopters has featured in an article by Kellock (1990).

4.5.4 'Make v Buy' at Lucas Aerospace, Power Systems Division

The manufacturing architecture definition process at the Hemel Hempstead site of Lucas Aerospace , Power Systems Division included a two filter make v buy process. The first filter was a 'C' item filter, whereby all 'C' items were defined as bought out. A 'C' item was determined as having less than 20 minutes process time. The second filter applied was concerned with matching parts to cells. If a suitable cell could not be identified the part was bought out. As the Manufacturing Systems Engineering Manager of the time said:

> 'If a cell to match the design requirements cannot be found, the item **must** be assumed Bought Out'

The 'C' item analysis showed, when applied to 13,000 parts that 12,100 parts accounted for 10% of the load and that 900 parts accounted for 90% of the load. The policy was adopted on the basis of a qualitative evaluation. The evaluation concluded that buying out 'C' items would 'free up' time as they diverted attention. This would allow the facility to concentrate on 'A' and 'B' items and hence become excellent. Clearly, a more appropriate analysis was required investigating both the dynamic financial effects of such a decision and the implications for issues such as overhead recovery.

4.5.5 Observations on the Manufacturing Architecture Definition Process

A number of conclusions regarding the Manufacturing Architecture Definition process may be drawn from the above analysis.

a) It is heavily weighted towards vertically integrated manufacturing structures with little consideration of alternatives. This may be appropriate and may aid the introduction of World Class Manufacturing. However, there are a number of proven alternatives to vertically integrated manufacturing units. For example, Group Technology (Gallagher & Knight, 1986) is a well proven approach to cellular manufacture, which could be more appropriate in some circumstances than the use of product orientated, vertically integrated manufacturing structures. This is a more extreme view on cellular independence than that put forward by Burbidge (1992, 1994), who proposes a view that process (functional) organisation is obsolete. This view in itself has been criticised as extreme and debatable.

b) The evaluation of manufacturing architectures is based on very subjective criteria. One could argue that the techniques such as those illustrated (Tables 4.7 and 4.8) above usually only ever work when one knows the 'answer' already (or knows what the 'desired' outcome is). Pseudo-numbering systems such as those illustrated above usually add variability to a process and are a very poor form of performance evaluation. Although the evaluation criteria that are illustrated above may be useful as a general filter they are not able to help select an optimal cell definition on the basis of manufacturing performance.

c) The investigation showed-up inconsistencies in the rigour of analysis undertaken for the definition of manufacturing architectures. This is illustrated by the different approaches taken in the Rists (a top down 'broad brush' approach influenced by strategic parameters) and Westland (a bottom up analytical approach, perhaps less influenced by strategic concerns) cases discussed above. On investigation, the reason for the lack of consistency in approach is a lack of clear direction, on the part of LE & S, on the process to be adopted for the definition of a manufacturing architecture. The goal is well defined ('vertically integrated, product aligned manufacturing structures'), but the process is articulated less well. It may well be that some combination of top down and bottom up analysis is required for the definition of a 'good' manufacturing architecture.

d) The 'C' item offload approach to 'make v buy' in the cell formation process, although possibly having some merit in reducing shopfloor complexity and confusion, is not an adequate approach to defining the manufacturing boundary of a business. The effect of such policy changes on operational and financial metrics should be more closely evaluated. For, example, the effect on overhead recovery should be investigated.

e) On the other hand, LE &S might be regarded as a fairly sophisticated user of analytical techniques such as Rank Order Clustering (ROC) (King & Nakornchai 1982). Wemmerlov & Hyer (1989) found that around only a third of companies introducing cellular used formal algorithms. In fact over 40% did not even consider examining current or planned routings.

4.6 Steady State Design

The steady state design phase follows the manufacturing architecture definition step. The objectives of the steady state design phase are to (LE & S Consultant) :

> '...define with minimum detail an ideal design specification and to design for optimal performance to meet customer requirements.'

The approach adopted is to be radical and ignore constraints such as existing working practices and interactions with other business systems. Resource is 'optimised' using average conditions for demand mix, demand volume, resource availability and performance. World Class Manufacturing principles are used in the steady state design phase (e.g. capable processes, short changeover times, flexible people). The methodology employed consists of three main steps. Firstly, the operation of individual workstations is considered in detail. Typically, this focuses on plant, although specialist skills are considered if they could be a problem. Spreadsheet calculations are undertaken using product demand and process data. Bottlenecks and their resolution are considered (for example, changeover reduction priorities are considered). The second step is to consider the integration of the individual workstations and give some consideration to local operating procedures. Some static calculation of inventory requirements also takes place. Finally, the overall cell layout is considered.

4.6.1 Spreadsheets at Lucas Aerospace Defence Fabrications

This project was concerned with the design of a manufacturing system for Rocket Motor Casings (RMC's). The product unit was designed to manufacture a large volume of a single product called HARM (High Speed Anti Radar Missile). A lowering of demand threatened to make the product uncompetitive. Therefore, the facility was redesigned so that other products could be manufactured, absorbing overheads and excess capacity. The task-force was faced with two key problems in the steady state phase of the project. Uncertainty over products to be manufactured and difficulty in estimating volumes and routeings. The only objective given to the steady state stage was to size the cells.

The approach taken was to assign probabilities to the winning orders. Two steady state designs were generated, one based on a maximum size and another based on a minimum size. The maximum scenario was based on analysing orders that the business had a high and medium probability of winning. The minimum scenario was based on analysing orders that the business had a high probability of winning. These steady state designs were modelled on a spreadsheet , with low probability contracts being used to test the design, but not for capacity calculation.

4.6.2 Databases and Spreadsheets at Lucas Diesel Systems

This case is concerned with activities of a team tasked with the redesign of a large general machine shop and focuses on the steady state design activities undertaken for one manufacturing cell. The approach taken was replicated across a number of other cells that were designed as part of the project. The cell in question is the 'Head and Rotor' cell . A head and rotor is an assembly consisting of a barrel, a sleeve (shrunk into a barrel to form a head) and a rotor which rotates within the sleeve. There are 73 types of barrels, 63 types of sleeve and 137 types of rotor that can be assembled into 244 different end item head and rotor assemblies. Total volume of head and rotor assemblies is around 71,000 per month. Each of the 244 different head and rotor assemblies can be characterised on the basis of 22 features such as type, number of cylinders and number of plungers.

A tool was developed combining dBASE III + and Lotus 123 to calculate operator hours required, setting hours required, machine load and to identify potential bottlenecks. These outputs were calculated using market data (type, volume and features), plant data (cycle time, set-up time and breakdown time), personnel data, (shifts, hours, overtime, lost time) and quality data (scrap, rework).

The key to the tool was the analysis of the 22 product features. Market data, including volume requirements and features were input into dBASE III+. These were then sorted on the feature fields and the volumes for each feature summated. As the feature fields dictate the use of particular machines, cycle times and set-up times, the volumes can be automatically transferred to a particular machine on the spreadsheet, which is characterised by machining parts with a particular combination of features. The spreadsheet had columns for available capacity, percentage scrap, percentage rework and so on. The spreadsheet could then be used for various forms of static capacity analysis.

The tool was used in the steady state design stage to test variety and volume mixes against capacity, identifying capacity bottlenecks and testing solutions, analysing the effects of overtime, scrap and rework on capacity. The tool was also used to assess the effect of cycle time reduction on capacity, the effects of changeover time reduction and a shift pattern analysis.

4.6.3 Observations on the Steady State Design Process

A number of conclusions regarding the steady state design process may be drawn from the investigation undertaken.

a) During the course of the investigation a substantial amount of spreadsheet analysis was detected. In fact, not one project that was discussed did not undertake spreadsheet and / or database analysis to undertake capacity - load calculations. Given that Wemmerlov and Hyer (1989) detected a :

> '...low level of sophistication..'

as far as the use of computer support in the cell design process was concerned, this indicates a significant capability and approach in this area.

b) In nearly all of the design situations analysed, good use was made of scenario generation and testing to ensure the viability of manufacturing systems designs. This appears to be a very good feature of the methodology.

c) During the investigation many examples of good practice in cellular layout were encountered. This included 'Nagare' cells (Parnaby et al 1988) and 'U' shaped assembly cells. Invariably, extensive process flow charting had taken place and a significant number of non-value-added activities eliminated. The steady state design phase in the methodology was shown to be an appropriate stage for the specification of many world class manufacturing concepts in the design, utilising the benefits of the cellular structure formed in the manufacturing architecture definition stage.

d) The concept of ignoring constraints, and designing a so-called 'ideal' system in the steady state design phase has caused a number of manufacturing systems design task-forces some considerable problems. For example, it has sparked off unnecessary industrial conflict on the basis of working practices that were never likely to be proposed by the facility management, let alone implemented. A degree of naivety was present in this area and the necessity of producing an 'ideal' design that is often unrealistic and unimplementable is questionable.

4.7 Dynamic Design

This stage is claimed as a test of robustness with variations in demand as the focus. The robustness of cell designs is determined by analysing the effects of variations on operational performance measures. The investigation includes variations considered to be typical, worst case and catastrophic. The measure of robustness is considered to be the ability to cope with these effects, perhaps by working overtime, or introducing selected double shifts.

The approach adopted by the methodology in the dynamic design phase proceeds along the following lines. Firstly, consideration is given to all of the constraints making the adoption of an ideal design difficult. Secondly, the 'pros' and 'cons' of accommodating these constraints are then evaluated. Thirdly, potential sources of variability are determined and quantified. Consideration is given as to how the system will deal with these variations. Variations considered usually include manning issues (such as absenteeism and performance), machine issues (such as breakdowns), material issues (including scrap and rework) and market issues such as sales mix and volume variation.

4.7.1 System Variation at Westland Helicopters Limited

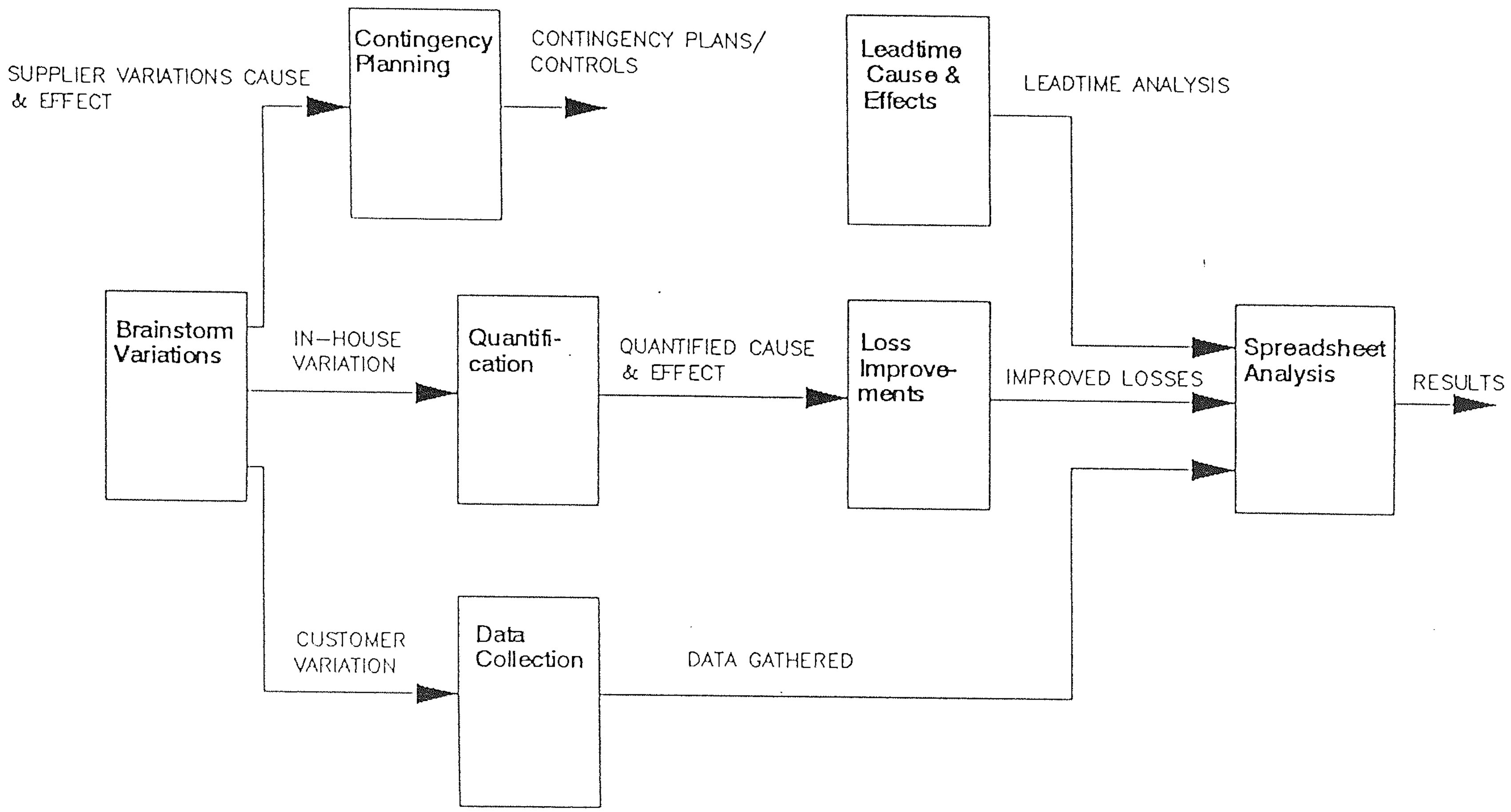
In this particular case the dynamic design phase was identified as having four objectives:

- Quantifying any increase in the direct labour required due to fluctuations from the steady state.
- Identifying (in more detail than the steady state design stage) potential bottle-neck facilities.
- Identifying areas where procedures were required to eliminate / minimise variation and its effect.
- Demonstrating that the cell designs were robust to changes internally and externally.

The detailed approach taken is illustrated in Figure 4.10. The approach was used to identify key sources of variation in three areas, the supplier sub-system, the in-house manufacturing sub-system and the customer sub-system. Key sources of variation were defined as being those to which the cells would be likely to be sensitive to changes in or those which were currently causing major problems. The potential variations were 'brain-stormed' for each sub-system.

After the variations were identified, their effect was sized. This was done by using spreadsheets to answer 'what-if' questions and by using cause-and-effect analysis, quantifying the effects on the basis of current data. The sized effects were examined across the whole of the manufacturing system to understand broad implications and then, by looking at the detailed implications for bottle-neck facilities. Variations were then classed as either typical (which the manufacturing system must be able to cope with on a regular basis - for example, minor breakdown), exceptional or catastrophic. The likely effects in the revised system were then estimated (including likely reductions

Figure 4.10 Dynamic Design at Westland Helicopters Limited



due to the introduction of cellular manufacture). A spreadsheet 'what-if' type analysis was also undertaken to establish the effects of overtime, changeover reduction, machine breakdown etc. Actions, policies and procedures were then included in the manufacturing system design.

4.7.2 Taguchi at Lucas Aerospace Defence Fabrications

This project was again concerned with the design of a manufacturing system for the HARM (High Speed Anti Radar Missile) Rocket Motor Casing (RMC) as discussed in section 4.5.1. The aim of the dynamic design stage was identified as improving the robustness of the cell designs and testing alternative scenarios. It was claimed that all sources of variation were determined through brainstorming. Values were assigned to the variations through estimates or the use of actual data. The largest sources of variation identified were volume / mix variations and these were identified as being so large that they might have a dramatic effect on the cell designs.

The task-force decided that a method of modelling the effect of these variations was required. A series of Taguchi experiments were undertaken. An L_{12} orthogonal array was used. The experiments were carried out using a capacity analysis spreadsheet by varying the input volumes in line with the values in the array. The results were then analysed to determine the viability of the cells, the decisions required to make them viable and the changes required to make the cells robust. In effect, the use of orthogonal arrays reduced the number of spreadsheet calculations required to map the required working envelope of the manufacturing system.

4.7.3 Observations on the Dynamic Design Process

The following observations on the dynamic design process may be drawn:

a) Very extensive use of cause-and-effect analysis was found in the dynamic design phase. Cause-and-effect diagrams were used to help focus task-forces on important issues that manufacturing systems had to be designed to contend successfully with. Quite often the causes and the effects were quantified. This exercise seemed to be very useful.

b) Most analysis undertaken in the dynamic design phase was anything but dynamic, in the sense of time-varying. The majority of modelling and analysis was static and deterministic (i.e. perfectly predictable) in nature relying on spreadsheet 'what-if' calculations. These series of steady state calculations were used to generate an envelope of cell capability. In only 25% of cases examined was any dynamic modelling (in the sense of time varying) used. In only 10% of the projects was any computer simulation used and in only a further 15% of cases was hand simulation utilised. Dynamic stochastic (i.e. using probability distributions) modelling was not used in any of the cases. All dynamic modelling was deterministic in nature. On investigation a number of reasons were given for this lack of dynamic modelling and analysis. Firstly, there was a perception that such analysis took a long time and would not necessarily generate any benefit. Secondly, because of the position of the dynamic design stage in the methodology (the middle step, but near the end in terms of the percentage of project time consumed) it was often felt that such 'detail' was best dealt with in the implementation phase. Thirdly, there was also a common view that by designing the manufacturing system at an 80% loading in the steady state design stage, any potential dynamic problems would not be an issue.

c) One strength that emerged concerning the dynamic design phase was that task-forces quite often looked at the whole logistics chain, not just the 'in-house' manufacturing system, but also suppliers and customers.

4.8 Control Systems Design

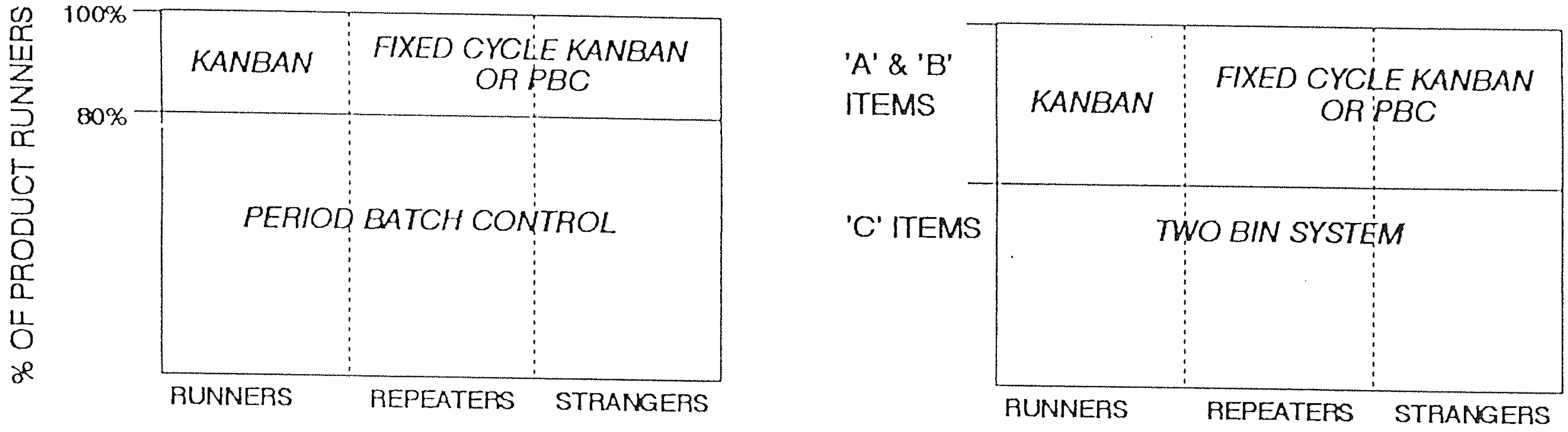
The control systems design phase of the methodology is the least defined in terms of a predetermined sequence of steps to follow. It does however have a number of principles that underpin it. The main principles that are used include:

i) A runners, repeaters and strangers analysis (Parnaby et al 1987). This analysis is used to help select the appropriate shopfloor control system. Runners are defined as products with a regular demand and strangers as products with a very unpredictable demand. Repeaters lie in the middle of this continuum. The runners, repeaters and strangers analysis is essentially concerned with the frequency of demand rather than the volume of demand. ABC type analysis is undertaken on a volume-value basis. Figure 4.11 shows the selection criteria that are used for shopfloor control systems. Figure 4.11 (a) indicates that if an environment has over 80% runners then kanban should be used for runners and either a fixed kanban system (whereby kanbans circulated for a fixed number of cycles rather than indefinitely) or Period Batch Control (PBC) (Parnaby et al, 1987, Zelenovic & Tersic, 1988, Burbidge, 1989) for repeaters and strangers. If less than 80% of the products manufactured are runners then consideration should be given to utilising a PBC system for all parts. Figure 4.11 (b) adds an ABC dimension to the selection of shopfloor control systems. For 'C' items consideration should be given to the adoption of a two bin system.

ii) Bottom-up tailored design. Typically, the approach is to design shopfloor control systems that are tailored exactly to local needs. However, it is recognised that top down systems do have an appropriate role to play.

iii) Decentralised control. This is related to the issue of bottom up design. The approach here is to implement a shopfloor control system that is 'owned' at the shopfloor level yet still maintains appropriate central control.

Figure 4.11 Shopfloor Control System Selection



(a) Control System Selection Based on % Runners and RRS Analysis

(b) Control System Selection Based on 'ABC' and RRS Analysis

iv) Levels of control. Any control system designed should have appropriate levels, with data passed between levels through well defined interfaces. Such data should include production plans and achievement against these plans.

Although many different control systems are often considered (e.g. tooling control and quality control) the focus was found to be shopfloor material flow control systems.

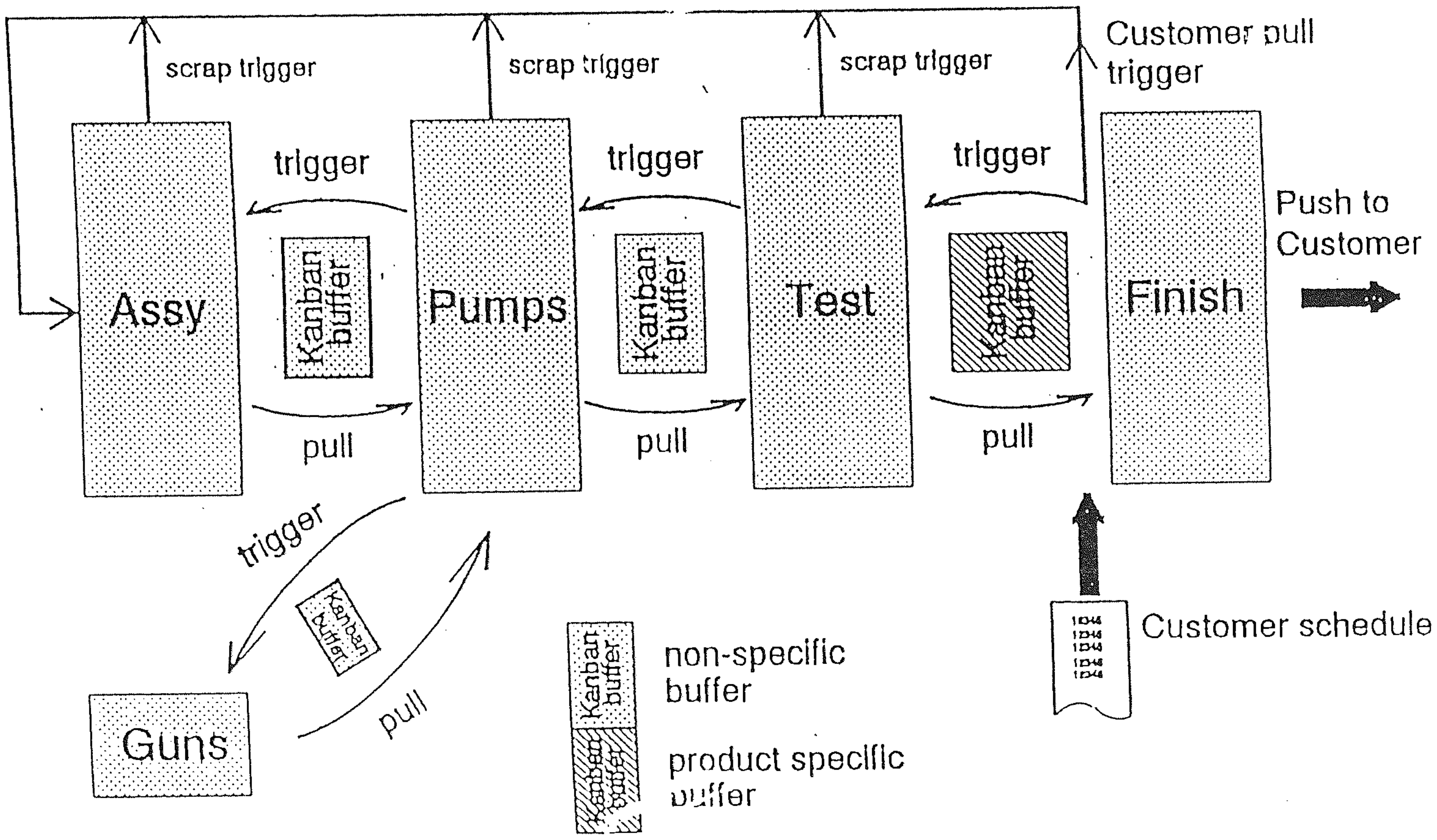
4.8.1 Kanban and MRP at EEV

The task-force undertook a runner, repeaters and strangers analysis and an ABC analysis. As a result of this analysis they designed an integrated control system using kanban, MRP and a 2-bin system. A two bin system was specified for ordering 'inexpensive' parts' (approximately 50%) from suppliers and MRP for placing purchase orders for 'expensive' parts (approximately 50%). Kanban was specified for shop material flow control with buffers between each of the major process steps (see Figure 4.12).

4.8.2 Kanban and OPT at Lucas Diesel Systems

This case is concerned with a facility (Lucas Diesel Systems, Sudbury), manufacturing a range of fuel injection equipment for agricultural, truck, military and marine applications. This equipment consists of injectors, nozzles (supplied with the injectors and as spares), filters and filter elements. Approximate volumes are 4.5 million injectors, 7 million nozzles, 1 million filters and 11 million filter elements per year. The manufacturing facility has been split into three product units : a nozzle product unit, an injector product unit and a filter product unit. Each of these product units have a number of manufacturing cells. These product units and cells were designed by multi-disciplinary task-forces supported by LE & S.

Figure 4.12 : Runners Material Control System at EEV



Interestingly, the project to implement the material control systems took place 2 years after the introduction of the product units and cells. Up until that time, the manufacturing cells had been struggling with a 'launch and expedite' approach. The project involved the design and implementation of a composite material control system, utilising OPT and Kanban. A runner, repeater stranger analysis was used to determine the suitability of a simple 'pull' type shopfloor control system. Once this was established as appropriate, a kanban system was designed utilising the approach documented by Lewis and Love (1993c). Kanban was used to provide 'automatic' shopfloor production control and as a mechanism for continuous improvement (through the removal of containers, thereby reducing work-in-progress).

OPT was used to provide schedules at final assembly and strategic points (such as variety breaks), modelling and 'what-if' analysis utilising the BUILDNET, SPLIT, SERVE and OPT modules of the software suite. The usual input data was provided, including routings, bills of material, consolidated customer demand, inventory, planned leadtimes, capacity and scrap.

Manufacture was divided into two halves, soft stage machining and hard stage machining, separated by a heat-treatment process. In the soft stage, oil and washing operations were combined in loops with their previous machining operation with only one stock location between each loop. Variety built up at each machining operation until parts were uniquely identified at a rollmark (or partmark) operation, where up to 30 rollmark types were specified. In essence, the operation acted as a variety break. The next operation (the last in the soft stage) was a bottle-neck operation requiring the use of an accumulator (to increase batchsizes). An OPT schedule was placed here to minimise the effects of changeovers. Consequently, all other operations in the soft stage were capable of keeping pace with the operation that initiated the 'pull'. This schedule was generated using the modelling capabilities of OPT. An accumulator was also placed between the soft stages and hard stages to build up batches with similar heat-treatment cycles for economic use of furnaces. A delivery-to-stores schedule was placed on the last operation of the hard stage and was the basis for pulling in this stage. All the machining operations in the hard stage were combined into one loop as the process was an automated transfer line working on a first-come first-served principle. The implementation of the proposed OPT - Kanban system resulted in a 50% improvement in the stock turnover ratio of the manufacturing cell concerned.

4.8.3 Period Flow Control at Lucas Engine Fabrications

Lucas Engine Fabrications, is a site employing just over two hundred people, with a total turnover of approximately £7 million. It manufactures make-to-print combustion fabrications for civil, defence and marine customers. The product mix is predominantly low volume, high variety. Period Flow Control (PFC), a form of PBC was selected as the shopfloor control system due to the demand characteristics of the products manufactured. PFC is characterised by the year being split into equal periods, orders being placed on the cells that 'own' products, all due dates being the same (i.e. the end of the period) and completed orders not being moved until the end of a period.

The approach taken was to select a period length. This was done by considering leadtimes, floor-to-floor times, work content and customer demand. After analysis a period length of 1 week was selected. Each routing was then 'partitioned'. This involved splitting manufacturing routes into sections or partitions. Each partition of a routing could be completed in one period. Therefore, the leadtime of a part was given by the number of partitions multiplied by the period length. Partitions were determined using run times, set-up times, delays, processes and subcontract leadtimes. Some consideration was given to overall loading.

4.8.4 Observations on the Control Systems Design Process

The following conclusions on the control systems design phase of the MSE methodology may be made:

a) The investigation showed that the MSE methodology, as applied by LE & S, led to the design and implementation of some very good shopfloor material flow control systems. These systems were innovative in their design and appropriate to the demand characteristics of the products. Particularly, useful is the composite nature of many of the control systems designed and implemented.

b) Interestingly , one of the most useful contributions of the LE & S approach in the area of control systems design (the runners, repeaters strangers analysis) was prominent by its omission from a formal methodology.

c) Nearly all design effort in the field of material control systems design was spent on the design of shopfloor systems. Little consideration was given to the top down systems and policy parameters within these systems. Equally, little attention was paid to the interfaces between top down and bottom up systems.

4.9 Consolidation

This phase of the manufacturing systems design methodology has a number of objectives. Firstly, a financial assessment is undertaken and a project plan with timescales and resources generated. The performance of the proposed design is also compared with the project objectives. Finally, before submission for approval some view of risk is taken.

4.9.1 EEV Performance Improvements

Referring to the EEV example, first mentioned in Section 4.4.1. The task-force considered and quantified the current primary cost drivers. For example, in the Helix module the direct labour cost of £784k was determined as being able to be cut by

£317k to £467k. This was to be achieved by reducing scrap to 40% (from 54%) and non-value-added activities (without defining what it meant in this context) by 30%. The direct material cost of £1717k could also be reduced by £256k by reducing scrap to 40% (from 54%) . It was also stated that the indirect labour cost of £406k could be reduced by £97k. 38% of this would be due to reduced administration, 28% due to fewer more effective meetings and 34% as a consequence of less hands on instruction. Whether these were real cash savings that were to be achieved or just the reallocation of overhead was not investigated in any detail.

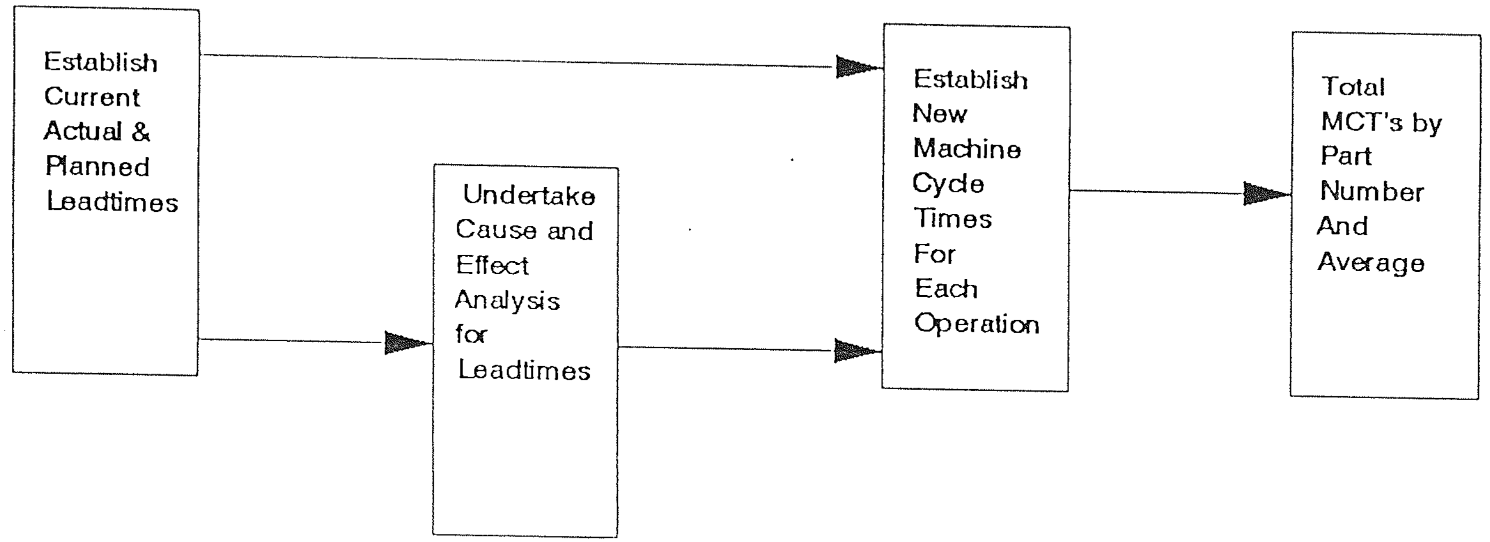
4.9.2 Leadtime reduction at Westland Helicopters Limited

One of the main benefits of a manufacturing systems redesign is a reduction in leadtime. Rarely are the new leadtimes, proposed as a consequence of an MSE project, evaluated by dynamic means. Usually, new leadtimes were found to be calculated through the use of a cause and effect analysis. Such analysis was used to determine the causes of current long leadtimes, and then making some assumptions about the effects of introducing cellular manufacturing and new material control systems potential reductions to leadtimes were identified. This process is illustrated in Figure 4.13 for the Westland Helicopters Gears project. Current actual and planned leadtimes were established. A cause and effect analysis was undertaken. New Machine Cycle Times (MCT's) were established for each operation (an MCT is the time taken for a batch to be processed through a workcentre. It includes input queueing, setting time, machine time and output queuing). When new MCT's had been established a database program was used to calculate new part leadtimes and establish an overall average leadtime.

4.9.3 Observations on the Consolidation Process

The following observations on the consolidation process can be made as a result of the investigation.

Figure 4.13 Leadtime Reduction Calculations at WHL



a) Evaluation usually took place on a payback and / or a discounted cashflow (DCF) basis. However, the improvements in operational metrics used to generate the cash benefits used in the analysis were questionable in many cases, the Westland Helicopter Gears and EEV projects being only two examples.

b) In all projects detailed plans for implementation were drawn up, giving consideration to logistical issues such as plant moves and construction work. Less well planned were the industrial relations issues. These tended to either surface early because of issues raised by the steady state design or very late due to the position of job design in the design methodology.

c) In no project examined in this investigation was the transient between the 'AS-IS' systems and the 'TO-BE' system modelled. In terms of effects on performance, no evaluation of the transient was made.

4.10 Benefits Claimed From the Application of MSE

Lucas Engineering and Systems claim significant operational benefits from the application of the manufacturing systems engineering methodology detailed above. A sample of these benefits is given in Table 4.14. The figures given, have where possible, been verified with the LE & S clients to ensure a 'biased' view has not been given. Dr Parnaby claims in his 1990 annual manufacturing technology report for Lucas Industries that the application of manufacturing systems engineering has consistently demonstrated leadtime and work-in-progress reductions of between 50% and 80%, increases in direct productivity of between 20% and 40% and space reductions of between 10% and 40%. This confirms the benefits that he reported in 1988 (Parnaby, 1988). However, it should be noted that all the benefits reported (including those in Table 4.14) are operationally orientated and do not relate to overall business performance.

Table 4.14 : Benefits and Results of MSE Projects Claimed by LE & S

Company	Business	Benefits
Lucas TVS, Madras, India	Electrical products for automotive industry (100,000 per component per annum)	53% improvement in Stockturn ratio 74% reduction in scrap 57% increase in value added per employee
Lucas Car Braking Systems, Cwmbran, UK (Girling)	Passenger car drum brakes (20,000 per week)	94% reduction in leadtimes 67% reduction in stock 90% reduction in batchsize
Sabwabco, Bromborough, UK (formerly part of Lucas Girling)	Railway braking systems (100 per month)	225% improvement in stockturn ratio 75% reduction in leadtime 82% reduction in batchsize 83% reduction in set-ups
Power Systems Division, Lucas Aerospace Netherton, UK	Constant speed drive gearbox for jet engine aircraft (200 per annum)	192% improvement in stockturn ratio 50% reduction in scrap 89% reduction in batch size
RR Aerospace Fabrications, Hucknall, UK	Engine fabrications	60% inventory reduction 100% reduction in arrears 75% reduction in leadtimes
Lucas Body Systems, Newcastle under Lyme, UK (formerly Lucas Rists)	Car wiring harnesses (400 pw)	180% improvement in stockturn ratio 75% reduction in leadtimes
Acuation Division, Lucas Aerospace, Wolverhampton, UK	Hydro-mechanical systems for aircraft (Transmission tubes)	80% reduction in batchsize 97% reduction in leadtime 100% improvement in schedule adherence
Power Systems Division, Lucas Aerospace, Willsden,UK	Electro-mechanical controls for stingray torpedo (20 - 30 per month)	50% reduction in leadtimes 45% reduction in inventory 47% reduction in scrap
HDA Forgings, BTR, Redditch, UK	Magnesium, steel and titanium forgings for the aerospace industry	33% reduction in scrap 50% reduction in leadtime 66% reduction in rework
Lucas Diesel Systems, Sudbury, UK (formerly Lucas CAV)	Fuel injection equipment (millions per annum)	130% increase in sales per employee 190% improvement in stockturn ratio 70% reduction in leadtime
Lucas Diesel Systems,Gillingham, UK (formerly Lucas CAV)	Diesel pump system components (50,000 per month)	51% improvement in stockturn ratio 99% reduction in leadtimes 93% reduction in batchsizes

4.11 Conclusions of the Investigation

From the above analysis of the investigation into the practical application of MSE a number of observations may be made at the level of individual methodology stages :

Manufacturing Architecture Definition : There is an over-emphasis on vertically integrated, product orientated structures, typically without the evaluation of credible alternatives. There is also poor evaluation of manufacturing architecture definition proposals. Evaluation appears to be based on subjective pseudo numbering systems designed to give the answer that is desired. The 'Make v Buy' analysis seems very superficial and may be regarded as no more than a crude 'C' Item offload.

Steady State Design : The so-called generation of an ideal design in the steady state phase causes a number of problems in implementation. Either spurious industrial relations problems are generated (over issues that would not seriously be considered by most managements) or impossible assumptions about constraints made. An example of problems being created occurred at Lucas Aerospace, Power Systems Division. It was felt that great flexibility of labour was required and the task-force proceeded to develop the idea that labour should be flexible across trades (perhaps not unreasonable), flexible across cell location (i.e. which cell they worked in on site) and flexible across different company sites (Hemel Hempstead, Willesden and Liverpool).

Dynamic Design : Dynamic design appears to be very limited and confined to brainstorming potential problems and generating solutions and contingency plans and exploring changes in demand through static deterministic analysis. There seems little awareness that the term 'dynamic design' implies some sort of time varying behaviour that may be undertaken under deterministic or stochastic conditions.

Control Systems Design : Little consideration of how designed shop-floor material flow control systems should be interfaced to top down systems such as MRP and the changes that should be made to policy variables such as planned leadtimes, reorder quantities and reorder levels

Consolidation : The methodology doesn't consider interactions between cells when statically evaluating performance improvements. The residual (remainder) is ignored when evaluating the manufacturing systems design proposals. The transient, between the current position and the desired position, is not considered as part of the implementation planning process.

It is clear from the above that the application of MSE by Lucas Engineering and Systems does not meet the systemic criteria drawn up in Chapter 2. For example, the whole system is clearly not considered and evaluation is less than complete. Furthermore, when considered as a whole, stages are sequential. Stages are rigidly followed one after another. The strengths of the methodology (other than the fact that it is systematic and considers many of the important issues in the design of a manufacturing system) are:

a) It utilises fairly sophisticated techniques for cell formation.

b) Good use is made of spreadsheets to analyse steady state loading and capacity.

c) Good design of shopfloor material flow control systems is undertaken. It is however, interesting to note that one of the most important contributions of the methodology (the concept of a runners, repeaters and strangers analysis) is not formalised.

The practical applications of MSE presented in this chapter resulted in a dilemma for the investigation. One on the one hand, it is clear that MSE, as discussed above, has a number of significant shortcomings. However, notwithstanding these shortcomings the application of MSE appears to result in significant benefits. A number of possible solutions can be suggested. Firstly, the existing manufacturing systems might have been so poor to start with, that doing anything remotely sensible would have improved manufacturing performance. Bigger improvements might have been achieved by the use of a more complete methodology. Secondly, the benefits discussed could be a 'snap-shot' and refer to short-term achievements only. Thirdly, the benefits might apply only to a part of the business that has been cellularised. These benefits might have been achieved at the expense of performance in the residual. Clearly, there is a need to look at the application of MSE across a longer period of time. The next chapter attempts to do this through a series of longitudinal casestudies.

Chapter 5

An Evaluation of Manufacturing Systems Engineering using Longitudinal Casestudies

5.1 Introduction

Chapter 4 presented an analysis of the manufacturing systems engineering approach to the design of manufacturing systems as practised by Lucas Engineering & Systems. This analysis highlighted a number of deficiencies in the LE & S methodology, in terms of its systemic nature (or lack of it). However, it was also recognised that considerable operational improvements were claimed from the application of the methodology. On reflection, it appeared that a more long term analysis of the benefits of utilising the manufacturing systems engineering methodology might be useful. This is because any problems with the solution generated by the use of methodology may not surface until some time after the initial implementation. A number of reasons for this can be given. Firstly, it is possible that productivity and costs might have improved as a consequence of the 'Hawthorne Effect'. It is not unusual for the performance of people to improve, particularly in the short term, when they are perceived to be part of something 'special', such as the introduction of a demonstrator for cellular manufacture. Secondly, most of the reported benefits have not been with respect to business metrics such as Return On Capital or Profit Margin. On the contrary, they have usually been reported in terms of operational metrics such as leadtime and efficiency, which may be easily manipulated in the short term. Also implicit in this method of evaluation is the assumption that there is a direct relationship between business metrics and operational metrics. Thirdly, benefits have not been tracked over a number of years but have tended to be measured a few months after implementation, the assumption being that 'things will only get better' in the longer term. Fourthly, as already identified in Chapter 3, a so-called 'residual' is often created by the introduction of cellular manufacture. It is possible that the benefits reported in Chapter 4 for individual manufacturing cells have been at the expense of the 'residual' and therefore, possibly, the business as a whole. This is recognised by a number of authors including, for example, Christy and Nandkeolyar (1986).

5.2 Longitudinal Studies

In an effort to address these concerns, and investigate the longer term effects of the manufacturing systems engineering approach to the design of manufacturing systems, two longitudinal studies were undertaken. Vitalari (1985) indicates significant advantages for longitudinal studies over data collected at one point in time, claiming that they :

> '...permit the exploration of phenomena, which develop over time'

The longitudinal case-studies were generated by the adoption of an enthnographic approach to the collection of contemporary data. Retrospective research and analysis were used to cover the period prior to the on-site activity. Bennett et al (1990, 1992) have also indicated a number of advantages of longitudinal studies. Of particular relevance to the casestudies presented below is the ability of enthnographic longitudinal analysis to help ensure that unbiased data is collected. This contrasts with the information that might be collected by short interviews, whereby parts of the organisation might use the exercise to let a biased view emerge. Clearly, there are a number of disadvantages of longitudinal analysis, particularly concerning the general applicability of conclusions drawn. However, given the objectives of the analysis, it was felt that the 'richness' of information generated more than compensated for the potential lack of generality.

5.3 Longitudinal Casestudy 1 - Lucas Aerospace Actuation Division (LAAD)

This case-study presents a longitudinal analysis over a five year period (1987 - 1991) of a business that introduced significant change in all its operations using the manufacturing systems design approach detailed in Chapter 4. The business analysed is Lucas Aerospace, Actuation Division (LAAD), based in Fordhouses, Wolverhampton (UK). The Fordhouses site is the only site that LAAD operates.

LAAD supplies systems and equipment to the major international aircraft constructors and engine manufacturers including Rolls Royce, Pratt and Whitney, Airbus Industrie, McDonnell Douglas, Boeing, Deutsche Airbus, Aerospatiale, and British Aerospace, in both the Military and Civil Markets. It supports over 200 customers in the aftermarket.

In 1987, the manufacturing facility was arranged in the traditional manner of similar processes grouped together. Each section, e.g. turning, milling, grinding undertook its specified operation(s), the batch then moved onto another section. In the words of the Operations Director at the time:

> 'Components travelled large distances in the course of manufacture and were prone to loss or damage. Problems were discovered way after the event ; ownership of any issue was difficult to identify and subsequently resolve. This culminated in long lead times, customer arrears and high internal costs.'

The businesss has been very profitable, averaging over 18% return on sales from 1982 - 1987, mainly due to half of its business being generated by cost plus military work (particularly Tornado) at a very healthy profit. LAAD has featured in a number of articles (Levi, 1990, Butler, 1992) concerning Lucas and has been proposed as a showpiece factory.

5.3.1 LAAD Market and Product Characterisation

The main product segments that LAAD operates in are engine actuation, secondary flying controls and primary flying controls. The company views itself as an actuation systems based business rather than just a supplier of components. Characteristics of the main market segments are given below:

a) Engine Actuation - Predominantly hydraulic piston jack actuators provided for the V2500, PW4000, CFM56, Trent and EJ200 engines. These are characterised by relatively high volumes and very stiff price competition

b) Secondary Flying Controls - Conventionally flap and slat systems form a large core of the business and are provided mainly for the Airbus programme.

c) Primary Flying Controls - Consisting predominantly of spoilers provided for the Airbus programme. The company has an active development programme in this area and is pioneering smart fly-by-light technology in association with McDonnel Douglas.

d) Spares - This business has a turnover of around £20 million. The business is won as a consequence of the company having gained the contract to supply the original equipment (OE) on the aircraft. Many customers are 'captive' in the sense that spares cannot be obtained from any other source. Civil airlines have been trying to reduce their costs by reducing their spares stocks, and relying on shorter leadtimes for the supply of spares. Delivery reliability on spares is crucial to winning future OE contracts.

e) Repair and Overhaul - A number of different order winning criteria apply in this market segment including price, delivery speed (turn-round time) and the fact that some of the business is 'captive' (i.e. customers have to have the repair / overhaul undertaken at LAAD).

Table 5.1 Civil - Military Split of LAAD Business (1987 - 1991)

Year	Civil	Military
1987	30%	70%
1988	35%	65%
1989	65%	35%
1990	75%	25%
1991	77%	23%

Quality is regarded as an order qualifying criteria in all market segments. In 1987, it was forecast that military demand would decrease, and that to maintain sales, LAAD would have to change to US-dollar-based civil business, which was highly competitive. With the demise of Tornado, profitability although still acceptable has declined. Table 5.1 shows how the balance of civil and military work changed between 1987 and 1991. This has required a more aggressive pricing and delivery policy than was necessary under previous cost plus military contracts.

5.3.2 LAAD Manufacturing Characterisation

The Fordhouses facility occupies a 31 acre site that includes some 208,000 square feet of covered factory area and 192,000 square feet of office area. Table 5.2 shows how the factory area is utilised.

Table 5.2 : LAAD Factory Area Usage

FACTORY USE	SQUARE FEET
Assembly	27,000
Machining	124,000
Stores	42,000
Processes	15,000
Total	208,000

The factory has over 300 machine tools including lathes (single spindle and CNC), prismatic machines (milling, jig boring and CNC machining centres), grinders (manual and CNC internal, external and surface grinders) and gear manufacturing machines (shapers, hobbers and grinders). The plant also has extensive heat treatment and plating facilities.The business employed 462 directs and 763 staff and indirects in 1991 (1225 total). This was reduced from 1750 employees in 1988.

5.3.3 The Manufacturing Systems Design Process at LAAD

In mid-1987 a new Director and General Manager was appointed and he in turn appointed a new Operations Director. The new Operations Director was tasked with radically improving manufacturing performance. Therefore, in late 1987, a new manufacturing strategy for the business was developed. The aim of this strategy was to produce clear measurable improvements in the business by the end of 1990. Characterising performance at the time, the Operations Director remarked:

> 'Our current performance is bad on almost any measurable dimension. Arrears are too high, adherence to schedule is low, quality costs are huge and structures are clumsy.'

The strategy was supposed to achieve a manufacturing operation that was, using the framework of Hayes and Wheelwright (1984), 'internally supportive', providing credible manufacturing support to the business strategy.

A strategy of adopting vertically integrated product units wherever possible was the major theme of this strategy. The definition of these product units was achieved through an analysis of forecast sales and resulted in the following three Product Units being defined:

Flap Actuator Product Unit (manufacturing 27 end items)

Thrust Reverser Product Unit (manufacturing 7 end items)
Transmission Product Unit (manufacturing 8 end items)

The remainder or residual machine shop, process area and assembly shop were considered to be the lowest priority as, in the words of the manufacturing strategy document produced:

> '...the returns would also be low.'

The first detail design was undertaken on a cell to manufacture torque tubes. This cell was to become part of the Transmission Product Unit. The cell was launched in early 1988. Some 8 months after the launch of the cell, it was considered a major success. Output was up by 300% and leadtimes were reduced by 29 weeks from 30 weeks to 1 week. Thus, the cellular concept was considered proven. More precisely, the concept of product orientated cells (as opposed to group technology type cells) was considered proven.

As a consequence of the success of the transmission tube cell, a manufacturing systems design programme covering all the product units identified above was initiated. Two cells were designed for the Flap Actuator Product Unit (Rotary Actuators and Offset Gearboxes), two cells for the Thrust Reverser Product Unit (Machining and Assembly) and one additional cell for the Transmission Product Unit (End Fittings). This resulted in the manufacturing architecture shown in Figure 5.3.

All of the cells were designed using the methodology detailed in Chapter 4. The design process commenced in 1988 and continued into 1989. Towards the end of 1989, a rolling implementation programme was started on the cells and implementation was complete by early 1990. All the design work was undertaken by multi-disciplinary task-forces with the close participation of the shopfloor trades union (AEU).

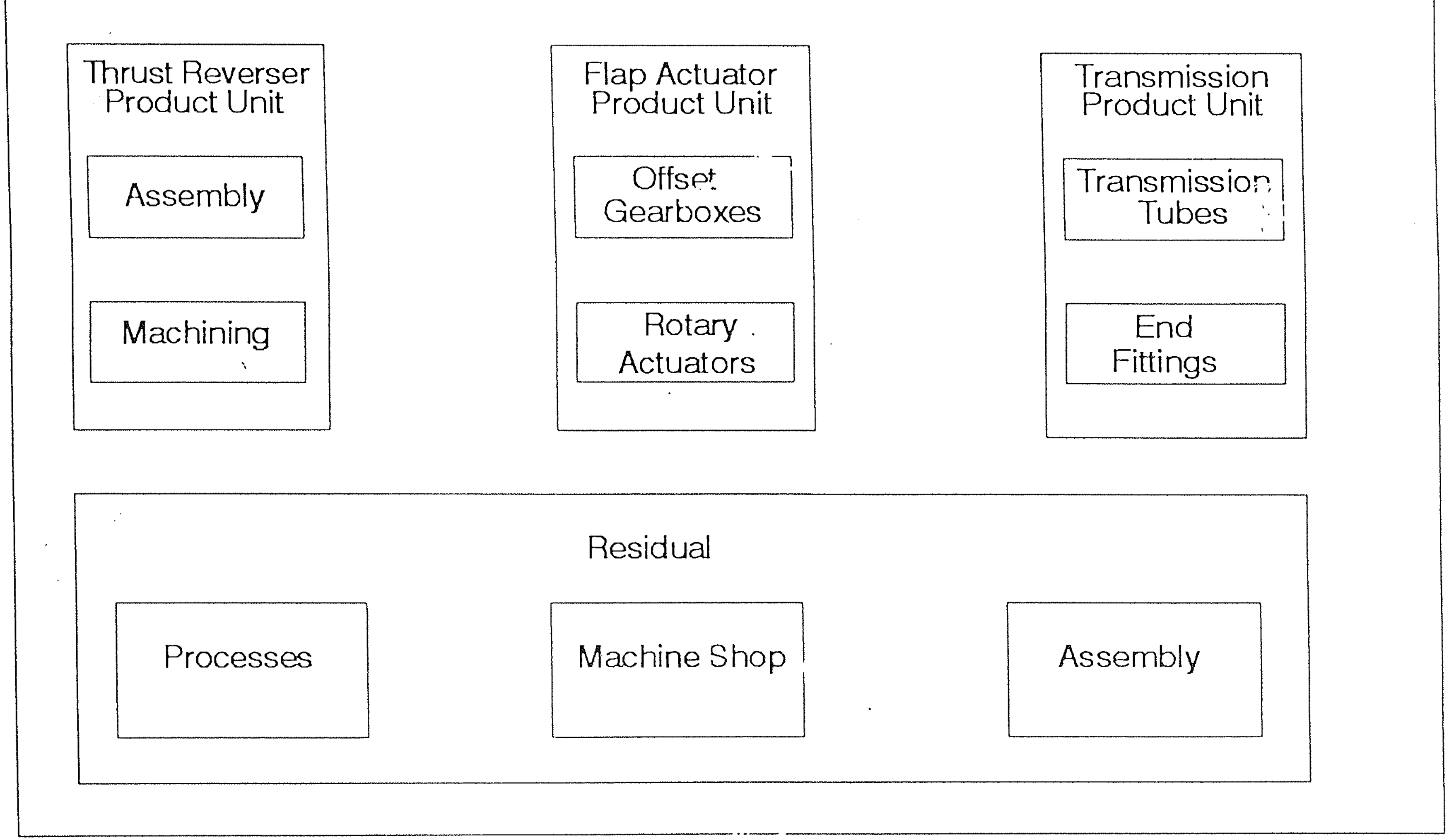


Figure 5.3 : Manufacturing Architecture at LAAD

5.3.4 High Inventory and Arrears at LAAD

It was expected that during 1990 the manufacturing performance (and thus business performance) at LAAD would dramatically improve. This expectation was based on the performance of the transmission tube cell implemented in 1988 and the notion that this improvement would be replicated across all of the recently implemented product cells. Output and schedule adherence were expected to go up, and inventory and arrears to reduce. However, this did not transpire. In fact inventory and arrears increased, with flap actuators and engine actuation equipment forming a significant proportion of this. For example, although 60% of all products were found as being arrears, 14 flap actuator and engine actuation products represented 50% of the arrears by value.

Not only did stock and arrears not fall but labour performance was also poor. Efficiency defined as standard hours output over clocked hours fell from around 70% before piece-work was removed to 45% after the product units and cells were implemented. The situation became so serious (from a Lucas Aerospace corporate view) that the Operations Director was replaced by a corporate Manufacturing Executive and a number of other personnel were drafted in to try and discover the causes of the poor performance and propose and implement solutions.

Analysis indicated a number of reasons for the poor performance. Firstly, material planning and control still focussed on the traditional factory wide approach. The process used produced unrealistic plans that led to increased expediting and the holding of over 65 expediting meetings per month. Whereas this approach had worked with a reasonable degree of success prior to the introduction of Product Units, it was a disaster after their introduction. For example, whereas first operation turning had previously had one queue and a large number of machines to service this queue, this facility was split down amongst the Product Units, resulting in a number of queues each serviced by only 1 or 2 machines (see Figure 5.4). This is the typical case when cellular manufacture is introduced. However, it requires the use of tailored material planning and control systems to ensure that the transition from a single-queue multi-server system to a single-queue single-server system does not result in a dramatic increase in queue length. A factory introducing cellular manufacture, loses what has been termed, by Suresh and Meredith (1994) 'Pooling Synergy'. Appropriate manufacturing control systems are one way in which the loss of this synergy may be alleviated. Change-over reduction is another potential method. In the case of LAAD the average queue length grew to 2.5 weeks. More particularly, the first operation turning queue grew to over four weeks. It is useful to note that leadtimes were planned with an average queue length of 1 week.

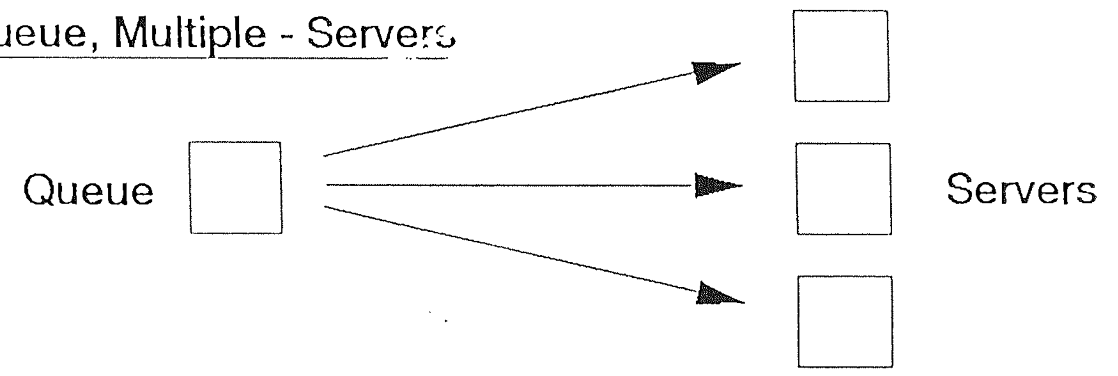
Secondly, there was a total lack of adequate capacity planning. Parameters in the MRP were not changed in good time to reflect the changes on the shopfloor. This resulted in an unrealistic Master Production Schedule (MPS). Thirdly, due to the continual non-achievement of delivery schedules, there was constant replanning, resulting in confusion over priorities on the shopfloor. Fourthly, the removal of piecework resulted in a clear reduction in labour performance. No consideration was given to an alternative system of appropriate incentives in the job design phase of the manufacturing systems design process.

5.3.5 Analysis of LAAD

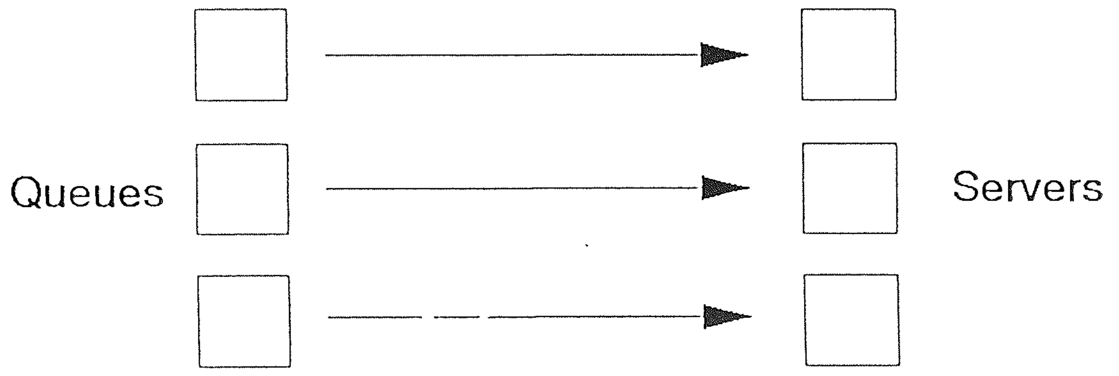
The business performance of LAAD in the period between 1987 and 1992 is illustrated in Table 5.5. Although performance improved between 1987 and 1988, it declined between 1988 and 1989. This can probably be explained, to some extent, by the disruption caused by the implementation of the new manufacturing systems and the massive switch that occurred in the civil - military balance of the business (see Table 5.1). It does appear from Tables 5.1 and 5.5 that LAAD successfully

Figure 5.4 : Schematic Diagram of First Operation Turning Queue

a) Single - Queue, Multiple - Servers



b) Multiple - Queues, Multiple - Servers



negotiated a significant transition in terms of the change in the civil - military balance in the business. However, whereas business metrics might have been expected to improve in 1990 as a consequence of the Product Units, they actually deteriorated. Even by 1991, some two years after implementation of the 'world-class' manufacturing system, performance in terms of arrears and inventory had only just returned to the 1988 levels.

Table 5.5 : LAAD Performance 1987 - 1992 (Calendar Years)

Year	Sales	Operating Profit	Inventory	Arrears	ROCE
1987	£60 million	£10 million	£23 million	£13million	30%
1988	£65 million	£11 million	£23 million	£10 million	33%
1989	£74 million	£8 million	£25 million	£8 million	24%
1990	£74 million	£3 million	£27 million	£12 million	8%
1991	£75 million	£5 million	£24 million	£9 million	15%

What, in the process used in the manufacturing systems design could have led to this situation ?

a) Product Unit definition was undertaken with very little quantative analysis, relying merely on the view that product orientated manufacture was what had to be implemented to achieve a significant improvement in manufacture. No objective evidence was sought or generated to demonstrate that the architecture proposed was appropriate from a performance-related perspective. There was perhaps an over-emphasis on product orientation.

b) LAAD were shipping around two hundred end items a month and only some 40 - 50 end items were manufactured in the Product Units, on which so much time and money had been spent. Significant resources were moved into the Product Units from the rest of the factory and although the performance of the Product Units did improve (for example, in the Thrust Reverser Product Unit leadtimes reduced from

60 weeks to 14 weeks and schedule adherence improved from 40% to 70%), it was clearly at the expense of the business as whole. The product units were ‘optimised’ at the expense of the residual machine shop and assembly shop sub-systems.

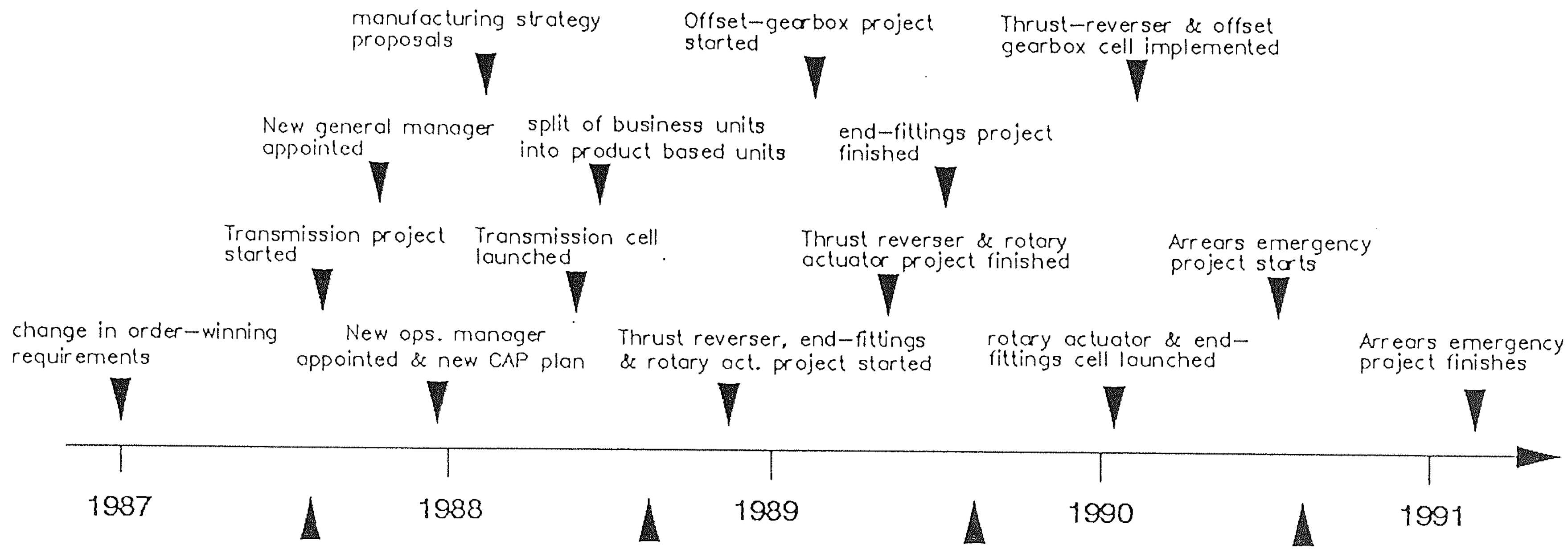
c) As dynamic design was left to near the end of the manufacturing systems design methodology, it was not undertaken with any degree of depth. Essentially, a standard cause and effect analysis was generated for all the Product Units and used as a basis for action to reduce variation and its impact.

d) The late consideration of control systems in the manufacturing systems engineering methodology, seems to have led, in this particular case, to it being rushed (or not done) in an effort to ensure early implementation. This is particularly true of the top-down MRP systems and its policy parameters. It is also true, although to a lesser extent, for shopfloor control systems.

e) It is evident that the transient between the phasing-out of the existing manufacturing system and the full-scale implementation of the new manufacturing system was not handled well. Although 'best practice' project management was employed and plant moves, construction work and personnel selection, for example, were achieved on schedule, the complex interactions between all the implementations and the existing machine shop were not understood. Indeed, no attempt was made to understand them.

Figure 5.6 summarises the key events in the period studied on a time-line. It appears from the above analysis that there is a strong temptation to undertake a simplistic view on the use of vertically orientated product units, define cells, undertake a steady state design and implement with the minimum of dynamic evaluation and control systems design.

Figure 5.6 A Longitudinal Study of the MSD Process at LAAD



Sales	60m	65m	74m	74m
Net Margin	10m	11m	8m	3m
Inventory	23m	23m	25m	27m
Arrears	13	10m	8m	12m
ROCE	30%	33%	24%	8%

5.4 Longitudinal Case Study 2 - Lucas Aerospace Power Equipment Corporation (LAPEC)

This second longitudinal case-study is concerned with examining the manufacturing systems design process and consequences at a major subsidiary company of Lucas Aerospace. The company investigated was Lucas Aerospace Power Equipment Corporation (LAPEC), based in Aurora, Ohio (USA). Aurora is approximately 40 miles from central Cleveland and is the only site that LAPEC operates. LAPEC was purchased by Lucas Industries in 1988 from a holding company who had, in turn, acquired the company from Lear Seigler Industries, where it operated as their Power Equipment Division.

5.4.1 LAPEC Market and Product Characterisation

LAPEC designs and manufactures DC starters, starter/generators, AC generators, generator control units and circuit protection devices for jet commuter aircraft, military and commercial turboprop fixed wing aircraft and helicopters. It is also involved in the design and manufacture of missile fin actuators and both linear and rotary motion electro-mechanical devices. The President characterises the pressures on the business as follows:

> ' The environment that PEC operates in is becoming increasingly competitive. Defence spending is down in real terms, the US government is actively promoting second sourcing, and commercial customers want lower prices, shorter leadtimes and higher quality'.

The company deals with five major market segments. These include :

a) Commercial and General Aircraft : The customers in this segment are original equipment manufacturers such as the Boeing Aircraft Corporation, who prefer to deal with companies that have a proven track record of performance. This segment has low cost and high quality as order qualifying criteria and product performance, short reliable lead-times and good technical support as order winning criteria. Products in this segment include mainly AC and DC generators.

b) Military Aircraft : The customers in this segment are original equipment manufacturers such as Lockheed. This segment has low cost and high quality as order qualifying criteria and product performance and reliable leadtimes as order winning criteria. Products in this segment include mainly AC and DC generators.

c) Missile Equipment : This equipment is supplied to prime contractors such as Martin Marietta. There is a requirement for a high product volume over a fixed period of time and the prime contractors are required to develop second sources. This segment has adequate product performance, good customer support and reliable delivery as order qualifying criteria and low cost of acquisition as order winning criteria. Products in this segment include actuators for the Tomahawk cruise missile and the Patriot anti-missile missile.

d) Repair and Overhaul : The customers in this segment are military and commercial aircraft operators. These operators are trying to minimise total cost and downtime. Therefore, this segment has low cost and high quality as order qualifying criteria and parts availability and quick turn-around times as order winning criteria. All products are covered in this business.

e) Spares : These are supplied to the end user of the product supplied. Order qualifying criteria include understanding the procurement process (particularly with military customers) and high quality. Low cost and quick delivery are order winning criteria. All products are covered in this business.

Sales are split approximately 50% to military customers and 50% to civil customers.

5.4.2 LAPEC Manufacturing Characterisation

The Aurora site has an area of some 29 acres, including 150,000 square feet of covered factory area and 150,000 square feet of office area. Table 5.7 shows how the factory area is utilised.

Table 5.7 : LAPEC Factory Area Usage

FACTORY USE	SQUARE FEET
Assembly	88,000
Machining	50,000
Stores	6,000
Processes	6,000
Total	150,000

The factory has over 400 machine tools including lathes (single spindle and CNC), prismatic machines (milling, jig boring and CNC machining centres), grinders (manual and CNC internal, external and surface grinders) and gear manufacturing machines (shapers and hobbers). The plant also has extensive heat treatment and plating facilities. In July 1992 the business employed some 290 directs and 450 indirects and staff (740 in total).

5.4.3 The Manufacturing Systems Design Process at LAPEC

The manufacturing systems design activities at LAPEC started in January 1989, shortly after the company was acquired by Lucas Industries. An initial task-force, the Manufacturing Operations Task-force, was established with the task of collecting data and creating a manufacturing architecture for the facility (Product Units and Cells). In other words, the task-force was asked to complete the first two steps of the manufacturing systems design methodology discussed in Chapter 4. The objectives placed on this task-force were to achieve 'ownership' of 75% - 80% and to create a manufacturing structure able to achieve a stockturn ratio of 5.

Flowcharting of material flow revealed the usual statistics such as products travelling 9 miles within the factory and having a ratio of approximately 4 non-value-added activities for every 1 value-added activity. The task-force also collected data on product volumes and the manufacturing facilities. Volume data was based on a short term (15 month horizon) unit based master production schedule and a 10 year sales based forecast (business plan) in dollar value . This was converted to a unit based forecast using average selling prices and mix. Data on order qualifying criteria and order winning criteria were collected and analysed resulting in the detail outlined in section 5.3.1.

After the initial data collection and analysis phase the task-force undertook a product unit definition exercise. This was very heavily influenced by the approach detailed in Chapter 4, whereby a very heavy emphasis is given to the definition of vertically aligned product units. The product unit definitions considered were a military / commercial split, a split based on market end use (e.g. commuter aircraft, missile, ground applications, etc.), geography (North America, Europe, etc.) and product line (AC, DC, Actuation & Repair and Overhaul). It is useful to note that a manufacturing based split on group technology principles or routeing data was not considered at the Product Unit definition stage.

A routeing database was used. It was a subset of the database held on the site Mainframe. This database was reduced from a 4,400 part number, 44,000 operation manufacturing database to a 756 part number, 7,429 operation database utilising 364 workcentres for product and cell definition purposes. This data was generated from a reference set of products established on both the Pareto concept (by value, contribution, volume and manufacturing hours) and the need to ensure that strategically important products were considered and used for the analysis. The workcentres used in the analysis were further reduced to 149 by eliminating 'portable' operations such as inspection and deburring. Processes thought likely to remain as central services were also excluded from the analysis. The whole analysis was directed towards a product line split by forcing components into cells aligned by AC products, DC products and Actuation Products. The structure recommended is shown in Figure 5.8.

Evaluation took place in terms of ownership (%), capital (high, medium, low), time to implement (short, medium, long) and effort required to implement (high, medium, low). For example, the structure illustrated in Figure 5.8 was calculated as providing average product unit ownership of 95% (product hours manufactured in product unit / total product hours manufactured). It was estimated that a spend of $2.39 million was required to implement the design and considerable process planning effort was also required.

In parallel with the product unit and cell definition activities a so-called 'Make v Buy' exercise was carried out. This was based on the reference product set. Essentially the exercise consisted of a pareto analysis, based on cumulative production hours and the number of issued works orders. Figure 5.9 illustrates this analysis. In effect, this exercise was essentially a C-item 'off-load', with the task-force recommending the purchase of C-items (defined as having a total process time of less than 20 minutes). The team also recommended the purchase of 'special' processes, such as plating due to the high costs of regulatory compliance. The task-force also made a further recommendation that:

> '...parts be reviewed to see how well they fitted into the cellular manufacturing redesign.'

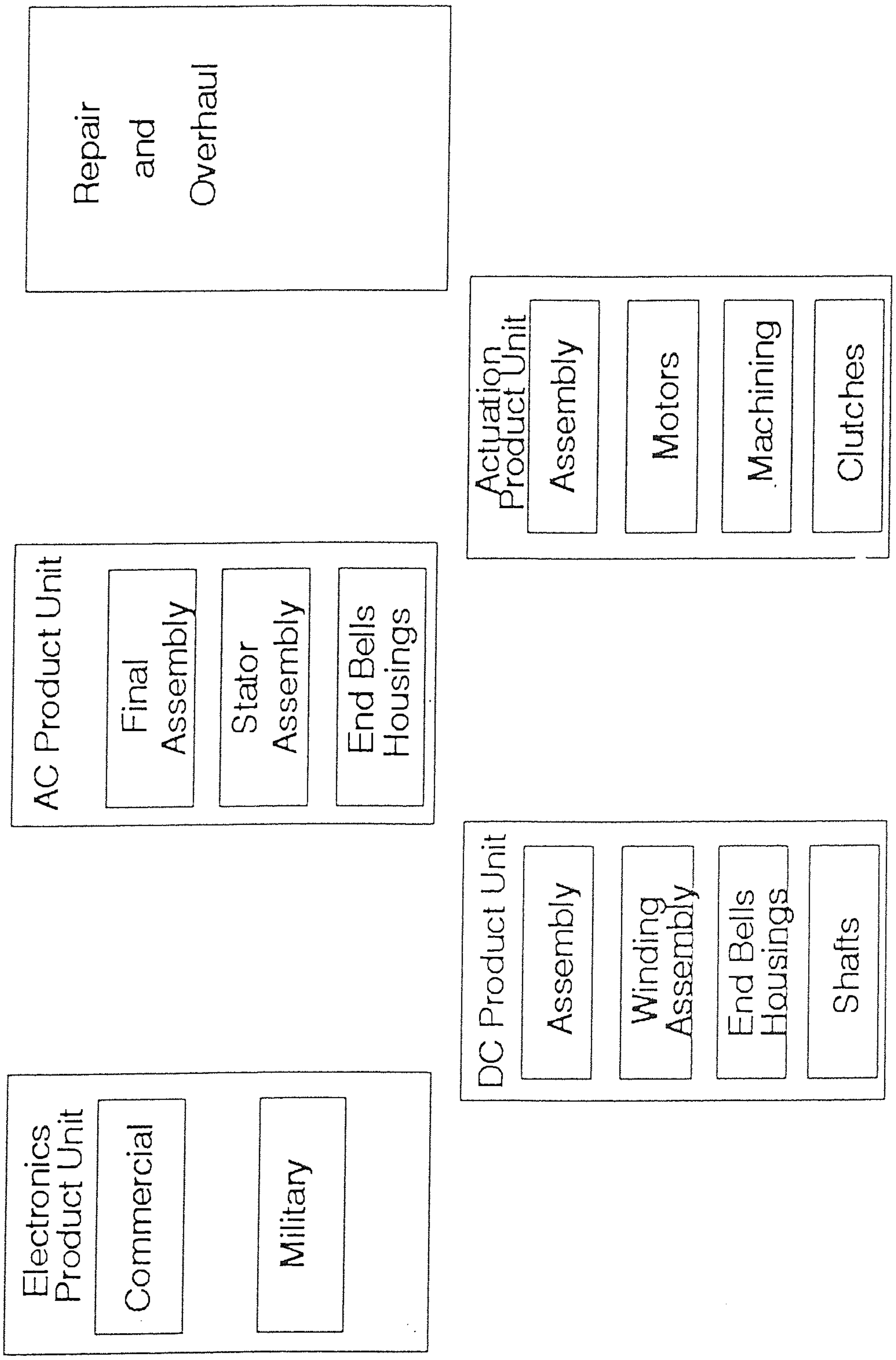
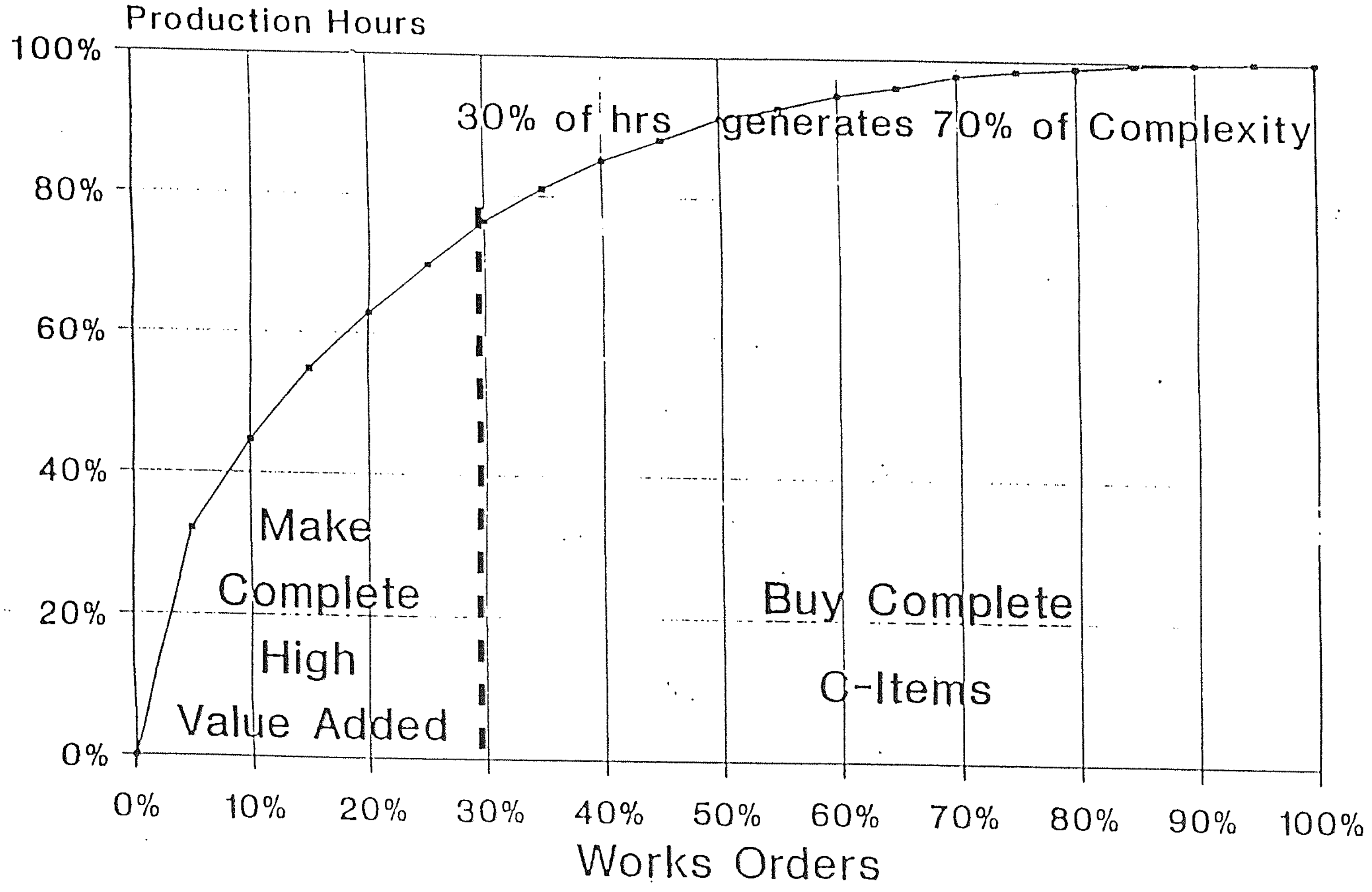


Figure 5.8 : Manufacturing Architecture at LAPEC

Figure 5.9 : Make v Buy Pareto



This, as has already been demonstrated in Chapter 4 is not an uncommon position taken in the Lucas application of manufacturing systems analysis. Evaluation of this 'Make v Buy' activity consisted of the assertion that the lower variety of parts manufactured in-house would lead to lower overall costs and shorter leadtimes.

In parallel with the Manufacturing Operations Task-force, an Electronics Task-force was established to design and implement a Product Unit manufacturing Generator Control Units (GCU) and Motor Control Units (MCU). This product unit was defined upfront in the manufacturing systems design process as a consequence of the need to locate the facility in a 'clean room'. The intention was that the Electronics Product Unit would act as a demonstrator to show what could be achieved through the application of manufacturing systems engineering.

This task-force went through the usual steps (cell definition, steady state design, etc.) in the design methodology and designed two cells. One cell was tasked with the manufacture of products for use by military customers (GCU & MCU) and another with the manufacture of products for commercial customers (GCU). This split was based on the different quality assurance systems required by customers. The task-force also designed cell control systems for control of work-in-progress utilising a container system based on kanban principles. The team undertook a fairly crude savings analysis that resulted in an estimated $960,000 saving per annum. This product unit was implemented in May 1989 and an 'immediate' 20% stock reduction and 12% productivity improvement was claimed.

It was determined at this time that the factory should move from its existing facility to a new purpose built facility (the original factory was built from wood to save vital war materials during the second world war). Therefore, it was decided that the proposed manufacturing systems designs would not be implemented at the existing site but would be implemented at the new site (with the exception of electronics). To facilitate the plant move a task-force was formed to project manage the logistics of this complex task. This included detailed plant moves, appropriate stock building and project liaison with the construction company. Much of the plant was readily movable and the move was substantially complete by 1990.

Also, in May 1989 task-forces were put in place to undertake the steady state design, dynamic design, control systems design, job design and consolidation activities of the manufacturing systems design methodology outlined in Chapter 4. Separate task-forces were set up for the AC Product Unit, DC Product Unit and Actuation Product Unit. These task-forces had the objective of achieving 95% 'ownership', 4 - 5 month leadtimes, zero arrears and a stockturn ratio of 5. This was against current leadtimes of 13 months, arrears of $15.6 million and a stockturn ratio of 2. During this period (May 1989 - April 1990), the implementation of the 'Make v Buy' exercise was expedited. Thus, by spring 1990 LAPEC was operating from a new facility, designed using the Lucas manufacturing systems methodology and utilising so-called world class manufacturing techniques.

5.4.4 Crisis at LAPEC

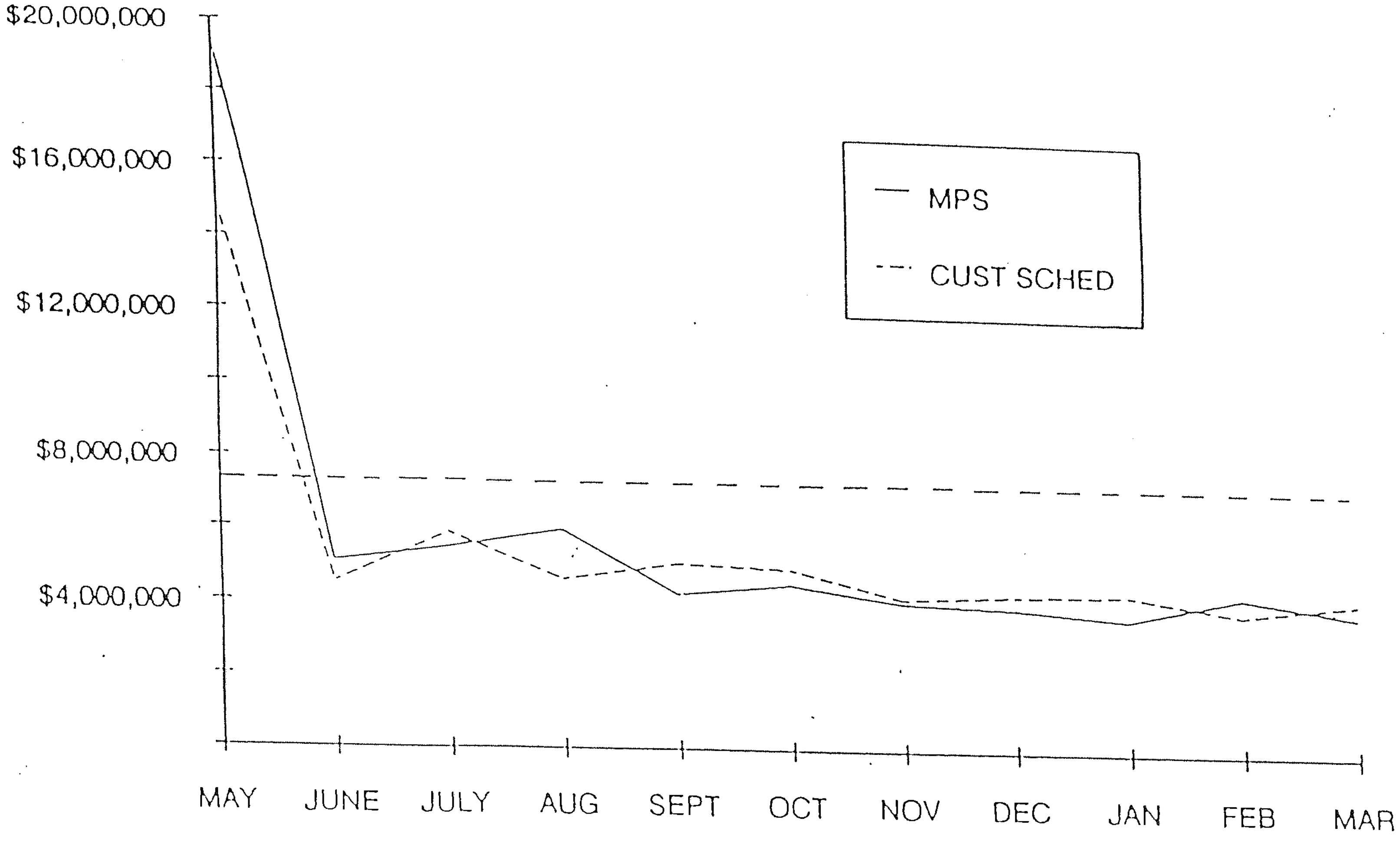
During the manufacturing systems design stage and implementation of the new Electronics Product Unit, the business achieved reasonable results (financial year ending July 31 1989). Sales grew by $9 million from $62 million to $71 million and operating profit grew from $3.6 million to $5.1 million. Return on Capital Employed (ROCE) grew from 9.7% to 12.4%. During the plant move and implementation of the redesigned manufacturing systems at the new facility, inventory rose by $4 million to $35 million (financial year ending July 31 1990). This was understandable, a consequence of the need to stock build to enable the continued delivery of customer orders during the time that the factory was being moved. Operating profit also fell marginally as more overtime was worked and expenses increased to cater for the move. Interestingly, arrears fell to a record low. This was due to careful customer management by the sales and marketing team. The firm order book stood at around $77 million, somewhat above 1 years sales. Thus, the business was in a reasonable financial position to take advantage of the newly implemented manufacturing systems.

However, events did not go to plan. During the second half of calendar 1990, inventory built up and arrears started to increase. This was all rather surprising to the plant management, as they expected their new 'world class' manufacturing systems to deliver shorter leadtimes (and hence lower inventory) and better schedule adherence. By the end of calendar 1990, the situation had reached crisis point and the plant management introduced drastic action. Project STOP was initiated. The prime objective of this project was to prevent the arrival on the goods inwards dock of any material that would not be shipped within the month. The intention was to reduce inventory and conserve cash. Needless to say, this initiative was less than a full success.

Therefore, in early February 1991 a small team was put in place to investigate the causes and propose solutions to the problems of high inventory, increasing arrears and low profitability. This team undertook a 'rough cut' logistics chain analysis, identifying the location and size of inventories along the material flow chain. In addition, a review of existing systems was also undertaken. From this analysis, the team identified three main reasons for the poor performance.

Firstly, the Master Production Schedule (MPS) was unrealistic and was driving in material, raising inventory and making priorities difficult to resolve. The MPS contained arrears that were front-end loaded such that the monthly load was three times higher than demonstrated capacity. The MPS itself was also loaded some 30 % higher than the customer schedule required (see Figure 5.10). As a consequence

Figure 5.10 : MPS Profile



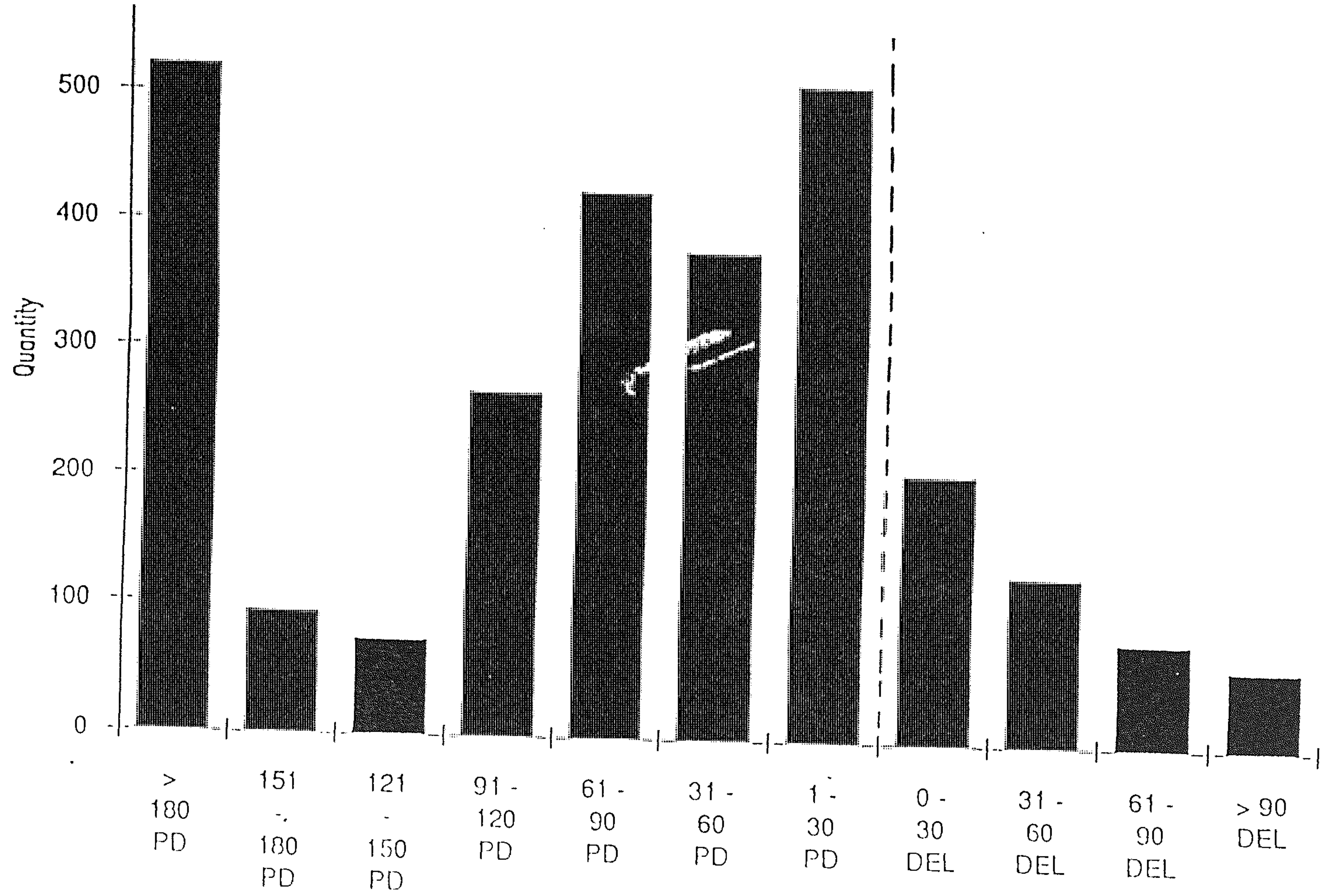
material was being purchased earlier than necessary with a consequential rise in stock. In addition, it was not possible to determine the 'real' priority of works orders on the factory floor from the MRP system as more than 80% were 'past due' (late). This is illustrated in Figure 5.11.

The poor state of the MPS as described above was a result of it not being maintained. There was no formal process for reviewing the MPS (e.g. structured meetings) and only gross sales were reported with performance against the MPS. The MPS was not reviewed end-item by end-item (i.e. no schedule adherence measure). Any rescheduling that was undertaken was only effective at the end-item level and not followed through to piece-part works orders. Thus, even if customer units were rescheduled out of arrears on the MPS, works orders remained on the factory floor with no formal change in priority.

Secondly, the linkage and integration between assembly cells and machining cells was inadequate. The product units had originally been conceived to vertically integrate assembly and machining cells under product unit managers (e.g. DC in one vertically integrated unit and AC in another). However, this was not working very well. Machining cell works orders were planned and released in assembly cells with a weekly materials shortage meeting constituting the only formal link between the assembly and machining areas. There was no planning and no organisational structure or systems in place to facilitate it.

The following provides an illustration of the effect of this lack of integration. It was found that generic items (e.g. shafts, housings) that were critical shortages were also items with high stocks, 50% of the generic shortages accounted for 30% of the finished parts stock (e.g. shafts were 17% of the shortages but 12% of the finished parts stock). This also indicates that problems were less about a lack of capacity and

Figure 5.11 : Works Order Due Date Profile



more concerned with its poor usage (i.e. through large batchsizes and bad priority planning).

Thirdly, the cells did not have any 'bottom up' local material flow control systems in place such as Kanban or Period Flow Control (PFC). In addition, the unrealistic schedule made the prioritisation of work through the machining cells difficult, leading to the existence of multiple plans. For example, assembly cells produced a 'Unit Stock Shortage Sheet' highlighting actual shortages to the MPS for the past dues and the following three months MPS output (i.e. effectively the next five months work since past dues equalled two months output). This meant that close to 100% of all released works orders appeared on this shortage sheet, with 80% of them being past due.

As a consequence of all works orders appearing on the 'Unit Stock Shortage Sheet', the machining cells produced a 'Machining Hot Sheet' based on the forecast output for the month. These orders were then placed in red jackets. However, because forecasts were unrealistic, 75% of all released works orders appeared on this Hot Sheet. In desperation, a third shortage sheet termed the 'Machining Super Criticals' was produced. This was based on the outcome of the weekly shortage meeting discussed above. Even so, 35% of all released works orders appeared on this shortage sheet for immediate expediting. Every works order appeared on at least one shortage sheet leading to confusion and difficulty in determining real priorities. As a consequence, parts queued at certain processes for one or two months and moved only when they became 'super critical'. Actual leadtimes were thus extended by up to 300% compared to planned leadtimes.

In summary, the team found a material flow planning and control system that was not designed to meet the task in hand. The poor material planning and control systems were responsible for the widespread confusion on the factory floor and performance that was unacceptable. It is worth noting that the root cause of the poor performance was not a capacity or bottle-neck issue, but rather a priority issue caused by an out of control MPS and inadequate planning and control systems. It is also clear that little effort was spent planning the transition from one mode of operation (traditional functional manufacturing) to another (cellular manufacturing).

5.4.5 Analysis of LAPEC

Examining some of the key business statistics for LAPEC (see Table 5.12) a number of interesting observations can be made. Performance deteriorated after the implementation of the manufacturing system designed using the methodology detailed in Chapter 4. This was after a period of consolidation after the factory move. Performance in 1992, some two years after the implementation of the new manufacturing system design, was only on an equal footing with performance in 1989. In essence, the manufacturing system design activities undertaken did not generate any business benefit. On the contrary, one could make the case that the new manufacturing systems had a negative impact. The early success of the Electronics Product Unit was not sustained and it may be that this early success was a consequence of the 'Hawthorne Effect'.

Examining the manufacturing systems design process a number of reasons for this may be hypothesised, including :

a) The single minded pursuit of vertically integrated product units early in the design phase may well have led to a less than 'optimum' manufacturing system. The architecture that was implemented was never evaluated on any quantitative basis. Costs were evaluated, but operational improvements were couched in terms of ownership and the elimination of the causes of poor performance (based on a cause and effect analysis). Targets for improving operational practises to ensure 'bottom-line' business benefit were never set.

Table 5.12 : LAPEC Performance 1987 - 1992 (Year Ending 31 July)

Year	Sales	Operating Profit	Inventory	Arrears	ROCE
1987	$43 million*	($1 million)	$22 million	$24 million	(3%)
1988	$62 million	$3.6 million	$27 million	$21 million	9.7%
1989	$71 million	$5.1 million	$31 million	$9 million	12.4%
1990	$73 million	$3.2 million	$35 million	$7 million	8%
1991	$73 million	$200k	$ 40 million	$12 million	0.4%
1992	$78 million	$5.2 million	$32 million	$9 million	12%

(* In 1987, under the stewardship of Lear Seigler Industries the facility was closed for a number of months by the US Department of Defence quality inspectorate for poor adherence to procedures and the shipping of defective equipment. During this shut-down new quality systems were introduced and staff were retrained in these quality systems. This accounts for the low sales and high arrears in 1987 and 1988.)

b) The 'Make v Buy' policy implemented also had two unforeseen consequences that were not examined in detail. Firstly, the C-items that were 'off loaded' to reduce 'complexity' were often parts that were made at short notice in the facility, allowing products to be shipped to customers. External suppliers could not match this level of flexibility and as a consequence arrears and inventory increased. A dynamic evaluation, prior to the implementation of the policy, might well have foreseen this problem. Secondly, a vastly increased number of orders started to arrive on the goods inwards dock, increasing queuing times in goods inwards, delaying the delivery of parts to stores and thus increasing delays in assembly (as well as the launch of machined parts as a consequence of raw material having to queue longer in goods inwards).

c) The early partitioning of the design problem in May 1989 might also have contributed to the problem. Partitioning the problem in itself cannot be overly criticised, it is standard practice in most systems design approaches. However, there is no evidence to suggest that the product unit designs were ever integrated except at the level of physical layout (i.e. ensuring that all product units could be accommodated in the facility). Thus, although individual product unit and cell designs might have been 'optimised' in some way the whole system was never evaluated.

d) It is also clear that there was an over-emphasis on physical layout in the design process. Top down material planning and control systems were not considered in any detail. Leadtimes and other policy parameters such as batchsizes were not adequately addressed. Material flow control systems were in effect nonexistent. It is also clear that the management of the MPS was inadequate.

e) Efficiency suffered in the introduction of cellular manufacturing. As can be seen from Table 5.13, efficiency fell from 63% immediately before the introduction of cellular manufacture to 55% after the cells had been in place for more than a year. On investigation, as with LAAD the reason appears to have been the removal of the piecework scheme without its replacement by some other form of appropriate performance-related payment system. This was not considered in the Job Design stage of the design process.

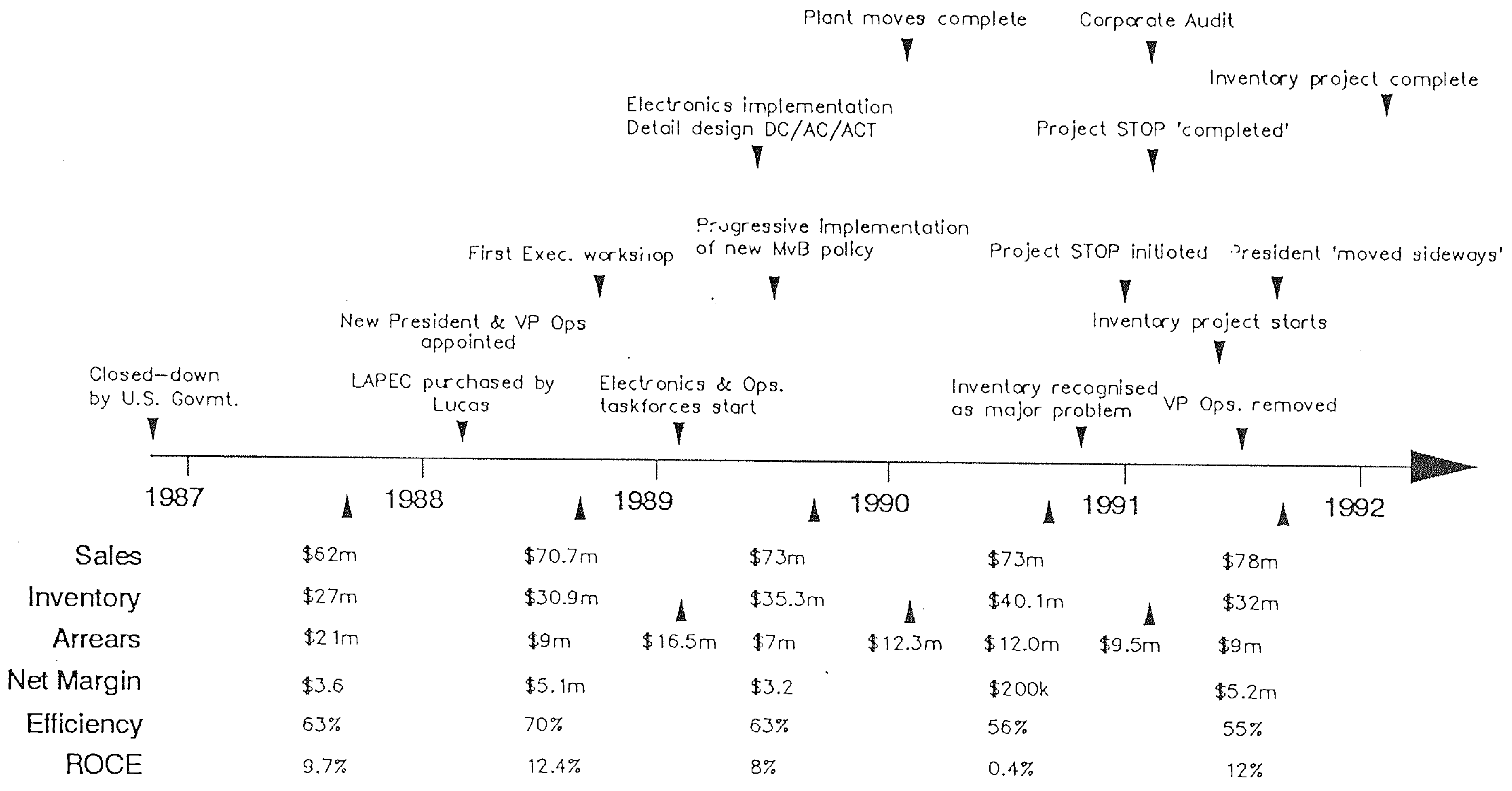
Table 5.13 : LAPEC Average Manufacturing Efficiency 1987 - 1992

Year	Efficiency*
1987	63%
1988	70%
1989	63%
1990	56%
1991	55%
1992	58%

(*Defined as 'good' standard hours produced / total direct clocked hours and averaged for the financial year)

Figure 5.14 summarises the key events in the period studied on a time-line.

Figure 5.14 LAPEC: A Review of Manufacturing Systems Design (A Longitudinal Study)



5.5 Conclusions on the Longitudinal Casestudies

This chapter has made the case that there are a number of systemic problems with the manufacturing systems engineering approach to the design of manufacturing systems. These problems with the methodology have led to worse than expected business performance.

5.5.1 Alternative Explanations for Poor Business Performance

It is possible that the poor business performance detailed above was not a consequence of inherent deficiencies. At least three alternative explanations for the poor performance of LAAD's and LAPEC's manufacturing systems may be postulated. Firstly, the design process could have been undertaken badly. Secondly, the implementation of the proposed design might have been poorly managed with logistical and human resource problems. Thirdly, the external environment (for example, a downturn in orders) might have had an adverse effect on the performance of the manufacturing system. Each of these are now examined in turn.

a) Poor Application of the Design Methodology - From an analysis of the design approaches utilised in the case-studies, the conclusion that the methodology detailed in Chapter 4 was closely followed may be drawn, with one exception, control systems design. The design of material control systems, appeared to get subsumed into the implementation process and as a consequence not as much time was spent on it as should have been. Shop layout changed but control system design lagged someway behind. This is particularly true for changes in MRP policy parameters. Buchanan and Preston (1991, 1992) commenting on the implementation of manufacturing systems engineering at the 'Mouldswitch' site of 'Trentco' indicate the main reason for a drop in morale and performance in manufacturing cell personnel was:

> '... the continuing intervention of foreman in work allocation and scheduling.'

The manufacturing cells were planned to run on a 'pull' type basis with operators working on batches on the basis of a 'control board'. Buchanan and Preston (op cit) put the 'intervention' down to inadequate training of supervision prior to the introduction of manufacturing systems engineering. An alternative explanation would concern the completeness of the shopfloor control system design and its interface with the top down corporate systems. There appears to be a gap between rhetoric and reality in this particular stage of the manufacturing systems design methodology. Experienced, proven and well trained LE & S manufacturing systems engineers, supported by knowledgeable local staff undertook the projects detailed above, leading one to the conclusion that competency was not a major issue in the outcomes achieved at LAPEC and LAAD.

b) Poor Implementation - The LAPEC implementation was very well handled from a logistical point of view. This is demonstrated by the fact that output was maintained during the factory move. Buchanan and Preston (op cit) have commented that the failure of manufacturing systems engineering to realise its potential could be a consequence of a lack of professional Human Resource Management (HRM) input (e.g. by the personnel function). In the case of LAAD, the whole project was managed by a 'Change Council', chaired by a 'Change Manager' who was the Personnel Director for LAAD. This ensured appropriate discussion of key HRM issues such as industrial relations, training and the introduction of new job designs. Constant communication was maintained with shopfloor, supervisory and technical Trades Unions.

c) Changes in the Business Environment - LAPEC did not suffer any major adverse consequences as a result of changes in the external environment, sales for example were maintained during the period under study and the size of the order book was maintained. LAAD did go through a significant change its business profile with the switch from a predominantly military order book to a majority civil order book. However, this change was substantially complete before the implementation of manufacturing systems engineering without drastically affecting sales and profitability.

On balance, it seems reasonable to conclude that the above influences were not significant causes of the poor performance reported in the above casestudies.

5.5.2 Potential Reasons for Differences in Reported Short Term Benefits and Longer Term Business Performance

The analysis presented in this chapter seems to support the contentions presented in Section 5.1 for the differences between the reported benefits and the long-term business impact of manufacturing systems. Firstly short-term benefits have been reported, based on a single snap-shot in time and not longer term trends. Secondly, benefits have been reported in terms of operational metrics such as leadtime or batchsize (or even proxies for these such as 'ownership'), not in terms of business metrics. Thirdly, it is clear from the above that these benefits have been related to a sub-set of the business rather than the business as a whole. It is the benefits of single cells and single product units that have been reported not complete businesses. These individual implementations may well have been proportionately over resourced (in terms of operational resources such men and machines). The operational benefits obtained from these implementations were then used as a justification for converting the whole plant without a detailed evaluation. Lastly, it is likely that the 'Hawthorne Effect' does have an impact in the initial introduction of cellular manufacture. For example, in the case of LAPEC the initial performance improvements reported for the Electronics Product Unit were not sustained in the longer term. Buchanan and

Preston (op cit) indicate that the 'Hawthorn Effect' may be at work when they quote a cell member as saying:

> 'we've lost the sparkle.'

5.5.3 Identified Weaknesses in the MSE Methodology as a Result of the Longitudinal Casestudies

The LAAD and LAPEC casestudies presented in this chapter highlight a number of weaknesses in the manufacturing systems engineering approach to the design of manufacturing systems that need to be addressed. These are detailed below.

a) The methodology should encourage the exploration of appropriate manufacturing architectures other than the purely vertically orientated and encourage dynamic evaluation.

b) Leaving the specification and design of control systems until the end of the design process appears to result in it not being undertaken in appropriate depth prior to implementation. Specification and design of control systems should start earlier.

c) The control system design phase is heavily orientated to the design of shop floor material control systems at the expense of examining the interfaces and integration with top down systems. This integration process should be undertaken and particular care should be taken in the investigation of MRP parameters such as leadtime.

d) Job design needs to start earlier and some consideration of reward systems should be included.

e) The transient, in terms of both the physical system and the control system should be dynamically investigated.

f) The overall effects of a manufacturing systems design should be evaluated, not just the benefit in the area where change has been implemented. This evaluation should not just take place in terms of operational metrics but should also include business metrics.

g) The adoption of over-simplistic Make v Buy policies should be avoided and the business impact of any proposed policy evaluated.

Clearly, some of the above observations back-up conclusions that have been reached in Chapters 3 and 4.

What is clear from these case-studies is that short-term operational benefits have failed to be converted into long-term business benefits. The two companies have had to undertake significant 'fire-fighting' activity to return to business performance levels achieved prior to the introduction of cellular manufacture. The short-comings in the methodology detailed in Chapter 4 have clearly contributed to the decline in business performance experienced by the two case-study companies. The lack of a systemic nature to the methodology appears to be significant and needs to be addressed in the development of a revised methodology.

Chapter 6

The Design of Cellular Manufacturing Systems and Whole Business Simulation

6.1 Introduction

From the foregoing analysis it is clear that many of the problems associated with the design of cellular manufacturing systems are connected with the evaluation of design decisions, particularly with respect to business level emergent properties. In this chapter, tools and techniques for the evaluation of cellular manufacturing systems designs are considered, with particular reference to simulation. In addition, the different metrics that are utilised to evaluate operational and business performance are considered. These two areas (simulation and metrics) are then brought together in an examination of the Whole Business Simulation (WBS) concept. Particular consideration is given to the place of WBS in the design of cellular manufacturing systems and how it can be used to evaluate emergent properties.

6.2 Simulation and its Role in the Design of Cellular Manufacturing Systems

A key facilitator of design evaluation decisions is appropriate computer software. There are essentially four types of computer support tool available to the cellular manufacturing systems design process:

Specific algorithms : Algorithms that have been computerised for assisting in the process of forming part-machine families. Typically, a solution is maximised (or minimised) with respect to an objective function that reflects what is thought to be desirable manufacturing cell characteristics (for example, Askin & Subramanian (1987) try and minimise operating cost). These algorithms are integral to the particular technique and cannot be separated from it. Therefore, in general, their use is limited to those occasions on which a particular technique is utilised.

General purpose packages : These are utilised extensively in cellular manufacturing system design processes. For example, spreadsheets are used to evaluate static load as demonstrated in Chapter 4 (also, see Tobias, 1991a, 1991b).

Knowledge based tools or expert systems : This is where a computer program utilising expert knowledge reaches a level of performance similar to a skilled human expert. Although much has been written about expert systems in general, there are few examples of their specific successful and practical implementation. Related to expert systems are Decision Support Systems (DSS) which are a means of providing (Son, 1991):

> '...support, by providing information and models, (to) managerial judgement in all decision processes of semi-structured tasks'.

Simulation : A model is created and used to comprehensively and accurately predict system behaviour.

It is proposed to examine simulation in more detail below because of its overwhelming popularity (Paul, 1991) and the fact that it is key to effective evaluation (Wu, 1994), a major issue in the design of cellular manufacturing systems as shown in Chapters 4 and 5.

6.2.1 Types of Simulation and its Benefits

There are a number of issues that need to be considered when utilising simulation and simulation models (Law & Kelton, 1991, Pidd, 1992, Wu, 1994).

Discrete and Continuous : There are essentially two ways of dealing with the way in which state variables change. Continuous simulation models change continuously and smoothly over time. The most advanced continuous models utilise mathematical modelling based on advances in the theory of queuing and reliability modelling. An example of this is the Rapid Modelling Technique (RMT) developed by Suri (Suri & Tomsicek, 1988). This technique was first embedded in the MANUPLAN software package which has more recently been superseded by MPX. For manufacturing systems, this type of simulation is, at best, only appropriate for rough cut aggregate decisions because of the large number of simplifying assumptions it makes to allow rapid modelling. Discrete simulation is used when discrete change is the major theme of a system being modelled, such as in a cellular manufacturing system. The technique is based on the logical interpretation of a system's state which depends upon time and is particularly useful for dynamic non-deterministic analysis.

Deterministic and Stochastic : A deterministic model is entirely predictable and does not have any element of probability attached to it or 'chance' events such as random breakdowns. As a consequence of not having any probability distributions attached to the model, deterministic simulations are repeatable, in that states of variables will be the same at the same point in time in two different simulation runs, given the same initial starting conditions. Stochastic models have random events occurring such as breakdowns and variability in run times and set-up times for example. This makes such models unpredictable, to the extent that several simulation runs have to be undertaken to generate statistical confidence intervals, to use as the basis of prediction.

Level of Aggregation : This issue is concerned with the level of detail that is within the simulation model. A highly aggregated model will have less detail associated with it than a disaggregated model. For example, an aggregated model may deal with work-centres having a certain number of servers, whereas a disaggregated model may have the detail of each work-station (the servers in an aggregated workcentre model) and simulate them individually.

To bring the above three factors together, a continuous model of a cellular manufacturing system would be considered as a deterministic, aggregated model.

Types of Simulation Software :Simulation software may be split into four categories (Paul, 1991) : The first category are computer programming languages such as Fortran, C and Pascal, where a program is written from first principles. The second category includes macro programming languages which allow the analyst to write a model in shorthand form. Examples of packages in this category include CAPS / ECSL and SIMSCRIPT. Thirdly, there are code generators which take a problem which is described in data or graphics and generate code. HOCUS is an example of a package that falls into this category. Finally, there are data driven or generic packages which take a users data as the basis of running a general model. These are often termed simulators. 'Witness' is an example of such a package. Some of these generic packages are specific to manufacturing only.

Simulation has a number of benefits. Chapter 5, for example, gave some indication of the very complex non-linear interactions and dynamics that characterise manufacturing businesses. Simulation is an appropriate tool to help in this type of analysis. In fact, computer simulation is probably the only technique available for the detailed evaluation of the dynamics of both the transient and long term behaviour of a manufacturing system. Clearly, the appropriate use of computer modelling and simulation should enable adequate planning for the introduction of cellular manufacturing systems and the ability to predict consequences (and thereby initiate evasive action if necessary), potentially avoiding many of the problems identified in Chapters 4 and 5.

6.2.2 Limitations of Simulation

Although it is claimed that simulation is popular, it has not been widely utilised. For example, in a survey undertaken by Wemmerlov & Hyer (1989), a number of conclusions regarding the use of computer software were made:

- The performance of load analysis utilising spreadsheet type programs was found to be most widespread (deterministic and static in nature).

- The use of dynamic simulation was very limited, utilised by about 15% of businesses that responded to the survey. This is no higher than found by Dale & Willey (1980) in a survey conducted 10 years earlier.

This has been supported by more recent UK based surveys. For example, Devereux et al (1994) found 48% of companies used spreadsheets in the design of manufacturing systems and 16% used simulation packages. From both the literature and the investigations undertaken in Chapters 4 and 5, four main reasons for this can be hypothesised :

- The perception that it takes considerable effort to produce an adequate model.

- The use of simulation is misunderstood. For example, Ghosh (1990) claims it is of use for 'fine tuning' only and Parnaby (1987) limits its use to dynamic design despite the fact that control systems design (which follows it) has a considerable effect on system performance.

- Simulation, along with other computer tools is often just used as an add-on to the process of design rather than an integral part of it. For example, Tobias (1991) describes the use of computer tools during the design process as shown in Table 6.1.

Table 6.1 : Use Of Computer Tools in Design Process (Tobias, 1991)

Data Collection	Data bases for storing and sorting data
Steady State Design	Spreadsheets used to aid design based on average values
Dynamic Design:	Simulation to understand dynamics

This contrasts strongly with design in the process industry, where whole systems engineering methodologies have been developed around appropriate computer tools (Mah, 1990). Computer tools are embedded in the design process rather than peripheral to it. The process of embedding simulation within a design methodology will also avoid the situation occurring, as noted in previous chapters, of simulation not being undertaken as a consequence of it being left to the end of the design process, with project timescales slipping such that it is not possible to undertake such analysis.

- The fact that measures of performance used in simulation evaluations (e.g. machine utilisation) often do not reflect those by which the business as a whole is measured (Chaharbaghi, 1990).

To make appropriate use of simulation the above limitations must be reflected on and a solution found. The ideal outcome can be postulated as a methodology where simulation is embedded (as an intricate part of it) rather than grafted on (usually at the end), that the simulation approach used is data driven and domain specific to manufacturing (reducing model building time) and that the simulation process is linked to both operational and business level metrics. It is interesting to note that a study funded by the UK Department of Trade and Industry (DTI) suggested that considerably more emphasis was required on the development of application methodologies that used simulation (DTI, 1990). Bridge (1990) has developed an appropriate data driven simulator (ATOMS) specifically for the manufacturing domain. ATOMS can also be overlaid, to some extent, onto the MSE approach to the design of cellular manufacturing systems. However, given the problems identified in previous chapters with the MSE approach to the design of CMS's and the lack of a link to business metrics such a solution is not appropriate.

6.2.3 Simulation and Cellular Manufacturing

Some interesting work has been undertaken in the application of simulation to the design of cellular manufacturing systems. The type of work that has been undertaken can be categorised into one of three types.

Comparison of Functional and Cellular Manufacturing Systems : There have been a number of studies undertaken to compare the performances of functionally organised and cellularly organised manufacturing systems (Flynn & Jacobs, 1986, 1987, Morris & Tersine, 1990, Biles et al, 1991, Sharper & Greene, 1993). Many of these studies have challenged the view that cellular manufacture is superior to traditional, functionally organised manufacture. Although a number of these studies may be criticised (Flynn & Jacobs (1986) for example, evaluate a manufacturing system where parts visit, on average, 7.3 cells, hardly meeting the goal that a part should be processed fully in one cell), there is a high degree of consensus among researchers in the area of simulation of CMS's, to support the contention that cellular manufacturing is not a panacea solution to manufacturing problems. Of course, there are others such as Burbidge (1992, 1994) who would contest this notion.

Analysis of Hybrid Manufacturing Systems : There are two types of hybrid cellular manufacturing system, that can be identified from the literature. The first type is where a manufacturing systems is partially cellularised, leaving a 'residual' or 'remainder'. Flynn & Jacobs (1986) use two such system in their analysis, indicating that they give 'worse' performance than a well laid out functional manufacturing system. Burgess et al (1993) on the other hand, indicate that such a hybrid manufacturing system gives better performance than either a pure cellular or a functional manufacturing system. Shafer and Meredith (1993) analysed a cellular manufacturing system with a remainder processing 81% of parts in the system and did not find much difference in performance. This was hardly surprising given the small degree of cellularisation.

The second type of hybrid is where the whole manufacturing system is cellularised,. but inter-cell movement is allowed. Ang & Willey (1984) analyse such a hybrid system. They indicate superior performance for this type of system compared to a cellular system with no inter-cell moves. However, the question that is raised by this work is, at what level of inter-cell moves is a functionally organised manufacturing system being analysed rather than a CMS.

Analysis of Suitable Environment for Cellular Manufacturing : The third area where work has been undertaken is in trying to diagnose the 'best' environment for the introduction of CMS. Such work has been undertaken by Shafer & Meredith (1993) and Morris & Tersine (1990). Table 6.2 indicates the results of this work.

A number of criticisms of the above simulation studies can be made. Firstly, the models used are inadequate and often do not represent the whole system or the synergistic benefits that often result as a consequence of cellular manufacture. For example, Flynn & Jacobs (1987) compared process and cellular layouts on the basis of First In First Out (FIFO) despatch rules at work stations, ignoring the fact that a cellular layout might allow a Kanban type material flow control system to be implemented with the benefits that such a technique may bring (Schonberger, 1982, Lewis & Love, 1993c).

Table 6.2 : Desirable Features of Manufacturing Systems for Successful Cellularisation

Author	Desirable Characteristics
Shafer & Meredith (1993)	more rather than less operations per part longer rather than shorter processing times presence rather than absence of natural part families absence rather than presence of bottle-neck machines
Morris & Tersine (1990)	set-up times are longer rather shorter demand is predictable period batch control can be used transport time is substantial unidirectional flow can be established

Secondly, when evaluating such models only a parochial view is taken, ignoring synergistic benefits that occur at a system level (e.g. elimination of production control departments leading to lower overhead and lower cost). Thirdly, evaluation takes place exclusively in terms of operational metrics such as mean flow time, mean waiting time and mean number of jobs in queues. Lastly, the scale and scope of models used is very limited as can be seen in Table 6.3, leading one to question the industrial relevance of many of the conclusions.

Table 6.3 : Size of Cellular Manufacturing Systems Simulated

Authors	No. of Parts	No. of M/C's	Type of Problem
Shafer & Meredith (1993)	Not Given	50 (Average)	Industrial
Sarper & Greene (1993)	12	52 (Max)	Synthetic
Flynn & Jacobs (1986)	25	38	Industrial
Ang & Willey (1984)	Random	40	Synthetic
Morris & Tersine (1990)	40	30	Synthetic
Sassani (1990)	71	28	Industrial
Suresh & Meredith (1994)	50	31	Synthetic
Burgess et al (1993)	147 (Max)	24	Synthetic

The above analysis, combined with the results presented in previous chapters throws the whole issue of cellular manufacturing into some confusion. There is significant survey evidence in the literature to suggest substantial performance improvement through the adoption of cellular manufacture (Dale & Willey, 1980, Wemmerlov & Hyer, 1989, Burbidge, 1992). However, there is simulation and longitudinal case-study evidence to suggest that cellular manufacture is not a panacea. Simulation studies suggest better performance for functional manufacturing systems than for wholly cellular manufacturing systems. Better performance for hybrid cellular manufacturing systems is suggested when compared to functional layouts. However, the consensus is by no means total and the evidence is not conclusive. The main conclusion that can be drawn, is that the above situation underlines the need for careful dynamic evaluation of cellular manufacturings system prior to implementation.

The simulation analysis that has been undertaken can be used to give an indication of key issues that need to be considered in the design of CMS's. These are shown in Table 6.4. These can be used to drive the design process in a goal orientated fashion. That is to say, for example, that transfer batches are considered in the design process or that set-up reductions are planned for and action taken to ensure that they are achieved.

The evidence above should not lead one to the conclusion that cellular manufacturing systems have no role to play in the improvement of manufacturing, only that contentions such as that proposed by Burbidge (1992), in his paper entitled :

> 'Change to group technology : process organisation is obsolete'

should not be accepted at face value and that implementations need to be carefully evaluated and take account of key issues that are likely to make them successful operationally. There is no doubt that the benefits in terms of team-working and 'ownership' are available (Alford, 1994).

Table 6.4 : Key Issues for the Design and Implementation of Cellular Manufacturing

Authors	Design Indicators
Shafer & Meredith (1993)	Extensive use of transfer batches
Sarper & Greene (1993)	Careful consideration of bottlenecks
Ang & Willey (1984)	Inter-cell movement can significantly enhance performance (95% 'ownership' might actually degrade performance)
Burgess et al (1993)	Consider whole factory (including remainder) operate cells at relatively higher levels of theoretical capacity then non-cell workcentres
Flynn & Jacobs (1986)	Ensure set-up reductions Ensure move time reductions
Suresh & Meredith (1994)	Reduce set-up times and batch sizes Reduce process times Reduce variability in processing times Reduce variability in inter-arrival times
Sassani (1990)	Use transfer batches

6.3 The Use of Metrics

When justifying and evaluating a CMS design, metrics have to be used. These metrics can be classed (in broad terms) in one of two categories. They may be either operational metrics, tracking operational improvements such as set-up reductions, process time reductions and lead-times. These are typically non-financial in nature. Alternatively, they may be classed as business metrics. These are typically financial in nature.

6.3.1 Operational Metrics

Many of the approaches to the design of cellular manufacturing systems evaluate solutions in terms of operational metrics. These metrics include, for example, measurement of queue lengths, waiting times and flow times. However, there are other kinds of operational performance measures that are suited to the approach of world class manufacture epitomised by the adoption of cellular manufacture (Schonberger, 1990). Johnson & Kaplan (1987) contend that maintaining and reporting a variety of non-financial metrics is more important than regularly measuring profit. They suggest that such measures should be based on the company's strategy. The following measures are typically employed in companies that have so-called world class manufacturing operations (see for example, Heim & Compton, 1992) :

Quality : World class manufacturing companies move from an inspection (detection) approach to quality to a prevention based approach. Measures used include parts-per-million defects rate and SPC (Statistical Process Control) chart usage.

Delivery : The aim is to ensure consistent and on-time delivery. Typical measures include schedule adherence and numbers of past-due orders.

Process Time : Typical measures include set-up times and lead-times.

Flexibility : This includes the ability to change product volumes and product mix quickly, have short leadtimes and be able to introduce new products quickly. Measures used include the number of different parts and the number of new products introduced each year.

Costs : These are not usually expressed in financial terms but are used to give an indication of the cost reduction activity that is being undertaken. Measures include percentage non-value-added activities and inventory turns to encourage inventory reduction.

Actual measures used may vary between locations in the same company. This is to reflect what is important locally. Similarly, the measures used may change over time as the needs of the business change. Finally, in general, these measures are intended to encourage continuous improvement rather than to monitor the effort of individuals.

6.3.2 Business Metrics

There is a body of opinion that recognises the following three business level metrics as being widely utilised in terms of corporate objectives and the external evaluation of corporate performance (Eilon, 1992, Hill, 1993) :

ROCE (Profit / Capital Employed)
Asset Turn (Sales / Capital Employed)
Net Margin (Profit / Sales)

Where :

Capital Employed = Fixed Assets + Current Assets - Current Liabilities
Profit = Sales - (Opening Stock - Closing Stock + Costs)

For example, Lucas Industries regards the following group of targets as acceptable business ratios for its constituent companies :

ROCE = 25%

Asset Turns = 2.5

Net Margin = 10%

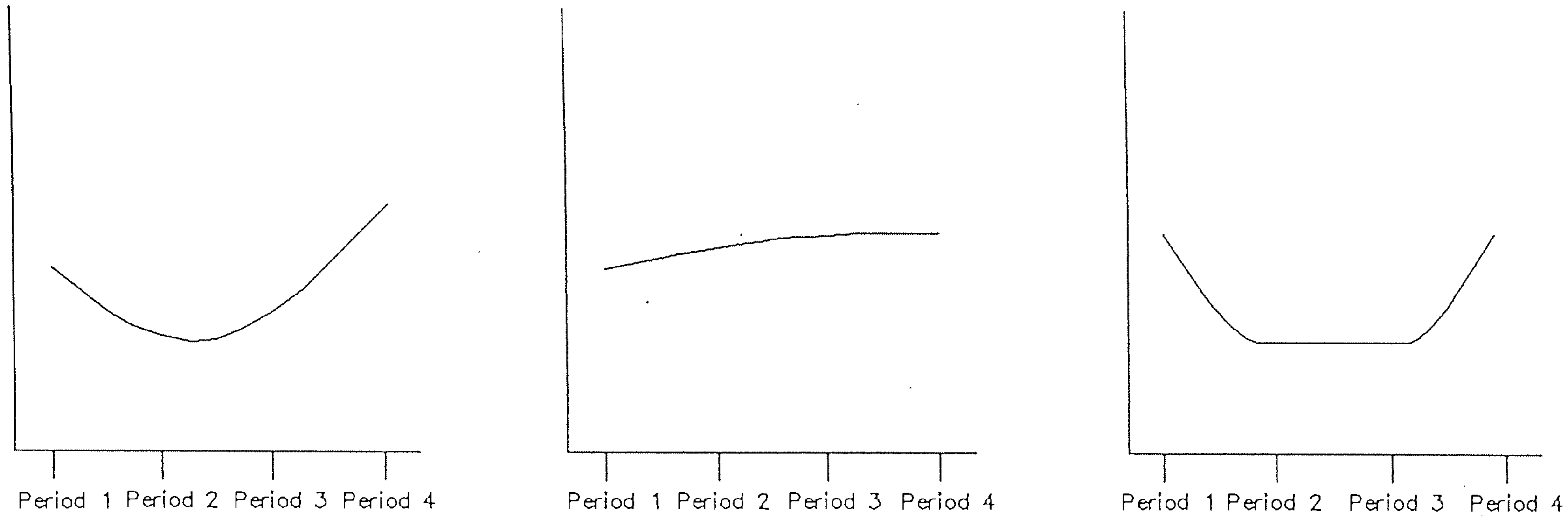
These business level metrics do not necessarily have positive relationships with the operational metrics discussed in Section 6.3.1. For example, examining ROCE and its relationship with inventory reductions (and hence leadtime reductions) reveals some interesting insights that should be considered during the design and implementation of a new cellular manufacturing system. Given the definition of ROCE, it is clear that an inventory reduction results in a decrease in capital employed which, all things being equal, would increase ROCE. However, a reduction in inventory may also reduce profit, as closing stock is reduced (see definition of profit). For example, reducing the work-in-progress and finished goods elements of inventory will reduce the amount of overhead that is absorbed into closing stock, hence reducing profits. Although the capital employed will have reduced, as long as ROCE is less than 100%, profit will decrease by a greater percentage and ROCE will be reduced. The higher the value of the inventory reduction the bigger the reduction in ROCE, placing a higher penalty on the reduction of finished goods as opposed to work-in-progress. This characteristic of inventory reduction also causes a reduction in the net margin ratio, although the asset turn ratio does improve.

The reductions in the ROCE and net margin ratios, as a consequence of reduced inventory and leadtimes are not permanent reductions. When a stock reduction programme has been completed ROCE, net margin and asset turns should (all things being equal, with for example no change in sales or costs) all have improved. This is demonstrated, by example in Table 6.5 and Figure 6.6. This illustrates how ROCE, net margin and asset turns change over time because of reduced closing stocks. In this contrived example, ROCE reduces between periods 1 and 2, improves between 2

Table 6.5 The Inventory/Profit/ROCE Relationship (a)

	PERIOD 1		PERIOD 2		PERIOD 3		PERIOD 4	
SALES (£K)		100		100		100		100
OPENING STOCK (£K)	100		100		75		50	
CLOSING STOCK (£K)	100		75		50		50	
	0		25		25		0	
EXPENSES (£K)	50		50		50		50	
	50	50	75	75	75	75	50	50
PROFIT (£K)		50		25		25		50
CAPITAL EMPLOYED (£K)	200		175		150		150	
ROCE	25%		14.28%		16.6%		33%	
ASSET TURNS	0.5		0.57		0.66		0.66	
NET MARGIN	50%		25%		25%		50%	

Figure 6.6 The Inventory/Profit/ROCE Relationship (b)



i) ROCE

ii) Asset Turns

iii) Net Margin

and 3 reaching a new high between periods 3 and 4. Asset turns improve until there is no more stock reduction in period 4, reflecting the reduction in capital employed. Net margin reduces between periods 1 and 2, remains static between periods 2 and 3, returning to its previous value in period 4. This example illustrates the transitory nature of the problem. It is thus very important to manage the implementation of world class manufacturing practices, such as cellular manufacturing, which reduce inventory (especially in a non growth period). For example, tighter control of the other elements of working capital might help. Alternatively, careful thought on the phasing of inventory reductions may be required. Another approach is to communicate to the people who are most interested in ROCE (usually shareholders) what is happening and gain their support. It should be noted that an inventory reduction improves cash flow in all cases. Given the importance of the business metrics detailed in this section, it is clear that they should be utilised when designing and implementing CMS's.

6.3.3 A Balanced Set of Metrics

Any approach that claims to effectively and holistically evaluate a cellular manufacturing system design must use a balanced set of operational and business metrics. Operational metrics are required to ensure that improvements in quality, on-time delivery and lead-times are encouraged and continuous improvement undertaken. These issues are important to customers. In addition, business metrics such as ROCE, asset turns and net profit margin are required to ensure that the requirements of the 'bottom line' are met and understood.

6.4 Whole Business Simulation

Whole Business Simulation (WBS) (Lewis & Love, 1993a, 1993b, Love & Barton, 1993) and its integration with an appropriate design methodology is a concept that is well suited to overcoming the weaknesses of current approaches to cellular manufacturing systems design that have been discussed above. Such an approach would include a systematic and systemic methodology, simulation and evaluation of operational and business metrics.

6.4.1 What is Whole Business Simulation ?

This section will discuss WBS and its core elements. Whole Business Simulation has been developed as a decision evaluation system capable of appraising the impact on the business performance of the whole company of a decision made virtually anywhere in the organisation. The system is a computer simulation incorporating a mixture of real software systems and specialist simulation elements. WBS includes the following functions:

- customer demand model
- product design
- production engineering (process planning)
- material requirements planning
- supplier(s)
- manufacturing operations
- ancillary cost generators (to generate those overhead costs not covered elsewhere)
- and an accounting system

The above would represent a 'minimum' system, but the architecture could be extended readily to include any other function. The elements of the system are linked by the same kind of transactions that occur in the real world. The basic process can be illustrated by the following example that relates to Figure 6.7.

A group of elements covers all the basic operations of the factory: sales, materials planning and control, manufacturing operations and purchasing. Additional elements are needed to represent the activities of external companies, such as suppliers and customers. A sales demand triggers sales orders to be passed to the materials requirements planning (MRP) system. Works orders and purchase orders are generated by the MRP system, using the usual algorithm. These orders are passed to the factory simulator and supplier model as appropriate. Local planning or scheduling rules are applied in the factory module that simulates production and warehousing activities. Stock movements are posted to the MRP system, as are works orders completions, shipments to customers and deliveries to suppliers. The system is self-contained requiring no external order or demand data streams.

Standard accounting transactions are generated from events that occur in the operations group of elements. For example, sales orders and deliveries lead to invoices being issued to the company's 'customers'. Following an appropriate delay invoices are paid and the 'books' updated. Purchased items are dealt with in a similar fashion. Where transactions cannot be related to driver activities in the core elements of the model, an ancillary generator is used to produce them. This approach may be used to cover the cost of general overhead expenses. At the end of each accounting period, the accounting system can produce a complete set of accounts for the company, including the profit & loss statement, balance sheet and funds flow statement. Appendix 2 contains flowcharts generated in the development of WBS processes. A WBS demonstrator exists, utilising the 'UNIPLAN' MRP package, the ATOMS simulator and the DBFLEX accounting system (Barton and Love, 1993). This is shown in Figure 6.8.

Figure 6.7 The Whole Business Simulation (WBS)

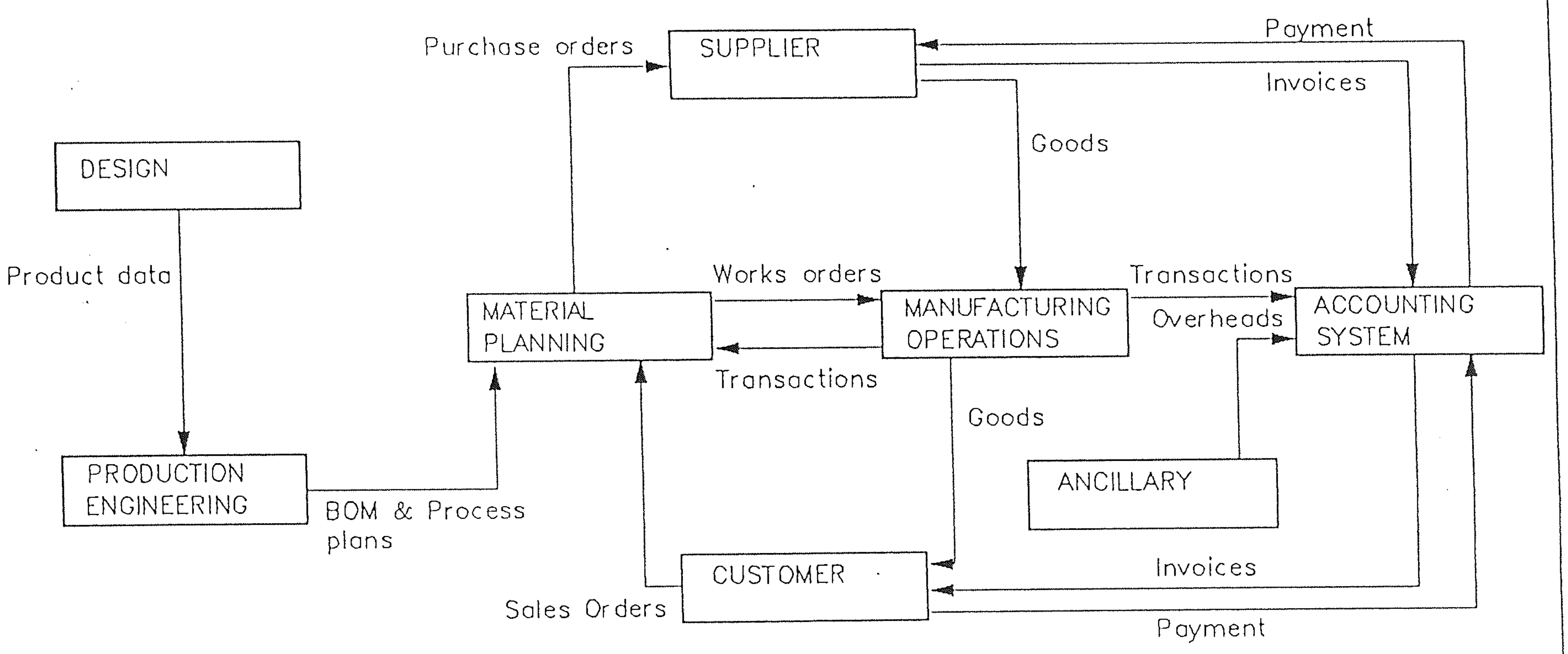
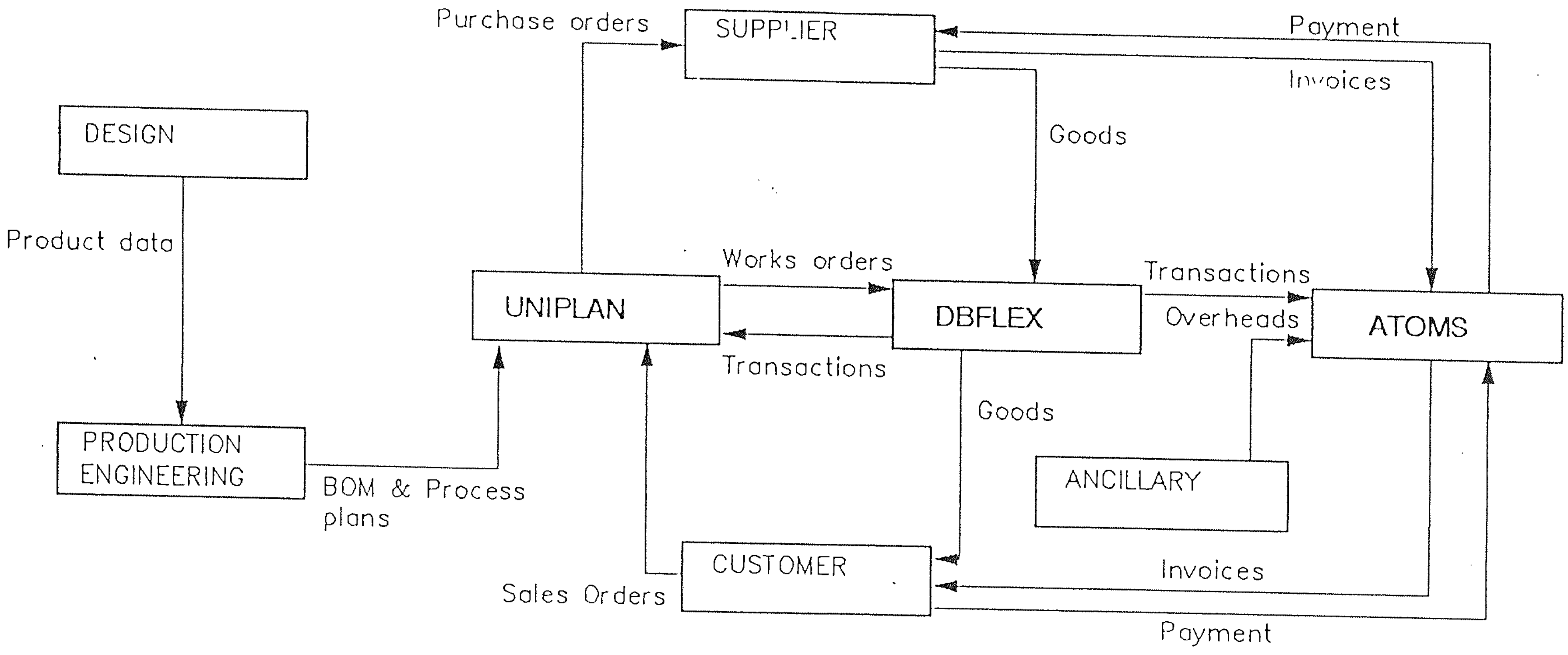


Figure 6.8 The WBS Demonstrator



The WBS model is able to evaluate changes in any one of the system elements to assess its impact on the financial situation of the company. The model can be run and analysed with and without the change and the effect compared. Changes in manufacturing planning and control policies, overtime policies, change-over times or even accounting practise could be evaluated by the system. Clearly, the WBS concept goes someway to overcoming the contention of Fritz et al (1993) that :

> '.. simulation models can only represent a small range of the activities needed in the real system...'

A demonstrator WBS has been developed and although it has near full functionality, it is essentially modelling no more than a small cellular manufacturing system rather than a whole business (Love and Barton, 1993). To evaluate the potential of WBS, a full scale whole business experimental model will need to be developed (see Chapter 8).

6.4.2 The Need to Use Discrete Event Models in WBS

Given the broad nature and scope of the task that WBS is trying to address, it seems reasonable to ask the question as to why the level of detail given by a discrete event simulation approach is required ? The alternative to the use of discrete event based models is the use of a continuous analytical Queueing Network Model (QNM) based on techniques such as that made available by software packages including MPX. This question has added significance given the fact that Jackman and Johnson (1993) conclude that MANUPLAN runs some 200 times faster than a discrete event model to solve the same problem. A number of reasons can be put forward as to why the level of detail proposed is required.

Firstly, QNMs make a number of simplifying assumptions that are, in most cases unrealistic (Chaharbaghi, 1990, Adiga & Glassey, 1991, Jackman & Johnson, 1993).

These include the assumption of stationary stochastic processes, stochastically independent jobs and exponentially distributed service times. Secondly, the system is assumed to have a steady state. This assumption indicates that a QNM cannot be used to evaluate transient behaviour, identified as a significant problem in previous chapters. QNMs cannot be used to evaluate the short term effects of change. Discrete event simulation is able to capture the transient behaviour that QNMs are not able to evaluate. Clearly, this is a problem as far as the implementation of cellular manufacturing system is concerned. However, the wider question is whether manufacturing systems are ever in steady state in the current competitive era.

Thirdly, QNMs cannot give a system capacity. All they can indicate is whether a certain system configuration is able to manufacture the requirements of a certain schedule. If the system is not able to cope with a particular schedule of requirements, it ceases operation. Lastly, Jackman and Johnson (1993) have undertaken a detailed comparison of QNM's and discrete simulation and reached a number of interesting conclusions. Firstly, QNM's give a close match with discrete event simulation (at the 95% confidence level) as far as average utilisation is concerned. However, with regard to work-in-progress and flow-time (lead-time) they found very little correlation, indicating the need for a very cautious interpretation of data from QNMs. It would be very unwise to evaluate both business and operational metrics on such data. Therefore, it is reasonable to conclude that discrete event modelling is required in WBS for it to fulfill the objectives and tasks discussed in section 6.4.1.

6.4.3 Alternatives to Whole Business Simulation

There are potentially a number of other approaches to achieving the objective of reflecting business metrics in the evaluation of cellular manufacturing systems. Christy & Kleindorfer (1990) for example, consider the integration of simulation and spreadsheets. Data is collected from a number of simulation runs and spreadsheets are used to plot cashflows. However, these are crude cost analyses that reflect costing systems rather than accounting systems. WBS, by modelling company accounting systems rather than cost systems avoids (Love & Barton, 1993) :

> '...the assumptions inherent in any abstract costing system and thus ensure(s) much more reliable model performance.'

Another possible alternative to the use of WBS is financial modelling. Typically, a financial business planning model is spreadsheet based. Financial data on depreciation rates, creditors, debtors, settlement profiles, interest rates etc. is input. Once the current financial situation is constructed the model is extended through the addition of sales data. Projections can then be made. Changes in asset profiles, material costs and other operational factors can be input at (usually) one month intervals. Although such models give an indication of financial performance (using business metrics) they are in no way able to evaluate dynamic performance (and therefore transients, for example, identified as a key issue above). Additionally, business planning models are unable to evaluate operational metrics. Enterprise modelling through the use of methodologies such as IDEF (Colquhoun et al, 1993) may also be alternative approaches for the systemic design and evaluation of cellular manufacturing systems. However, such approaches have been criticised as being too abstract. Additionally, the dynamic aspects of such methodologies ($IDEF_2$ in the case of IDEF) do not appear to be very well developed (Wu, 1994). Information processes are typically modelled and ways found to make the processes interact more efficiently. The focus of Enterprise Modelling has not been on shopfloor activities but has tended to concentrate more on computer systems (Goranson, 1992).

6.5 Whole Business Simulation and Cellular Manufacturing Systems Design

WBS can be used to compare different cellular manufacturing systems designs. Providing the simulator used is appropriately flexible, the system described above could be used to compare different designs. The accounting transactions associated (including both initial investments and operating costs) with each alternative design would be catered for in the same way as they would occur in the 'real world'. Savings associated with the cellular manufacturing designs such as reduced current assets (in for example, the form of work-in-progress) or reduced expenses would show automatically in the accounts. Each design variant would be tested and the alternative that had the 'best' impact on for example, return on capital employed would be selected. The impact of delays in implementation (the transient) or the effect of excessive or inadequate demand could be assessed in terms of its financial impact on the company. In terms of evaluation, decisions would be made on the basis of the firms accounting systems rather than its costing systems. The result should potentially be much more accurate than any abstract cost model. Performance in terms of operational metrics would be available from the results produced by the simulator.

6.6 Summary

The integration of WBS with an appropriate design methodology (based on the systems approach) would go some significant way to produce an approach to the design of cellular manufacturing systems that was both **systematic** and **systemic**. Such an approach would allow:

- Consideration of overall system performance. As WBS can model the whole business inappropriate system boundaries would not be drawn around individual cells, leading to the neglect of the sometimes large so-called 'residual' or 'remainder'. The total manufacturing system would be evaluated.

- Indication of the relative importance of the criteria detailed in Table 6.4, in particular company circumstances.

- The design and evaluation of cellular manufacturing systems with respect to overall desired emergent properties based on business metrics such as return on capital employed, whilst maintaining the ability to evaluate operational metrics.

- The integration of cellular manufacturing systems design into the strategic decision making process. As WBS can model the effect of changes in the manufacturing system on the performance of the whole business, the profile of manufacturing will be raised in companies and information of interest to senior management produced, rather than just details on local performance. This would complement the approach of DRAMA (see Chapter 3).

Chapter 7

Developing a Systemic Methodology for the Design of Cellular Manufacturing Systems

7.1 Introduction

Previous chapters have identified a number of problems with approaches to the design of cellular manufacturing systems in general and the manufacturing systems engineering approach in particular. Although some of these shortcomings are concerned with not undertaking particular aspects of the design process effectively, the fundamental problem underlying all of these approaches is their lack of a systemic nature. This chapter has the objective of developing a systemic methodology that also addresses the design deficiencies identified in other CMS approaches. The key systemic foundations of the methodology are:

a) That the scope is such that the complete design problem is addressed, not a partial problem. All of the system should be considered (structurally), all aspects of the system should be considered (including 'top down' material control systems, for example) and they should be considered simultaneously, not sequentially. The focus of the methodology should not merely be on the solution of the cell formation problem but should consider issues such as control system and specification and design.

b) That design alternatives are evaluated in terms of emergent properties and not just local operational metrics (although it is recognised that these have a significant role).

The methodology is firmly placed in the domain of the design and implementation of cellular manufacturing systems. It is not intended as a methodology for the design of more general manufacturing systems, although many of the considerations and principles are generic to the general manufacturing system design problem.

7.2 Requirements Definition for a Systemic Methodology for the Design of Cellular Manufacturing Systems

In addition to the key foundations of the methodology detailed above, there are a number of general requirements for the methodology that are evident from the analysis presented in previous chapters. These general requirements can be brought together into a 'Requirements Definition' statement or specification identifying issues that the methodology must address. The key elements of this statement are given below (the comment in brackets refers to the phase of the proposed methodology in which the activity takes place) :

a) Adequate consideration should be given to the diagnosis of reasons for current levels of performance in the manufacturing system under consideration. The assumption that 'total' cellularisation is appropriate should be avoided as should the notion that cells **must** have complete ownership of the production processes required for a component. Consideration should be given to the levels of performance required in terms of both operational and business metrics at the start of the design process (Phase 1).

b) The Whole Business Simulation concept should be embedded within the methodology (All Phases).

c) An early runners, repeaters and strangers analysis should be undertaken. This should be included as an explicit activity (Phase 1).

d) Design issues that are addressed near the end of the MSE methodology (control systems design and job design) need to be tackled earlier and an incremental approach taken to the generation of the proposed solution. This includes the evaluation of solutions (Bridge, 1990). If evaluation is left until the end of the design process then there the danger that previous 'ownership' will mean that the design team will not necessarily be objective in the view that it takes. Evaluation will be seen merely as a hurdle to clear (All Phases).

e) Consideration of the manufacturing architecture should not be limited to the consideration of vertical architectures (Phase 3).

f) Make v Buy analysis should take place at a strategic level and avoid the 'C' item off-load syndrome presented in previous chapters (Phase 2).

g) Unrealistic, naive assumptions to produce a perceived 'ideal' design solution should be avoided (All Phases).

h) Dynamic evaluation should be undertaken and such evaluation should not be limited to deterministic analysis but should include, where appropriate, stochastic analysis (All Phases).

i) Control systems design should not focus only on the shop-floor material control element but should also examine the interfaces and policy parameters of the top down system (Phase 3).

j) The methodology should ensure that 'goal' orientated metrics are established. For example, if a certain workstation requires a set-up reduction goal to be achieved, this should be recorded and audited (All Phases).

k) The transient behaviour of the whole system should be assessed (Phase 6).

7.3 Overview of the Proposed Methodology

The proposed methodology has six phases each with three dimensions, supported implicitly by the assumption of best practice change management. This assumption has been made as a consequence of the commonality of this to all initiatives that seek to significantly improve organisational effectiveness : it is not peculiar to the design and implementation of cellular manufacturing systems. The broad outline of the methodology is shown schematically in Figure 7.1. Essentially, the methodology is based on the systems engineering approach (Figure 2.2). The system analysis stage has been split into two phases (System Characterisation and Boundary Definition) recognising the importance of the 'make v buy' decision. The system design stage has been split into three phases (Concept, Configuration and Detail). This is akin to the process used in engineering product design and ensures the appropriate addition of detail as the design process proceeds. Finally, system implementation follows. The proposed methodology does not deal with the day-to-day operation of the CMS. Figure 7.2 shows how the Lucas approach to MSE may be mapped onto the proposed methodology. The six phases in the methodology are given below.

Phase 1 : System Characterisation and Diagnostic - This phase of the methodology has the objective of characterising the existing system, its performance and possible explanations for any unsatisfactory performance. An As-Is WBS model is built, verified and then validated against current operational and business metrics.

Phase 2 : System Boundary Definition - The boundary of the manufacturing system with regard to parts that are to be made in and those to be bought out or sub-contracted is established. This exercise is undertaken as a strategic exercise and an overall system evaluation is undertaken.

Figure 7.1 A Systemic Methodology for the Design of Cellular Manufacturing Systems

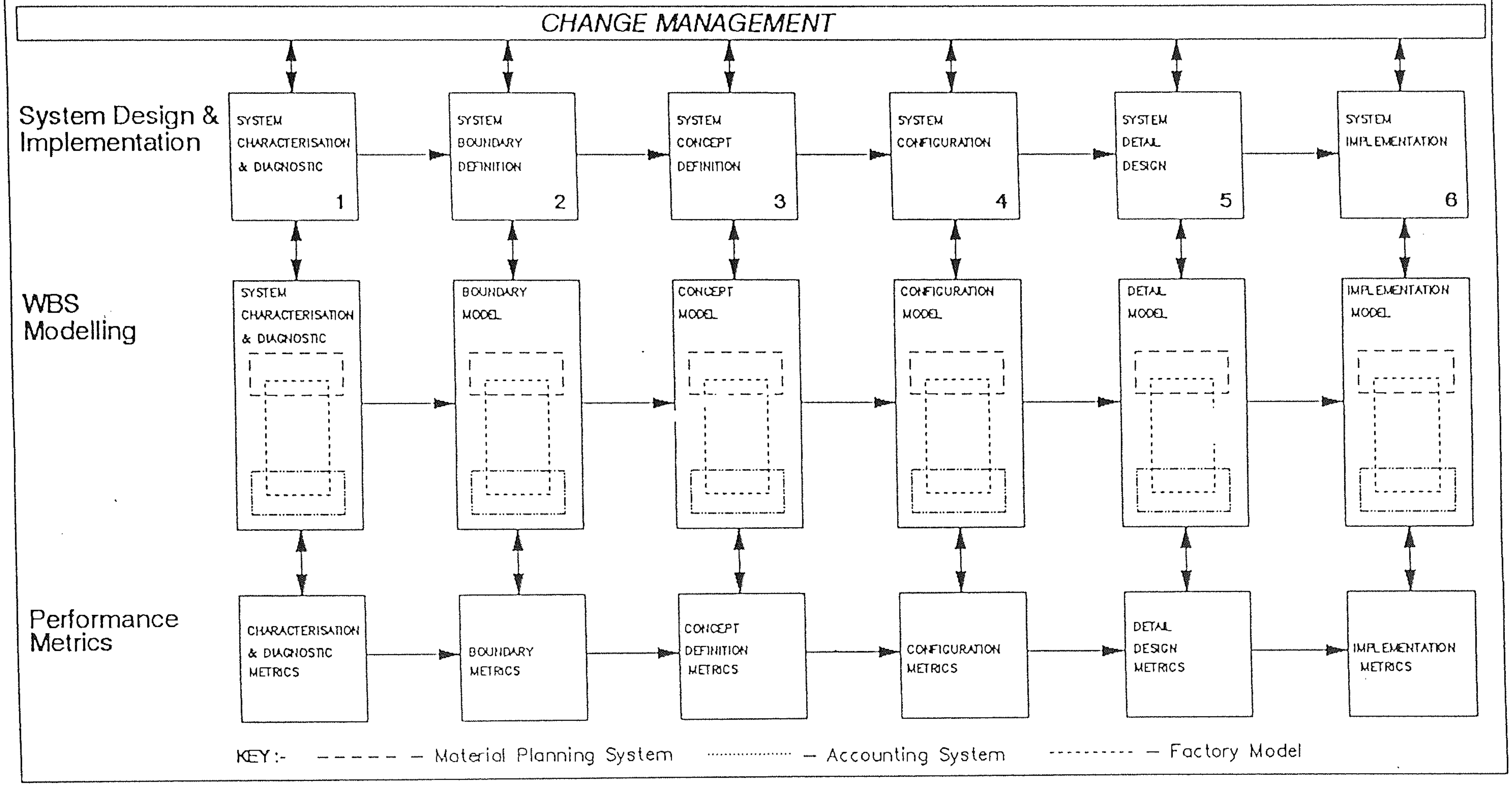


Figure 7.2 Schematic of Proposed Methodology Mapped onto the Lucas MSE Approach

SYSTEM CHARACTERISATION & DIAGNOSTIC	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION
SYSTEM BOUNDARY DEFINITION	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION
SYSTEM CONCEPT DEFINITION	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION
SYSTEM CONFIGURATION	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION
SYSTEM DETAIL DESIGN	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION
SYSTEM IMPLEMENTATION	DATA COLLECTION	CELL DEFINITION	STEADY STATE	DYNAMIC	CONTROL SYSTEMS	JOB DESIGN	CONSOLID-ATION

Phase 3 : System Concept Definition - After establishing the required manufacturing envelope in Phase 2 the concept design of the manufacturing system can be defined. An appropriate manufacturing architecture is defined, as is a manufacturing mission for each segment, types of control system to be utilised and a concept organisation structure.

Phase 4 : System Configuration - In this phase the overall factory is configured, ensuring that all planned manufacturing elements (product units, modules, cells) can be accommodated. This phase is used to 'firm up' on the underlying ideas of the concept design. It is similar in nature to what Pahl & Beitz (1988) call 'Embodiment Design' in the engineering design process. In the system configuration phase, the first stochastic elements are added to the dynamic model. The top down and shop-floor material control systems are configured in this phase.

Phase 5 : System Detail Design - The detail of cell resources, material control systems and job designs are determined in this phase. The overall design proposal is integrated at this stage. This ensures that the system has no 'loose ends'.

Phase 6 : System Implementation - Finally, the detailed planning for implementation is undertaken, the transient modelled and system resources acquired, made ready and the system launched and audited.

The three dimensions that are utilised in each phase of the methodology are:

Dimension 1 : System Design and Implementation - This dimension of the methodology deals with the characterisation, definition, design and implementation issues.

Dimension 2 : WBS Modelling - This dimension is concerned with the modelling of the whole business through the use of WBS (see Chapter 6). In each successive phase of the methodology the WBS model is both augmented with extra necessary detail or changed to reflect the design decisions made. Clearly, the base WBS model that is built is an As-Is model to reflect the current business situation. This model will need to be verified and validated.

Dimension 3 : Performance Metrics - This dimension is concerned with evaluating appropriate (to the phase) operational and business metrics. The base data for such metrics will be provided from the WBS model.

These dimensions are not always explicitly stated in each phase but their presence is clear from the descriptions that are given for each step in the methodology. Throughout the application of the methodology there is the simultaneous development of steady state and dynamic models. The model development process is illustrated in Figure 7.3. Figures 7.4a and 7.4b list the key outputs from each phase of the methodology.

7.4 Phase 1 : System Characterisation and Diagnostic

This phase of the methodology has the objective of characterising the current situation, diagnosing the reasons for any problems and setting targets for improvement. It is of vital importance to understand the current or As-Is (using IDEF notation) situation before proposing what are usually, significant changes to the manufacturing enterprise. As Goldman & Cullinane (1987) contend :

> '...in order for an enterprise to modernise, an analysis of the present condition throughout the enterprise needs to be undertaken'

Figure 7.3 Simultaneous Steady State and Dynamic Model Development

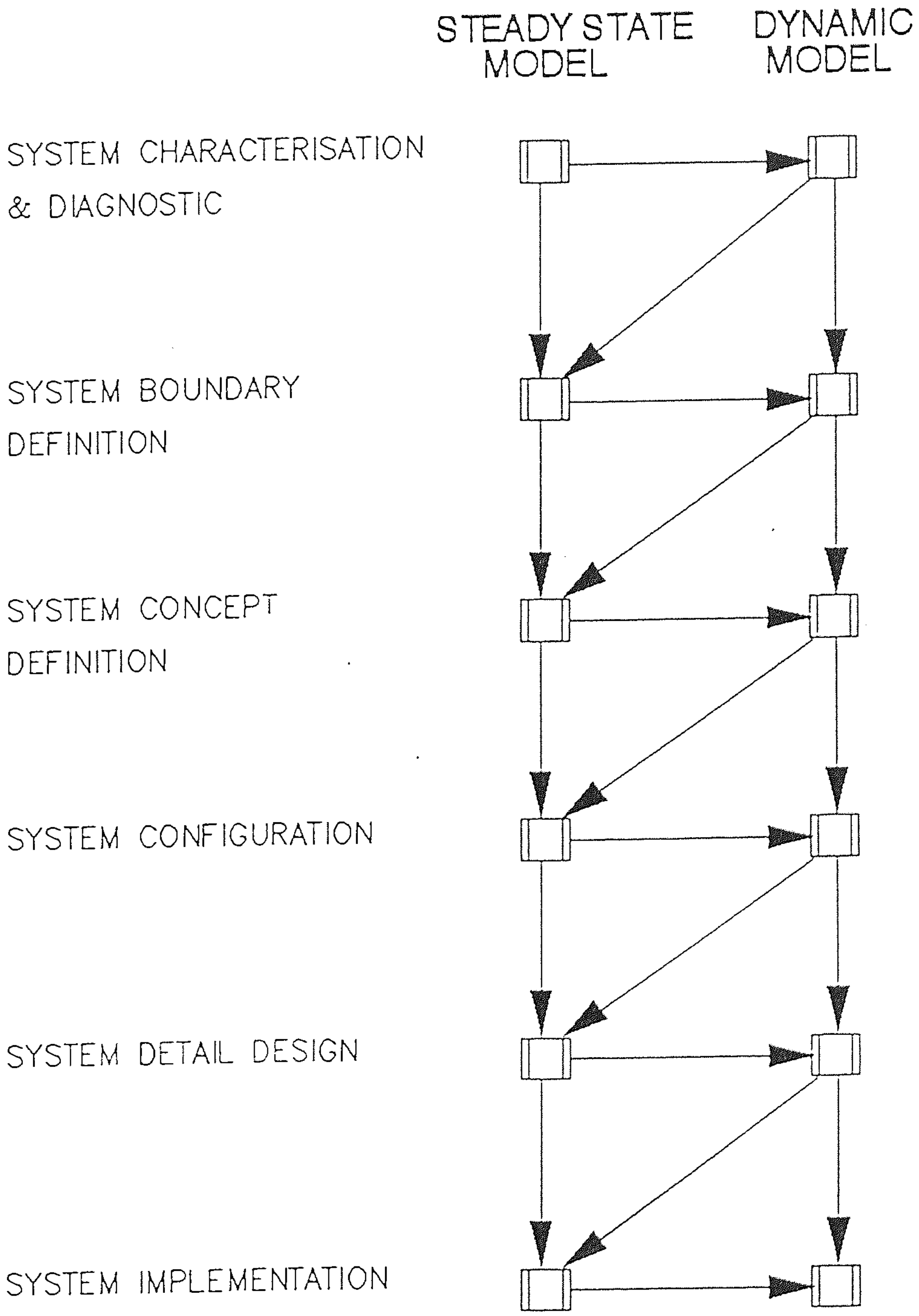


Figure 7.4a : Outputs from Each Phase of the Proposed Methodology

PHASE	KEY OUTPUTS
System Characterisation & Diagnostic	Data on processes, products and markets Defined runners, repeaters and strangers Contextualisation of CMS design within the business and manufacturing strategy Product and parts families Sample of products and parts for analysis Key organisational issues As - Is WBS model Objectives for the CMS redesign
System Boundary Definition	List of strategic processes and capabilities Families of parts to make in, families of parts to buy out and families that may be made in or bought out Recommendation on overall make v buy split Boundary WBS model
System Concept Definition	Overall manufacturing architecture (segmentation) including appropriate levels Recommendation on manufacturing control system Statement on resources in cell and resources in 'residual' Concept organisation design Concept WBS model Supplier Assessment System

Figure 7.4b : Outputs from Each Phase of the Proposed Methodology

PHASE	KEY OUTPUTS
System Configuration	Overall factory layout (factory and product unit level) List of key resources Statement on technology to be employed First pass working practices (shift system etc) First pass operating procedures (shop control etc) List of top down planning system parameter changes Configuration WBS model
System Detail Design	Detailed statement of resource requirements by cell and module shopfloor material control system Order of priority for use of stochastic data Detailed finalised working practices and operating procedures Job Designs and Job Descriptions Detailed WBS model Suppliers for bought out parts families
System Implementation	Policy for introduction of material planning system changes A detailed plan for the transient period during implementation Implemented auditted system

Such a process is concerned with problem recognition. There are 12 steps in this phase of the methodology. These steps are detailed below and Figure 7.5 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 1.1 : Process Characterisation - This step is concerned with characterising the current manufacturing processes. This includes developing a full plant list, skills required for plant to operate, information on process capabilities and process reliability records. Key plant should be identified and replacement values identified.

Step 1.2 : Product Characterisation - Products should be characterised on key parameters that will help identify potential manufacturing segments. Consideration should also be given to product life. This product characterisation may include an analysis of components if appropriate. Such an analysis would be based on more detailed information such as bills of material and manufacturing requirements.

Step 1.3 : Market Characterisation - The market and its requirements need to be understood. A database of customer demand requirements for original equipment (OE) and spares needs to built up. This data can usually be obtained from past demand history, current forecasts and current gross requirements. In addition to this quantitative data, more qualitative data regarding order qualifying and winning criteria by market segment will be required. This step should also be used to establish the business drivers of the manufacturing strategy.

Step 1.4 : Volume and Frequency Analysis - A runners, repeaters and strangers analysis should be carried out at an early stage. This will provide data for use in the boundary definition and concept design phases. Such an analysis involves examining volume requirements and frequency of deliveries. Rules can then be formulated that

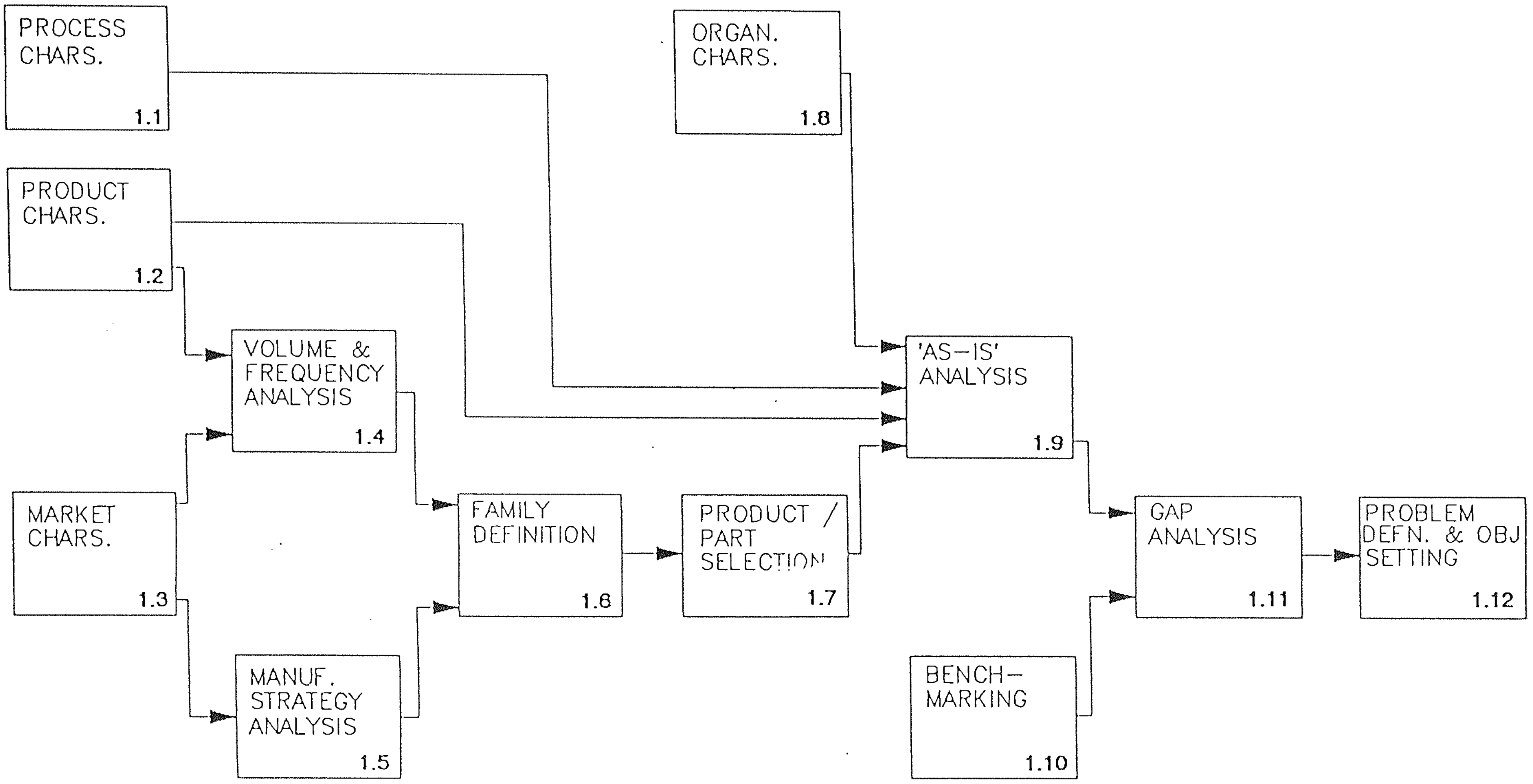


Figure 7.5 : System Characterisation and Diagnostic

allow all products and parts to be classified as runners, repeaters and strangers. An example of a rule might be:

> 'If a component demand occurs 12 or more times in any 47 week period (i.e. more than twelve times per year, or once per month), then it is deemed to be a runner.'

Step 1.5 : Manufacturing Strategy Analysis - The intention of this step is to ensure that the content of the manufacturing strategy is considered. The implementation of a cellular manufacturing system is clearly a strategic issue that should be identified in the strategy. Typically, the manufacturing strategy will address structural issues (such as plant and equipment) and infrastructural issues (including production planning and control systems) (Hayes and Wheelwright, 1984). The cellular system will need to be designed with these strategic criteria as major considerations.

Step 1.6 : Family Definition - Both product and part families might need to be developed. A product may be defined as an end item (although this definition is slightly confused by the sale of spares). Product families are usually defined on a 'top down' basis and reflect strategic criteria such as customer segments. Typically, product families can form the basis for vertically aligned manufacturing units as discussed in previous chapters. Part families can typically be developed from a detailed understanding of requirements and the use of techniques such as coding and classification. The objective in this step of the methodology is to gain a balanced 'top down' and 'bottom up' perspective on the segmentation of manufacturing. It is not usually necessary to analyse every product and component, as a Pareto principle may be used. Care can also be taken to evaluate representatives of the type of components used across the defined product families. Usually product families will be defined before part families. This does not however mean that they will be the main 'driver' of the cellular manufacturing system design process. Each family should be 'sized' in static terms to determine the load that it places on internal and external manufacturing facilities.

Step 1.7 : Product / Part Sample Selection - If a substantial business is to be evaluated as part of the design process, it is most unlikely that all products and parts manufactured will be considered in detail. A sample will be selected to base the cellular manufacturing system design on. This sample should be a group of numerically (Pareto) and strategically important products. Care should be taken in ensuring that the sample includes representative products from all of the families defined in Step 1.6.

Step 1.8 : Organisation Characterisation - The existing manufacturing and support organisation needs to be investigated and key issues such as payment systems identified as early possible. Data collected will range from the traditional organisational chart (with numbers of personnel in each section and department) to that concerned with helping to formulate a view on the business culture. Interaction between departments should be investigated to determine potential waste.

Step 1.9 : As-Is Model Building and Analysis - An 'As-Is Model' of the current situation needs to be built. This model will then need to be verified and validated. The WBS model can be used to generate both operational and business metrics that are determined as being appropriate for the particular business under consideration. There are essentially three key elements in developing a WBS model that can be used to evaluate decisions in the design of cellular manufacturing systems:

a) The material control system aspect of WBS will need to utilise data from Bills of Material (BOM) and stock record files (for information such as re-order quantities, re-order levels and lead-times and costs). Either the existing material control system can be used in WBS or a system which is already configured for WBS may be used.

If the existing material control system is used and WBS is not configured for it, then there is some element of software development required. If a material control system for which WBS is already configured is used, then the data will have to be transferred and processed from the existing system to the one to be used for the WBS model. There is thus an element of trade-off. If the existing system is used, a faithful replication of current practice will be modelled, this will however incur software development activity and all the uncertainties that are associated with such activity. Alternatively, if a system for which WBS is already configured is used, only data will have to be converted and transferred. Such data can usually be obtained by the use of an SQL (Standard Query Language) programme. This data can then be processed by the use of database software such as DBASE IV and Foxpro. However, the WBS system will not be an exact replica of existing practices. On the other hand, given that most 'top down' material control systems use similar algorithms, this may not be a problem. One other issue to consider is that it is likely that only a subset of the parts and products manufactured will be used in the analysis. Therefore, the existing system data will have to be amended.

b) A factory model must be built. In principle any simulation package can be used for this purpose, as long as it is flexible. In practice it is likely that a data driven manufacturing based simulator would be most appropriate. In this phase a deterministic dynamic model will be built. The key data utilised will include routing files with set-up times and run times, workstation data, operator data (numbers by trade group and trade group efficiency), shift patterns and material records.

c) The accounting system of the business under investigation must be included in the WBS model. A conscious difference is drawn between the accounting system and the cost system. Again either the actual system may be used or a system for which WBS is already configured may be used. The same trade-offs as detailed for the material control system apply. However, it is likely that in the case of the accounting system higher levels of abstraction will be possible without jeopardizing the validity of the WBS system. The key elements of the balance sheet will have to be established (assets, shareholders funds etc.), nominal accounts set-up, customer accounts set-up and supplier accounts established. Enough detail to enable profit and loss accounts and balance sheets to be calculated is required.

The WBS model that is built then needs to be verified and validated. Verification is concerned with establishing that the programmes are correct and with checking for clerical errors. Validation is concerned with the degree of fit between the 'real world' and the model. Validity can be established at a number of levels (Hermann, 1967, Love, 1980). The WBS model could be subjected to a 'Face Validity' assessment, where the validity is established by subjective opinion regarding the initial view on the model's realism. 'Variable Parameter Validity' can be established by the use of sensitivity analysis. Such a test ascertains whether the effect of a change in model parameters is similar to the effect of such changes in the modelled system. 'Event Validity' compares the 'predictions' of the model with the history of the modelled system. Finally, 'Hypothesis Validity' may be determined by the examination of connections between system elements with a view to establishing whether the model reproduces the relationship. The approach to validation detailed above is a combination of what Pidd (1992) terms 'black box' and 'white box' validation.

Step 1.10 : Benchmarking - Benchmarking is a major project in its own right and should be carried by the business as whole to establish where it stands in relation to its key competitors. However, in terms of the design of cellular manufacturing systems, it may be useful to benchmark at the operational level.

Step 1.11 : Gap Analysis - This step brings together the analysis of the current situation and the required performance to identify shortcomings in operational and business performance. The gap analysis should also identify shortcomings in the operational processes that are utilised. A cause and effect analysis can be used to help identify the causes of any unsatisfactory performance. Required capabilities should also be established in this step.

Step 1.12 : Problem Definition and Objective Setting - This step integrates the phase and specifies what the main problems of the business are and gives some view on the causes of the problem. Desired performance criteria in terms of operational metrics and business metrics are established. Clearly, 'top down' business policy will determine, to a large extent, the requirements of business metrics. For example, as given in Chapter 6, the Lucas corporate head office has a clear view on what business level performance is acceptable.

7.5 Phase 2 : System Boundary Definition

This phase of the methodology is concerned with establishing the manufacturing envelope that is appropriate to the needs of the company. It is essentially a question of 'process choice' (Hill, 1993). The company is considering the fundamental issues of:

- The boundaries that it should place around its activities.
- How it should construct its relationships with other firms, including suppliers and customers.
- Under what circumstances the business changes its boundaries and the effect that these changes have on the business' competitive position.

An understanding of the strategic importance of manufacturing processes is established. An analysis process then determines those parts that 'must be made', those that 'should be bought' and those that 'might be made or bought'. Suppliers are identified and a static evaluation of internal and external costs undertaken. This evaluation results in a recommendation that is modelled and evaluated by WBS.

There are 7 steps in this phase of the methodology. These steps are detailed below and Figure 7.6 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 2.1 : Establish Strategic Processes and Capabilities - Utilising the data generated in Phase 1, it is necessary to establish which processes are of strategic importance to the business. As a consequence of their strategic importance they are processes that should be retained 'in-house'. Examples of such processes may be those that are crucial to satisfying customer quality requirements, the only processes capable of manufacturing key proprietary parts or processes that nobody else possesses. Limits on potential capital spend over a 5 - 10 year timeframe should be established. Such limits may be estimated from an understanding of what level of ROCE is required and how the elements involved in this calculation (see Chapter 6) may change. This step determines what manufacturing processes the business 'must do' and what manufacturing support it 'must have'.

Step 2.2 : Strategic Make v Buy Analysis - This step is concerned with establishing which parts families 'must be made', which 'should be bought' and which might be made or bought. This activity should not be treated as a 'C' item off-load. Such an exercise does not address the issues of process technology, order winning criteria and quality levels. A machine-part matrix can be used to ascertain those part families that are to be retained in-house as a consequence of using strategic processes.

Step 2.3 : Supplier Search and Assessment - It is not necessary at this stage to get a detailed picture of all possible suppliers for a parts family. It is however necessary to ensure that a representative sample of suppliers are found and assessed. This ensures

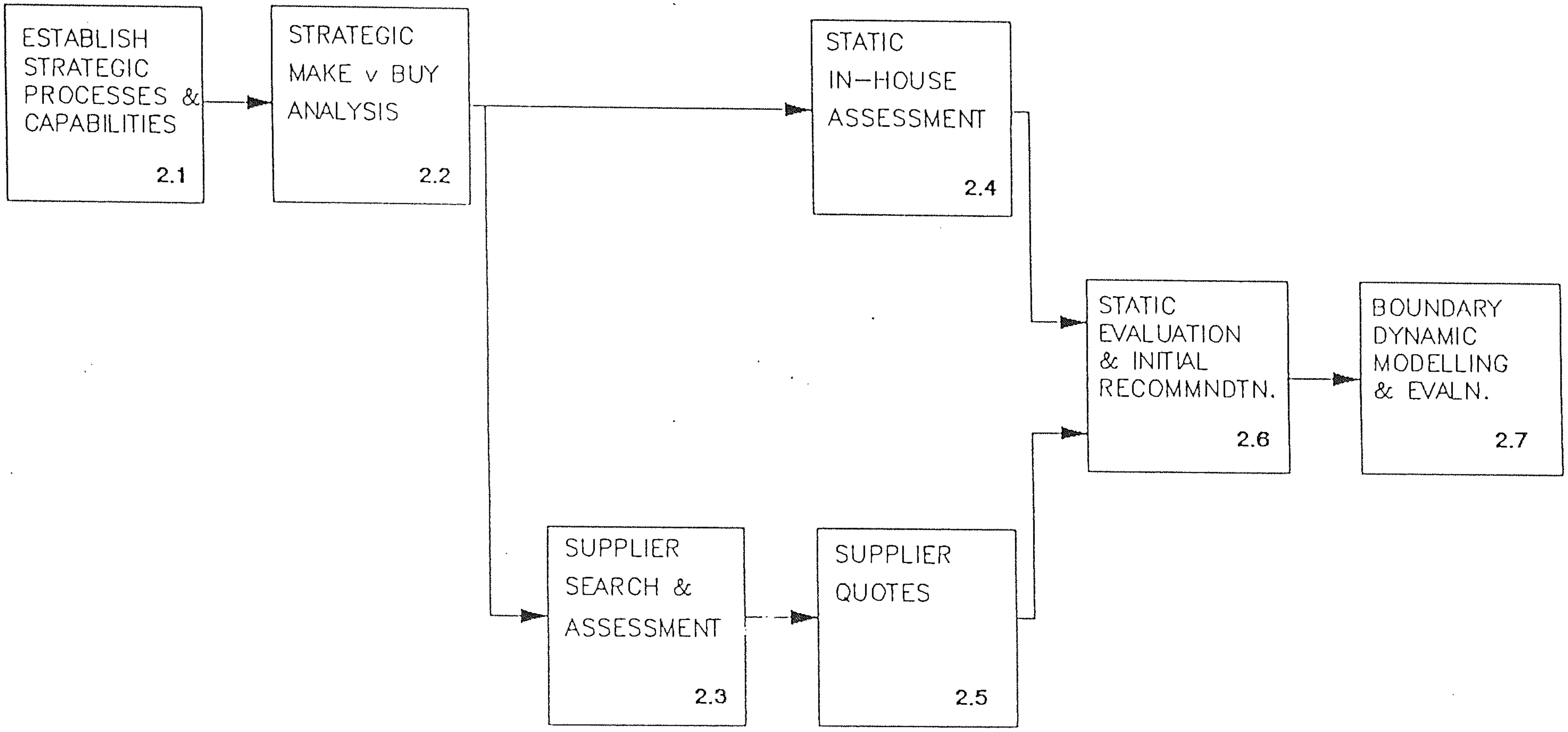


Figure 7.6 : System Boundary Definition

that scenarios (families to be made in or bought out) generated for evaluation are feasible in practice. Consideration of a supplier assessment system should be given in this step. The assessment system should be tailored to the needs of parts families.

Step 2.4 : Static In-house Assessment - This step is concerned with establishing the in-house cost of manufacturing a parts family. An internal cost model should be established. This requires significantly more analysis than merely adding up the costs given on a cost system. The costs on a cost system include elements of overhead that are either semi-variable or fixed. In other words, if a parts family is changed from 'made-in' to 'bought-out', the actual cost reduction may be substantially less than the sum of the costs shown on the costing system. Careful evaluation is required to establish break points at which cost may be significantly reduced. For example, space may be freed up for use by other businesses if out-sourcing is substantial enough. Such a change may represent a 'real' reduction in fixed overheads. This phenomena is one key reason why dynamic analysis is required.

Step 2.5 : Supplier Quotes - A number of supplier quotes will need to be obtained to allow a comparison between the 'status quo' and any alternatives considered to be made. Typically, quotes should be focussed on whole product families.

Step 2.6 : Static Evaluation and Initial Recommendation - A static evaluation of the made in and bought out costs is made in this step. A matrix of value added v cost ratio (in-house cost / bought out cost) may be drawn up. A number of scenarios should be generated and the relative advantage of sourcing different families outside of the business made. A small number of scenarios should be recommended for more detailed dynamic assessment.

Step 2.7 Boundary Dynamic Modelling and Evaluation - The 'Boundary Model' that is developed in this step can be used to evaluate the likely operational and business effect of implementing proposed changes in the current manufacturing envelope of a manufacturing operation. In a similar fashion to the As-Is model developed in phase 1, the material control system, factory model and accounting system will be of prime consideration in the design of cellular manufacturing systems. The boundary model can be developed by modifying the As-Is model built in Phase 1. A number of different alternative models (representing different scenarios) can be generated from the original As-Is model and the outcome on operational and business metrics established. The following changes to the As-Is model may need to be made:

a) The material control system will have to have the bill of material structures altered to ensure that purchase orders are produced for items that are designated as bought out items rather than made in. For purchase orders to be produced rather than works orders an item must be at the last level in a structure. Stock records will have to be altered to reflect the new status of parts, lead-times changed and re-order quantities and re-order levels re-assessed for items that are changed from 'made-in' to 'bought-out'. New buying prices will also have to be inserted. Finally, 'made-in' lead-times may have to be altered.

b) The factory model (which is still deterministic in this phase) will need to be adjusted. The number of machine tools may have to be reduced, the number of operators reduced, routings changed and the level of indirect support adjusted as appropriate.

c) The asset base on the accounting system will have to be adjusted (either through a write off or a sale at book value), changes made to operating costs and new supplier accounts and nominal accounts created as appropriate.

If any assumptions have been made that are shown to effect the operational and business metrics, these should be documented at this stage. Typical assumptions will include the amount of labour to be utilised, prices to be paid and assets to be released. These will then become goals for the implementation process.

7.6 Phase 3 : System Concept Definition

The previous phase essentially determined the in-house manufacturing envelope. This phase is concerned with establishing an overall concept manufacturing design to become effective within that manufacturing envelope. This phase includes the process of cell formation, control systems selection, concept organisation design as well as WBS modelling.

There are 11 steps in this phase of the methodology. These steps are detailed below and Figure 7.7 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 3.1 : Inhouse Manufacturing Segmentation - This process is akin to the process of product unit definition in the Lucas MSE approach. However, the focus is not purely 'vertically' orientated. The process requires the consideration of business objectives and the available opportunities to fulfill them cost-effectively, given particular customer demand patterns. Consideration should be given to the key success factors for manufacturing, demand characteristics and opportunities to change cost structures. All of this data is generated from previous phases of the methodology. For each manufacturing segment defined a mission, technology envelope, appropriate organisation and operational performance metrics should be established. Different operational performance metrics may be appropriate in different

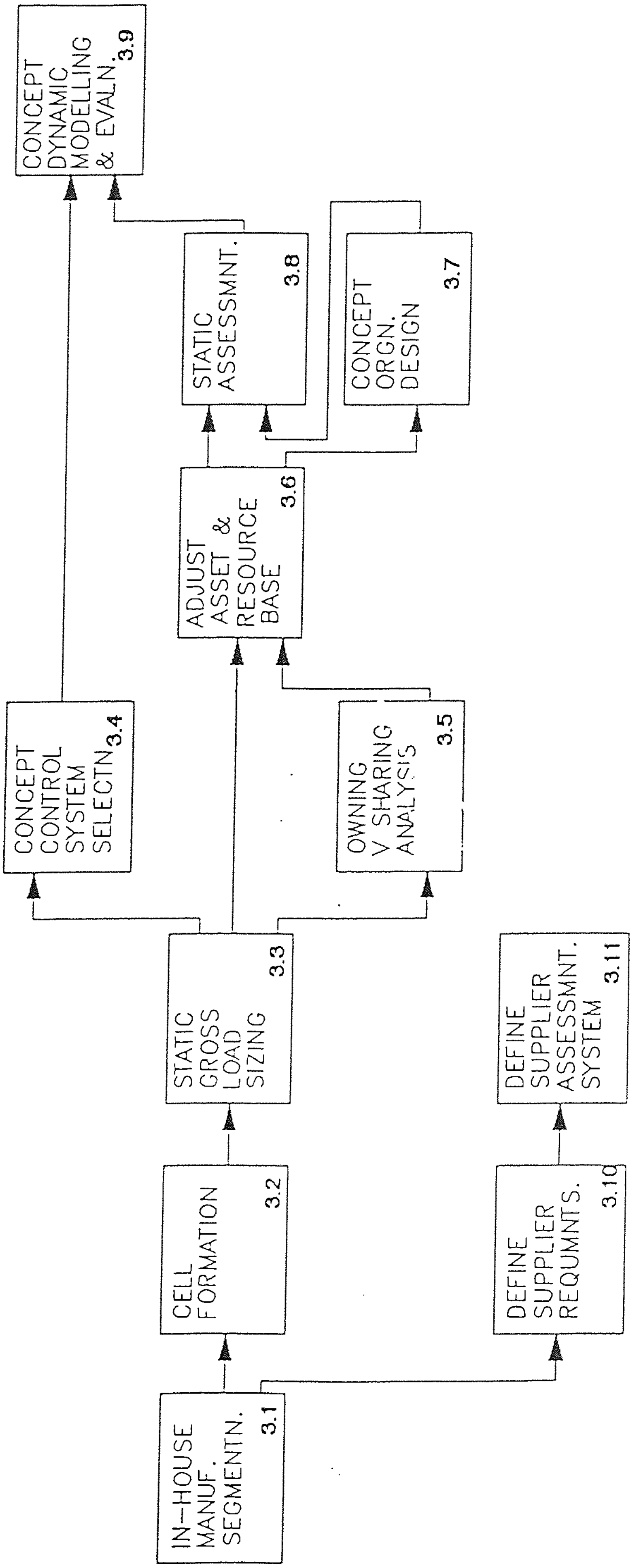


Figure 7.7 : System Concept Design

manufacturing segments to reflect the mission of the segment. Clear thought should also be given to the role of any residual manufacturing facility.

Step 3.2 : Cell Formation - The cell formation process should be undertaken in the context of the manufacturing segmentation results. There is clearly a particularly strong iterative loop between these two stages. Particular algorithms and techniques can be used appropriately at this stage. The cell formation process should generate options from both a 'top down' strategic view and a 'bottom up' manufacturing characteristics view. Consideration should be given to the effective use of inter-cell moves to improve manufacturing effectiveness.

Step 3.3 : Static Gross Load Sizing - A static model of the different manufacturing architectures proposed should be undertaken. The objective of this step is to understand the size of each building block to establish whether the numbers of people and products are appropriate and meet the requirements of the manufacturing strategy.

Step 3.4 : Concept Control System Selection - Given the manufacturing segmentation process and the runners, repeaters and strangers analysis undertaken in Phase 1 it should be possible to select appropriate control systems, at a top level for each manufacturing segment. For example, a manufacturing segment based on runners may be able to utilise 'pull' type production control techniques as there is some likelihood of a levelled load.

Step 3.5 : 'Owning v Sharing' Analysis - Static consideration should be given to which resources are to be shared between manufacturing building blocks (such as cells and product units) and which resources are to be owned by particular manufacturing building blocks. The logic for the decisions made should be explicit. The assumption of 'complete ownership' should be avoided unless it is possible that dynamic evaluation may indicate some advantage to this arrangement. Again, the judicious use of inter-cell moves should be considered as an aid to improving the potential of the alternative cellular manufacturing systems designs.

Step 3.6 : Adjust Asset and Resource Base - When the 'owning v sharing' analysis has ben completed a view may be determined as to how existing resources may be allocated, what new system resources are required and what existing resources will no longer be required.

Step 3.7 : Concept Organisation Design - Given the overall physical manufacturing structure it is possible, at this stage, to postulate a likely organisational structure and ascertain the changes required in comparison with current working practice. Consideration should also be given to the overall concept of payment systems at this stage.

Step 3.8 : Static Assessment - This analysis should generate plant and operator requirements for each product unit, module and cell of the alternative concept designs to be considered. Such analysis can be undertaken on a spreadsheet. The objective is to provide the data to enable the WBS boundary to be adjusted as appropriate.

Step 3.9 : Concept Dynamic Modelling and Evaluation - The resulting manufacturing concept design alternatives may be dynamically evaluated by WBS. The main changes from the boundary model established in Phase 2 will be in the factory model.

a) There are no changes to the control system model at this stage. However, depending on the flexibility of the manufacturing simulator used it may be possible to assign shop-floor control system characteristics to each different material record.

b) The following changes will have to be made in the factory model. Routings will have to be changed to reflect the manufacturing architecture. The number of operators and their allocation will have to be altered in line with the gross load assessment. In addition, the number of workstations, the allocation of workstations to workcentres and the shopfloor control system assigned to materials will have to be altered. The effect on changeover reductions may also need to be examined in this step.

c) The accounting system will have to be changed to reflect the new structure of the proposed manufacturing systems. For example, the asset base will have to be adjusted, nominal accounts assigned to each cell and the level of indirect activity adjusted.

The operational improvements required to achieve the business performance predicted must be explicitly recorded at this stage.

Step 3.10 : Define Supplier Requirements - Having undertaken a 'first pass' analysis to test the feasibility of sourcing families of parts outside of the internal manufacturing system, it is necessary to define what is required of potential suppliers. This should include detail such as quality systems, lead-times and logistic chain management requirements.

Step 3.11 : Define Supplier Assessment System - Again, following the 'first pass' analysis undertaken in Phase 2 and the further detail established in Step 3.10, it should be possible to define a detailed supplier assessment system for each parts family to be outsourced.

7.7 Phase 4 : System Configuration

This phase of the methodology is concerned with firming up on the underlying ideas of the concept design. It forms a 'bridge' between the concept design and the detail design. It is similar in nature to what Pahl and Beitz (1988) term 'Embodiment Design' in the engineering design process. The task is to clarify and confirm design issues prior to detail design.

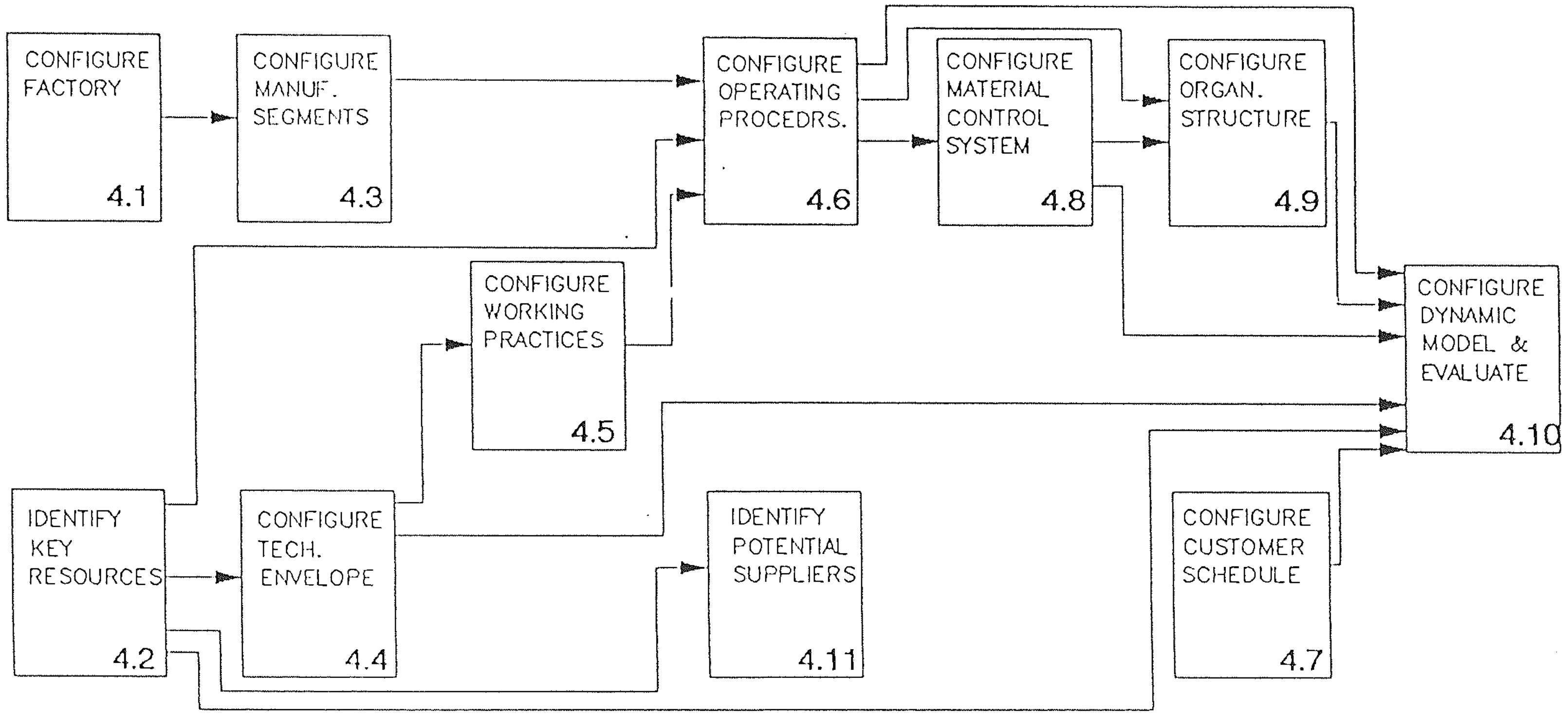
There are 11 steps in this phase of the methodology. These steps are detailed below and Figure 7.8 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 4.1 : Configure Factory - The overall factory must configured. This involves determining the geographical position of each product unit. The space required can be calculated by determining the approximate resource requirements and allowing a percentage of space for gangways and appropriate administrative activities.

Step 4.2 : Identification of Key Resources - The dynamic analysis carried out in Phase 3 of the methodology should allow the identification of key resources. Stochastic detail should then be collected for these resources to allow for a more realistic dynamic model to be built.

Step 4.3 : Configure Manufacturing Segments - Each product unit or manufacturing segment should be configured. This involves positioning each module (if required) and positioning each cell. The 'first pass' space envelope required by each module and cell can be determined in the same way as Step 4.1. Clearly, best practice layout techniques such as 'from-to' analysis should be used in this step.

Figure 7.8 System Configuration



Step 4.4 : Configure Technology Envelope - Consideration should be given as to whether the use of alternative manufacturing technology is required. It may be that less capital intensive equipment is required. The essence of this step is to determine the Appropriate Manufacturing Technology required not the Advanced Manufacturing Technology thought to be required.

Step 4.5 : Configure Working Practices - At this stage in the design process, it is possible to take a view on work practices and configure shift patterns and multi-machine manning policies.

Step 4.6 : Configure Operating Procedures - Given the 'first pass' layout, manning requirements, machine requirements and control system concept and including the likely working practices, it will be possible to determine the key operating procedures in each manufacturing segment.

Step 4.7 : Configure Customer Schedule - A detailed customer schedule is configured in this step. Rather than an average schedule, variation in terms of quantity and due-date should be introduced to better test the dynamic response of the manufacturing system.

Step 4.8 : Configure Material Control System - The 'top down' material control system policy parameters can be re-assessed and appropriate changes made. The detail of these changes is given in Step 4.10. In addition, stock locations and nominal stocks can be determined. If a 'kanban-type' system is to be used, loop locations and the approximate number of kanbans needed can be determined. This is in line with the approach detailed by Lewis & Love (1993c). If a Period Batch Control system is to be used, then the period length should be determined in this step.

Step 4.9 : Configure Organisational Structure - A view should be taken on the key issues that will be raised by the implementation of the concept organisation design derived in Phase 3. This step is concerned with determining which individuals or groups of individuals will be retained and planning the exit of those who will not be required. Clearly, there is a whole body of human resource management expertise required in this step.

Step 4.10 : Configuration Dynamic Modelling and Evaluation - As with the WBS models developed in previous phases, the detail of the material control system, factory and accounting system will have to be modelled. The following modelling issues will have to be addressed in this phase:

a) Issues such as phantoming, lead-time adjustment, batchsizing and safety stocks in the 'top down' material control system are considered in this phase. The main concern is to 'configure' the material planning system.

b) Appropriate transport devices can be added to the model, stochastic elements added to the run-times and set-times of parts that visit key workcentres. Particular emphasis should be given to transfer batches.

c) The accounts will need to be adjusted to reflect any proposed changes in the asset base and changes in cost.

Step 4.11 : Identify Potential Suppliers - In this step a number of suppliers who potentially meet the requirements determined in Step 3.10 should be identified and short-listed.

The activities undertaken in this phase of the methodology help to clarify and confirm the direction of the design process. This will allow the detail design phase to proceed without great risk.

7.8 Phase 5 : System Detail Design

This phase of the methodology is concerned with finalising the detail of the proposed cellular manufacturing system. There are 10 steps in this phase of the methodology. These steps are detailed below and Figure 7.9 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 5.1 : Detail Cell Resource Requirements and Layout - The detail of the cell resource requirements is determined in this step. The precise mix of skills, machine functions, and equipment is determined by static analysis. The final layout of each manufacturing cell should also be determined. This should utilise appropriate best practice such as 'U' shaped layouts to minimise space requirements. Whereas the System Configuration Phase started from a 'top down' perspective, the System Detail Design Phase starts from a 'bottom up' perspective, working within the context of the criteria laid down by the System Configuration Phase. Figure 7.10 illustrates this concept.

Step 5.2 : Detail Module Resource Requirements and Layout - Given the detail resource requirements and layout of each cell, the detail design of the module / product unit may be undertaken.

Step 5.3 : Detail Material Control System - This step should focus on placing the final detail on the shop-floor material control systems. For MRP (Material

Figure 7.9 System Detail Design

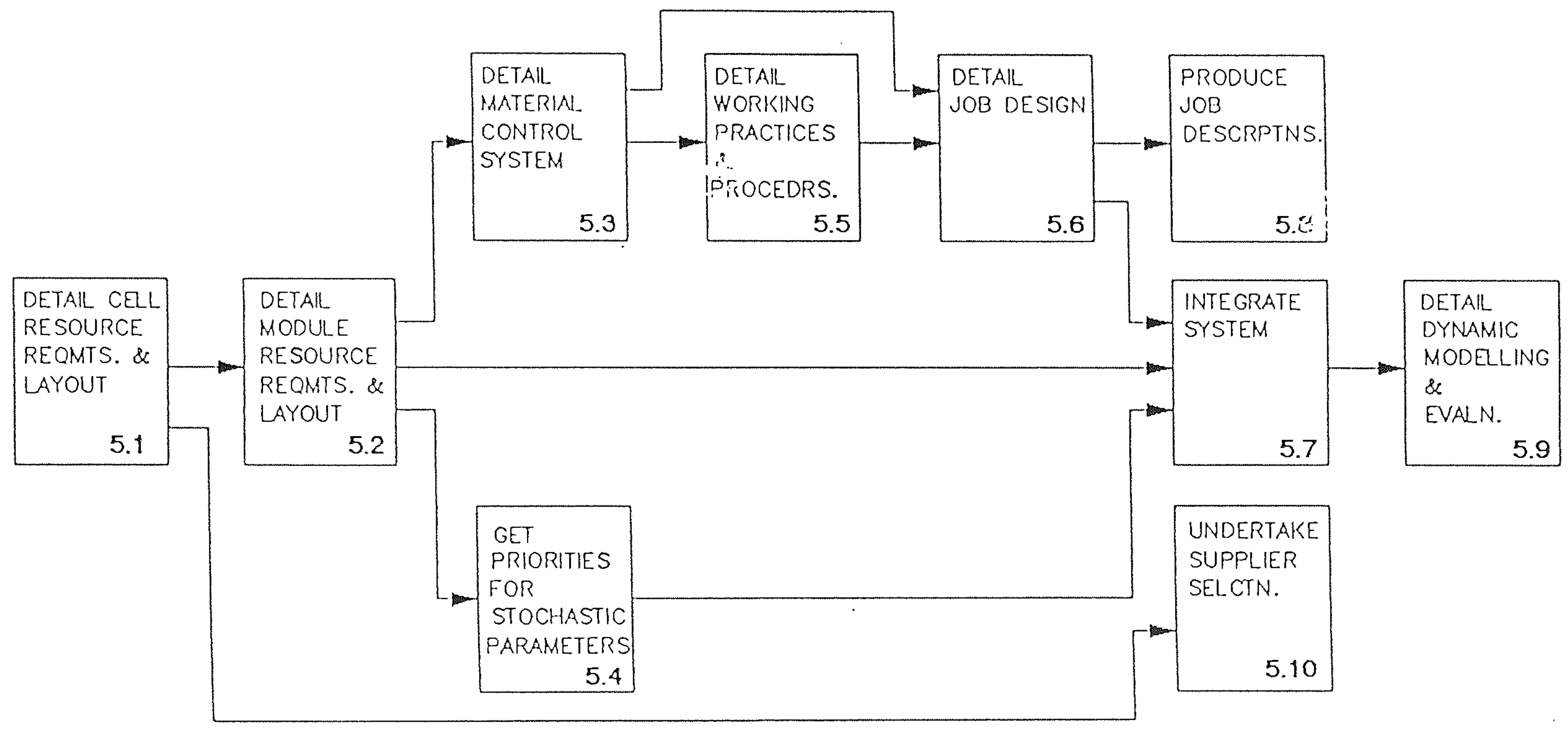
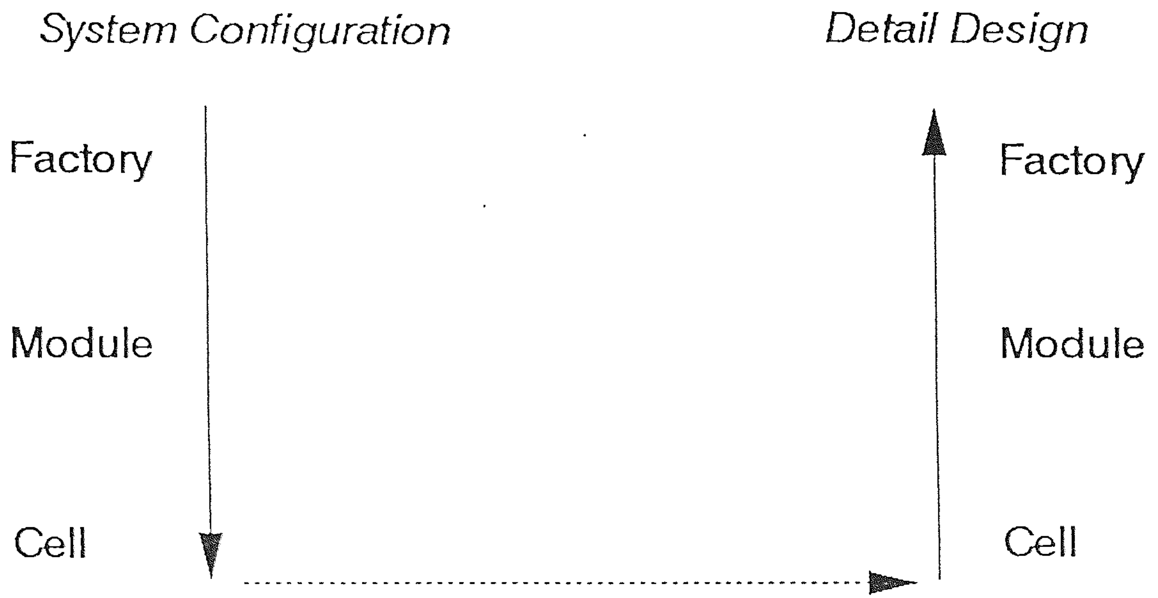


Figure 7.10 System Configuration and Detail Design



Requirements Planning) planned parts, consideration should be given to the use of different scheduling rules and the role of transfer quantities. For materials that are to be 'kanbaned', the use of 'accumulators' (to accumulate kanbans to increase batchsizes for long changeover processes (Lewis & Love, 1993c)) should be evaluated, as should container design and operating procedures. If PBC is to be used, then routings will have to be 'partitioned' (i.e. split into segments that can be completed in a 'period', a length of time determined in the System Configuration Phase) .

Step 5.4 : Detail Priorities for Stochastic Parameters - Consideration should be given to the addition of further stochastic detail. The operational performance of the model should be evaluated to determine where the use of such extra detail might provide useful insights. Extra detail that might be added would include breakdown distributions and scrap distributions.

Step 5.5 : Detail Working Practices & Operating Procedures - This step should be used to finalise how each element of the manufacturing architecture will operate and how the material control system will work. It should be a process of refining previous design decisions.

Step 5.6 : Detail Job Design - Given the finalised resources, working practices and operational procedures, a final detailed list of tasks that need to be undertaken can be drawn up. These tasks can then be grouped into job designs. These job designs can then be further refined into job descriptions (see Step 5.8).

Step 5.7 : System Integration - The previous phases and steps of the methodology have addressed a number of wide ranging issues that have been identified as important in the design of cellular manufacturing systems. This step is concerned with bringing together all these issues and ensuring that there are no 'loose ends'.

Step 5.8 : Generate Job Descriptions - Job designs outlining tasks to be carried out in the re-designed manufacturing system should be converted in to formal job descriptions that allow personnel to be appointed. The job descriptions should be sufficiently flexible to allow the manufacturing system to operate but not unnecessarily demanding (there is no point in building in requirements that are not going to be used).

Step 5.9 : Detail Dynamic Modelling and Evaluation - The final proposed cellular manufacturing system design is dynamically evaluated at this stage. The detail added at this stage will be primarily concerned with the factory model. Breakdowns will be added to workstations (key ones first), scheduling rules at workcentres refined (i.e. not necessarily relying on First In First Out rules), scrap distributions could be added and the work sequence of operators fine tuned. Required operational performance (for example operator and workstation efficiency) should also be finalised in this step.

The capital base in the accounting system may need to be modified to reflect any changes. The use of the accounting system will allow a view on the likely financial performance to be taken. The data from this dynamic modelling can be used for a detailed financial and operational justification of any proposed cellular manufacturing system implementation.

Step 5.10 : Undertake Supplier Selection - The shortlist of suppliers compiled in Phase 4 should be assessed against the supplier assessment schedule and the quotes obtained. The supplier selection process should not be driven solely by price, although it is acknowledged that price is an important consideration. Clearly, the Boundary definition model will have assessed the financial implications of changing the made in and bought out boundary.

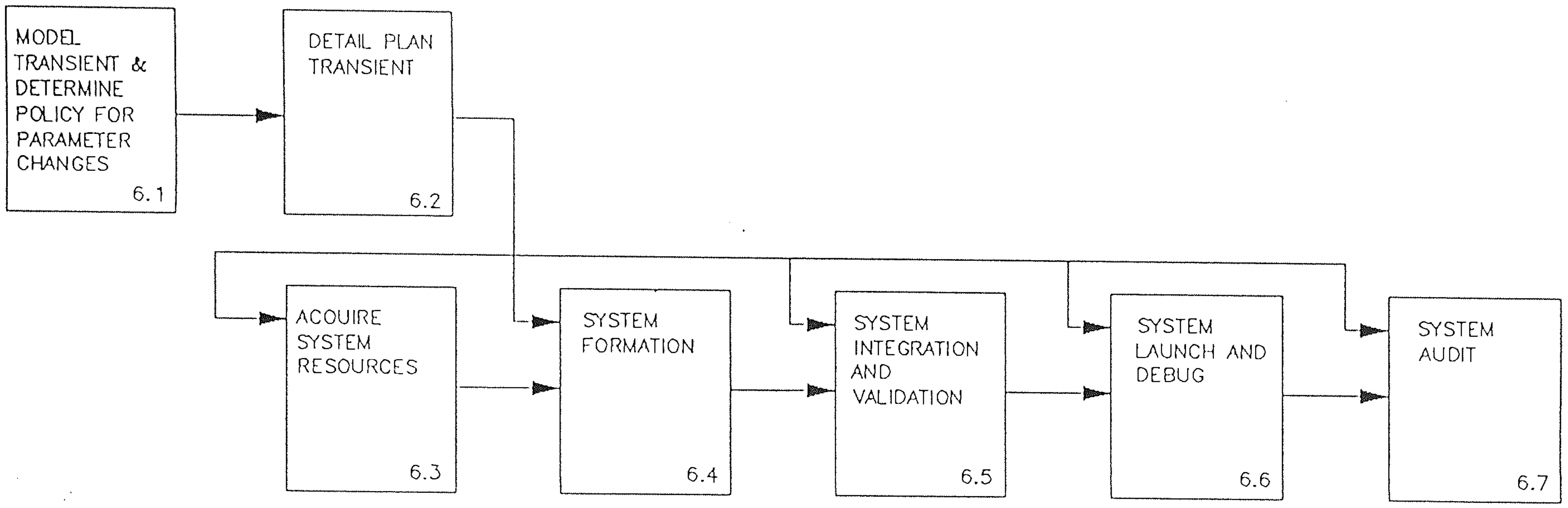
At the end of this phase, the design process for a cellular manufacturing system may be considered as substantially complete. The next issue to consider is the implementation options and process.

7.9 Phase 6 : System Implementation

The final phase of the methodology is Systems Implementation. A number of these steps may legitimately be considered as pre-implementation as they are concerned with implementation planning. An assumption of the use of best practice project management is made in this phase (Bennett and Forrester (1993) detail some of the key considerations of such an approach). There are 7 steps in this phase of the methodology. These steps are detailed below and Figure 7.11 illustrates the broad relationship and information flow between each step (it should be noted that not all iterative loops are shown on the diagram).

Step 6.1 : Model Transient & Determine Policy for Parameter Changes - It has previously been identified that the poor management of the transient has caused considerable problems in the implementation of cellular manufacturing systems. This is true not just of the physical structure of the factory but also for policy changes in materials planning and control systems (such as planned leadtimes, batchsizes and re-order levels). In this step different scenarios for introducing required plant moves and policy changes should be modelled on WBS. Such policy changes will determine the building up and running down of stocks as appropriate. This step should also include prioritisation of the required operational improvements identified in previous phases. In this modelling process, care should be given to minimising cash demands and ensuring that, as far as possible, business performance is maintained.

Figure 7.11 System Implementation



Step 6.2 : Detail Plan the Transient - Given the results from the WBS modelling in the previous step, a detail plan for the implementation process can be generated. This should include the order in which cells are implemented, the rate at which plant is moved from any 'remainder', the implementation of policy changes in any MRP system utilised and the training of personnel. This is in addition to the usual detail associated with a movement of plant (e.g. building services and plant relocation).

Step 6.3 : Acquire System Resources - Any new resources required by the cellular manufacturing system must be acquired. This includes plant, equipment and personnel. This step also includes the selection of internal personnel as appropriate.

Step 6.4 : System Formation - The resources required for the cellular manufacturing system must be brought together so that the system can be integrated and validated. This step is particularly concerned with the physical formation of the manufacturing system and the shopfloor control system.

Step 6.5 : System Integration and Validation - In this step processes should be signed off as being reliable and capable. The system should be primed with the appropriate inventory and procedures should be validated. It is interesting to note that traditional systems engineering puts this step before installation and commissioning. This assumes that the system can be assembled and tested off-site - typical of software projects but not of the implementation of cellular manufacturing systems.

Step 6.6 : System Launch and Debug - Once the elements of the cellular manufacturing system are in place the system (or sub-systems if the implementation is to be phased) then a launch may take place. Inevitably, there will be initial problems with the designed systems, despite the thorough design and implementation process, and it is to be expected that the system will have to be debugged (to a greater or lesser extent).

Step 6.7 : System Audit - During and after the implementation of each element of the cellular manufacturing system, the system should be audited. This audit should include a review of systems, processes, procedures, products and performance (operational and business). Such an audit process allows early action to be taken if implementation is not going 'according to plan'.

Each step of the System Implementation Phase includes the appropriate implementation of the required operational performance improvements identified in the WBS modelling steps. It should be noted that there may be considerable overlap between these steps depending on the phasing of implementation. Although Steps 6.1 and 6.2 may only be undertaken once, others may be executed a number of times. For example, Steps 6.3 to 6.7 may be undertaken for each product unit or cell implemented.

7.10 Summary

This chapter has presented a methodology for the design of cellular manufacturing systems that aims to address the weaknesses, previously identified, of other approaches to the solution of the problem. The methodology is founded on a systems approach and the results of analysis presented in previous chapters.

Chapter 8

An Evaluation of the Proposed Systemic Methodology for the Design of Cellular Manufacturing Systems

8.1 Introduction

The next stage in the development of the systemic methodology was to test its feasibility. It was proposed that, by addressing the problems that have been identified in existing methodologies, the application of the methodology developed in this project will give a 'better' solution. However, it was not clear that certain aspects of the methodology, particularly those concerning WBS, were feasible. This was especially so given that prior to this project, WBS had only been available in demonstrator form. This demonstrator had been used on a model called 'Cell 12' (Bridge, 1990, Love & Barton, 1993). There are 17 machines (of 5 types), a heat treatment plant, and 40 personnel producing 4 different end-items. Each end-item is made up of two components. There are 2 suppliers and 2 customers in the model. To establish the feasibility of the WBS modelling approach, it was necessary to develop a model of a substantial whole business.

Therefore, the purpose of this chapter is to report on the tests undertaken to establish the feasibility of the most contentious elements of the proposed systemic methodology detailed in Chapter 7. This chapter does not propose to demonstrate that the application of the methodology will result in the implementation of a 'better' solution. Clearly, since the proposed methodology addresses key systemic deficiencies (such as the link between business metrics and operational metrics) that are present in current approaches, it is likely that it *will* design a 'better' cellular manufacturing system. This, however, is an area for further work which will be discussed in Chapter 9. The following elements of the methodology have been identified for detailed investigation and experimentation:

System Characterisation and Diagnostic (Phase 1) : It was necessary to demonstrate that a WBS model of a substantial business could be built. The objective of this experiment was to produce a verified and validated 'As-Is' model that can be used to examine business and operational metrics.

System Boundary Definition (Phase 2) : It was necessary in this phase to demonstrate that families of parts that can be 'made-in' or 'bought-out' could be generated. By 'buying-out' a family of parts that is currently 'made-in' the boundary of the business will be changed. Therefore, it was necessary to demonstrate that the material control system, the factory model and the accounting system could be changed to reflect the revised boundary. It was also considered important to be able to investigate the effect of the boundary change on business and operational metrics.

System Concept Definition (Phase 3) : In this phase the ability of the WBS model to be changed to reflect different manufacturing segmentations (and their associated cellular formations) was tested. The effects of any changes in the manufacturing segmentation should be able to be investigated through business and operational metrics.

System Detail Design (Phase 5) : The addition of stochastic data into the factory model needed to be demonstrated. Again the effect of this change on business and operational metrics needed to be examinable.

It was not proposed to investigate the System Configuration (Phase 4) or the System Implementation (Phase 6) phases. This is because, if the above could be demonstrated, then this would show that the activities required in these two phases could also be undertaken. For example, if the material control system could be configured for the 'As-Is' situation, it could be re-configured in the System Configuration phase. Similarly, if the model could be changed in the System Concept Definition phase it could be changed in the implementation phase.

The following research methodology was adopted for these experiments. The experiments were all undertaken with respect to one case-study company (BroomCo). A combination of action research and laboratory based research was undertaken. The action research involved working with BroomCo to determine the parts families for the boundary definition (Phase 2) and the different scenarios of made-in and bought-out. As well as helping to contribute to the development of the methodology, the action research phase helped to resolve some of the practical issues of BroomCo. This was particular true in structuring a strategic 'make v buy' policy and segmenting manufacturing. The laboratory experiments were primarily concerned with the detailed development of a WBS model of BroomCo. The data for these laboratory based experiments was collected during the on-site action research phase.

8.2 The Experimental Situation

8.2.1 The Case-study Company

The experiments were undertaken in, and using the data of, a large U.K. based manufacturer of high-voltage switchgear. For the purposes of confidentiality this company will be referred to as BroomCo. The product range includes indoor switchboards and circuit breakers based on a range of insulating technologies such as oil, air and gas. In addition, outdoor switchgear in the form of overhead line equipment was manufactured. There were approximately 40 end item products in the portfolio. Each of these end items was available in a number of variants. In addition, spares were provided for these products. Demand volumes for end items ranged from 10 to 10,000, with most of the end items falling in the range 100 to 1,000. Selling prices ranged from £15 to over £20,000. The company was split into two sites. One site was responsible for final assembly and test, product design and product support the other site was essentially responsible for the upstream activities of component and fabricated sub-assembly manufacture. Figure 8.1 shows a schematic diagram of the arrangement. The case-study experiments focused on the upstream component manufacturing business, which essentially provided 'kits' of parts to the assembly and test business. The site was treated as a separate business and all the financial data was available (although not easily) for it. The expected sales of the component manufacturing business was £22.4 million. The expected (budgeted) costs of the component part manufacturing operation were £19.4 million. This cost base was split as follows:

Materials	£11.5 million
Direct Labour	£2.3 million
Overheads	£5.7 million

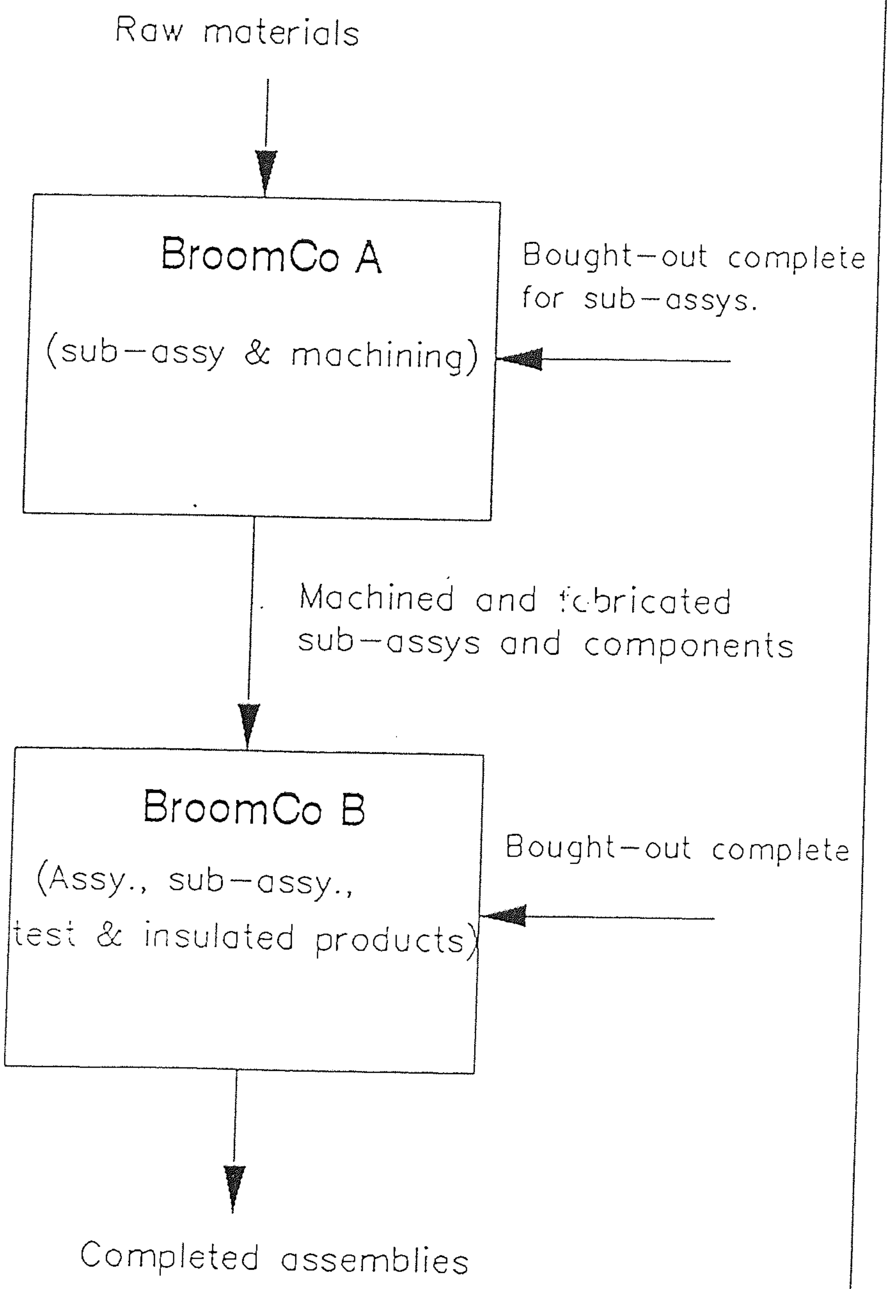
The expected annual net profit in the upstream component part manufacturing operation was therefore in the region of £3 million. The budgeted level of net assets in the business typically lay at around the £9 - £10 million mark.

The business employed approximately 410 people at any one time of whom 210 were classed as indirect labour and staff (e.g. supervision, toolmakers, labourers) and 200 who were classed as direct labour (operators). (Note : Dates have been omitted to preserve commercial confidentiality).

8.2.2 WBS and Model Development

Prior to the commencement of the experiments described in this chapter, WBS had been used for modelling a small cellular manufacturing system rather than a whole business (Love and Barton, 1993). Significantly increasing the size of the model to be executed by WBS would clearly require further software development work to be undertaken. This was achieved by the author and Mr Jeff Barton working in parallel

Figure 8.1: Schematic of BroomCo Organisation



and exchanging ideas and experiences. The authors role was concerned with building the model (setting up the demand generator, material control system, factory model and accounting system). Mr Barton was concerned with utilising WBS in the context of product design and was responsible for the development of the bulk of the software. Once the model had been built further issues were raised during 'runtime'. These were jointly 'debugged' and the model refined. Mr Bartons contribution is clearly acknowledged in the acknowledgements on page 4 of this thesis.

8.3 Experiment 1 : Characterisation

The purpose of this experiment was to demonstrate that a WBS model for a substantial business could be built and reasonably validated. If such a model could be built then the methodology proposed in Chapter 7 would be able to be used in the design of cellular manufacturing systems. A WBS model for the component manufacturing business outlined in Section 8.2 was built.

8.3.1 Building the Characterisation Model

A significant amount of data had to be collected before a model of the whole business could be built. In line with the methodology detailed in Chapter 7 (Step 1.7), a sample of numerically and strategically important products were identified for use in the analysis. These products were selected from product families that were previously defined (Step 1.6). Care was taken to ensure that all product families were represented. This process of sample selection resulted in the use of 11 end items that represented over 60% of turnover (nearer to 80%, if variants of these end items are included) in the model. The demand of these end items was then factored up by 1.66 to represent the total scale of demand. This is illustrated in Table 8.2a. The total annual sales resulting from the use of the demand profile shown in Table 8.2a is

£22.3 million. This compares very well with the budgeted £22.4 million (0.45% difference).

Table 8.2a : End Items and Demands used in the WBS Model

	Factored Demand	Selling Price	Revenue
FCL	3318	£15	£50,556
FTL	38	£1,022	£39,058
RCL	3318	£278	£923,589
RDL	264	£2,3114	£6,099,906
36O	228	£3,795	£863,433
PMO	2584	£500	£1,291,122
VMS	5307	£8,26	£4,384,042
VMT	2461	£1,346	£3,311,074
36S	502	£2,873	£1,443,344
HGT	2539	£1,386	£3,517,960
HVT	382	£1,146	£438,110
		Total Turnover	£22,362,195

The Demand Generator : The product demands given in Table 8.2a were levelled across the year in nominal fortnightly timebuckets. A degree of unpredictability into the placing of demand was introduced by using a stochastic element in the calculation that produced the due dates for sales orders.

The Material Control System : For the sample products, the bills of material (structures and quantities), planned leadtimes, re-order quantities, re-order levels and buying prices (if bought out) were obtained from BroomCo information systems. This data was configured into DBASE III+ files and two programs (one for the material record file and one for the bills of materials) were written to read the data into the UNIPLAN MRP system. The use of programs for this task not only speeded up the task but enhanced the accuracy of the data input. The programs were used to input 2416 stock records and the structures of the 11 end items and their associated sub-assemblies, piece parts and raw material requirements. UNIPLAN was used to produce purchase orders not only for raw materials, but for other items such as machine and process consumables. When the data was resident in UNIPLAN, the system was checked by using the gross requirements to generate works orders and purchase orders.

The Factory Model : The factory model was built in the ATOMS simulator using base data from both BroomCo information systems and data collection activities. This data was manipulated by DBASE III+ to produce files that could be directly input into ATOMS. An operator file, material file, workcentre file, workstation file and routing file were generated. The 200 direct operators were aggregated into 18 types (or trades). In addition, 80 of the indirects were modelled in the factory simulation (for example, process operators, painters, non-destruct testers and stores people). The factory model contained 96 workcentres and 220 workstations (workcentres typically consisting of a number of workstations). The routing file consisted of 7,430 records.

The Accounting System : DBFLEX had to be configured so that accounts data and reports (such as profit & loss accounts and balance sheets) could be produced. The accounts system had the highest level of aggregation of all the elements used in the model. The accounts system used 11 customer accounts, 50 supplier accounts and 92 nominal accounts. All financial transactions were triggered from outside of the accounting system (e.g. by the delivery of goods from a supplier being accompanied by an invoice that was automatically input into the accounting system), with the exception of 13 recurrent payments. These recurrent payments covered regular expenditure such as the uniform business rate, rent, water charges and insurance. Accounts were also set up for depreciation. Reports were also written so that profit and loss accounts and balance sheets could be produced using the nominal accounts that had been placed in the DBFLEX accounting system.

Of the budgeted £5.7 million overheads, approximately £2.8 million was generated without reference to activity within the WBS model. These were in effect treated as fixed costs. The bulk of this £2 million was accounted for by indirect labour (for example, production engineers and buyers).

Once the four main elements of the BroomCo WBS model, detailed above, had been assembled and debugged (in isolation), checks were carried out to ensure the consistency of data between the different elements. The main verification checks that were undertaken concerned the consistency of the data in the factory model and UNIPLAN. For example, each part has a 'kitting list' in ATOMS indicating what material is required before processing can be undertaken. The kitting lists were read in through the automatic model generation routine in ATOMS. However, during the verification of the model it became clear that elements of the kitting lists were missing. It was discovered that ATOMS could only read a 255 character kitting list in automatically. Given that the end items had kitting lists extending to 100's of 15 character sub-assemblies, components and raw materials, many had clearly been missed off. These were input by hand and it was found through the consistency checks, that some data inaccuracies had been introduced which needed to be rectified. Another example of the need for consistency checks was made apparent by the uniqueness of part-numbers. ATOMS can only deal with 15 character part-numbers, whereas some of BroomCo's part-numbers were sometimes longer. Manual attempts were made to make all part-numbers unique at the 15 character level, but again data inaccuracies were introduced. These were identified and rectified through the use of the consistency checking software.

After the individual elements of WBS had been 'debugged' and made consistent, it was possible to pass data between each element using the WBS software. The WBS demonstrator was used as the starting point for building the model of BroomCo. A number of 'up-front' changes were made to the software that was used to run the demonstrator. The above four elements (demand generator, material planning system, factory simulator and accounting system) then simply 'replaced' the equivalent element in the 'Cell 12' model. An iterative loop of running and 'debugging' the BroomCo WBS model was adopted. After each execution the model results were evaluated to verify the model. This process led to a number of changes in both the WBS software and the model elements. For example, changes to the factory model had to made, where the use of transfer batches had to be accurately modelled. All of the above actions led to the development of a verified 'As-Is' WBS model of BroomCo that could be run for a significant length of time so that it could be validated (i.e. it's behaviour compared with the behaviour of the real system).

8.3.2 Running the Characterisation Model

The size of the WBS software itself presented a problem. The only way to run the software was to disable the video graphics. Once this was done, there was enough base memory available to run the model. The model was first tried on a 486 SX (running at 33 MegaHertz) with 8 Megabytes of memory. However, it was found that the model was very slow for two reasons. Firstly, the processor was slow and secondly the large amount of disk access required by UNIPLAN was very limiting. Therefore it was necessary to run the model on a 486 DX2 (running at 66 MegaHertz) with 16 Megabytes of memory (allowing a 5 Megabyte smartdrive and hence reducing disk access time significantly). This realistically, is the minimum specification PC on which the model will run adequately. Two weeks of BroomCo WBS model activity initially took approximately 2 hours of real time. However, this rose to between 4 and 8 hours when the model reached steady state. The empty model requires 6 Megabytes of hard disk space (excluding the software packages) and the steady state model 56 Megabytes.

There were two alternatives for starting the WBS model. The first is to start it empty and to run the simulation to steady state, the other is to start with typical operating conditions. It was decided to start the model empty as all the sub-systems in WBS are interlinked (factory simulator, material planning etc.), meaning that all the sub-systems would have to be consistent with one another. It would be very difficult to maintain such consistency and, if there were consistency errors, the validity of the model would be questionable.

Therefore, once the model was running adequately it was necessary to determine how long to run the model for to establish the steady state conditions. This was done by tracking key business and operational metrics over time. The business metrics tracked were sales, net profit and net assets (it would also be possible to extract and track an expense such as the monthly tooling and consumables spend). The operational metrics tracked were the number of batches in work-in-progress, the number of output batches, hours worked and the queue length at a key work centre.

These **business metrics** were taken from the BroomCo WBS model after **every month** of WBS activity. Figures 8.2b shows an example of the profit and loss account generated and Figure 8.2c shows an example balance sheet. Figure 8.3 shows the monthly sales generated by the model. The sales were extracted from the monthly profit and loss accounts. It can be seen that sales did not start to rise significantly until Period 7 (Month 7 of the simulation). The sales rose and fell over time without there being a clear steady level. Figure 8.4 shows how the net profit moved from a loss of £800,000 in Period 1 to an approximate breakeven position in Month 6. The net profit varied quite considerably over the next thirteen periods. Hence, it was not clear if a steady state position had been reached. Figure 8.5 shows the graph of net assets over time. It appears that net assets reached steady state in Period 12 at a level of approximately £8.8 million. There is however, a slight rise in Periods 18 and 19.

Figure 8.2b Profit & Loss Account for Periods 1-10

SALES		
		247100.00
COST OF SALES		
Purchases	7943673.25	
Opening Stock	0.00	
Less Closing Stock	(9557394.00)	
Labour Costs	2053342.88	439622.13
GROSS PROFIT		(192522.13)
OVERHEADS		
General Admin. Expenses	16750.00	
Travel	7000.00	
Building Repairs	28000.00	
Tooling & Consumables	246927.20	
Depreciation	206220.47	
Bad Debts	0.00	
Insurance	37500.00	
Loan Interest	0.00	
Water	12500.00	
Training	28000.00	
Power, Heating & Lighting	99977.49	
Financial & Legal Expenses	20000.00	
Rent & Rates	156750.00	
Repairs & Maintenance	82058.35	
Safety Expenses	11000.00	
Stores Expenses	26500.00	
Salaries	72554.40	
Telephone	1795.08	
Distribution	203850.00	
		1257382.99
NET PROFIT		(1449905.12)

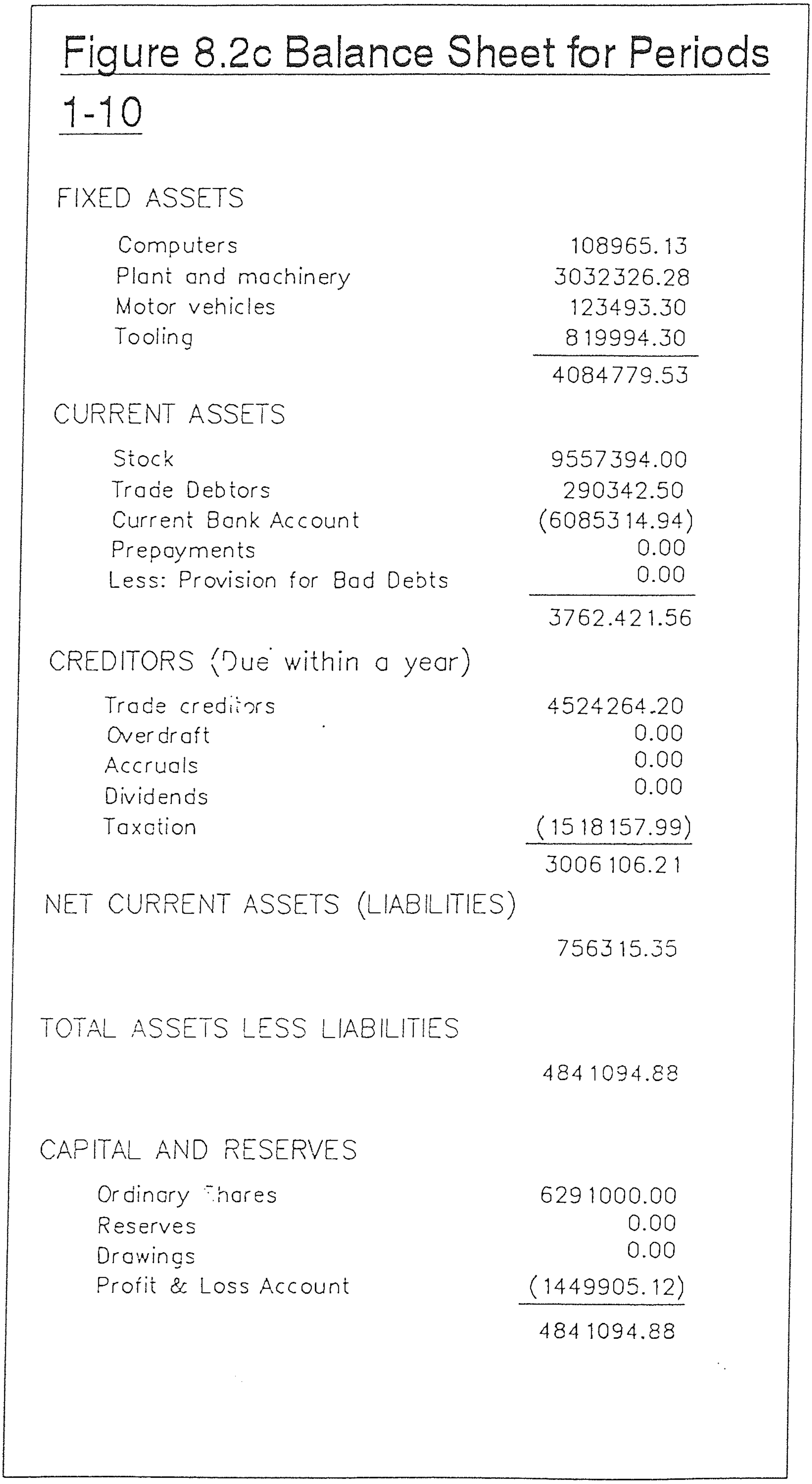


Figure 8.2c Balance Sheet for Periods 1-10

FIXED ASSETS	
Computers	108965.13
Plant and machinery	3032326.28
Motor vehicles	123493.30
Tooling	819994.30
	4084779.53
CURRENT ASSETS	
Stock	9557394.00
Trade Debtors	290342.50
Current Bank Account	(6085314.94)
Prepayments	0.00
Less: Provision for Bad Debts	0.00
	3762.421.56
CREDITORS (Due within a year)	
Trade creditors	4524264.20
Overdraft	0.00
Accruals	0.00
Dividends	0.00
Taxation	(1518157.99)
	3006106.21
NET CURRENT ASSETS (LIABILITIES)	
	756315.35
TOTAL ASSETS LESS LIABILITIES	
	4841094.88
CAPITAL AND RESERVES	
Ordinary Shares	6291000.00
Reserves	0.00
Drawings	0.00
Profit & Loss Account	(1449905.12)
	4841094.88

Figure 8.3 : Characterisation Model (Sales)

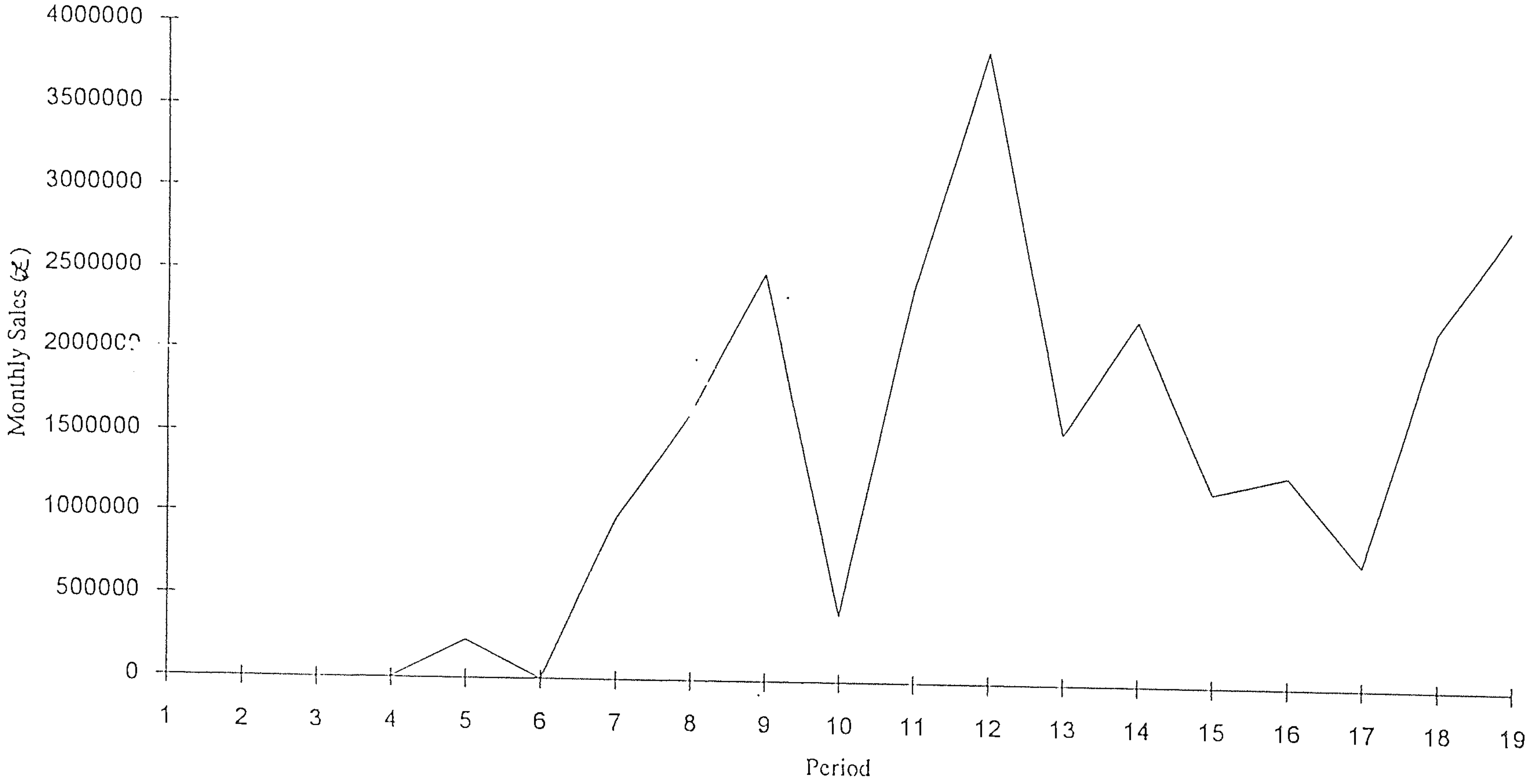


Figure 8.4 : Characterisation Model (Net Profit)

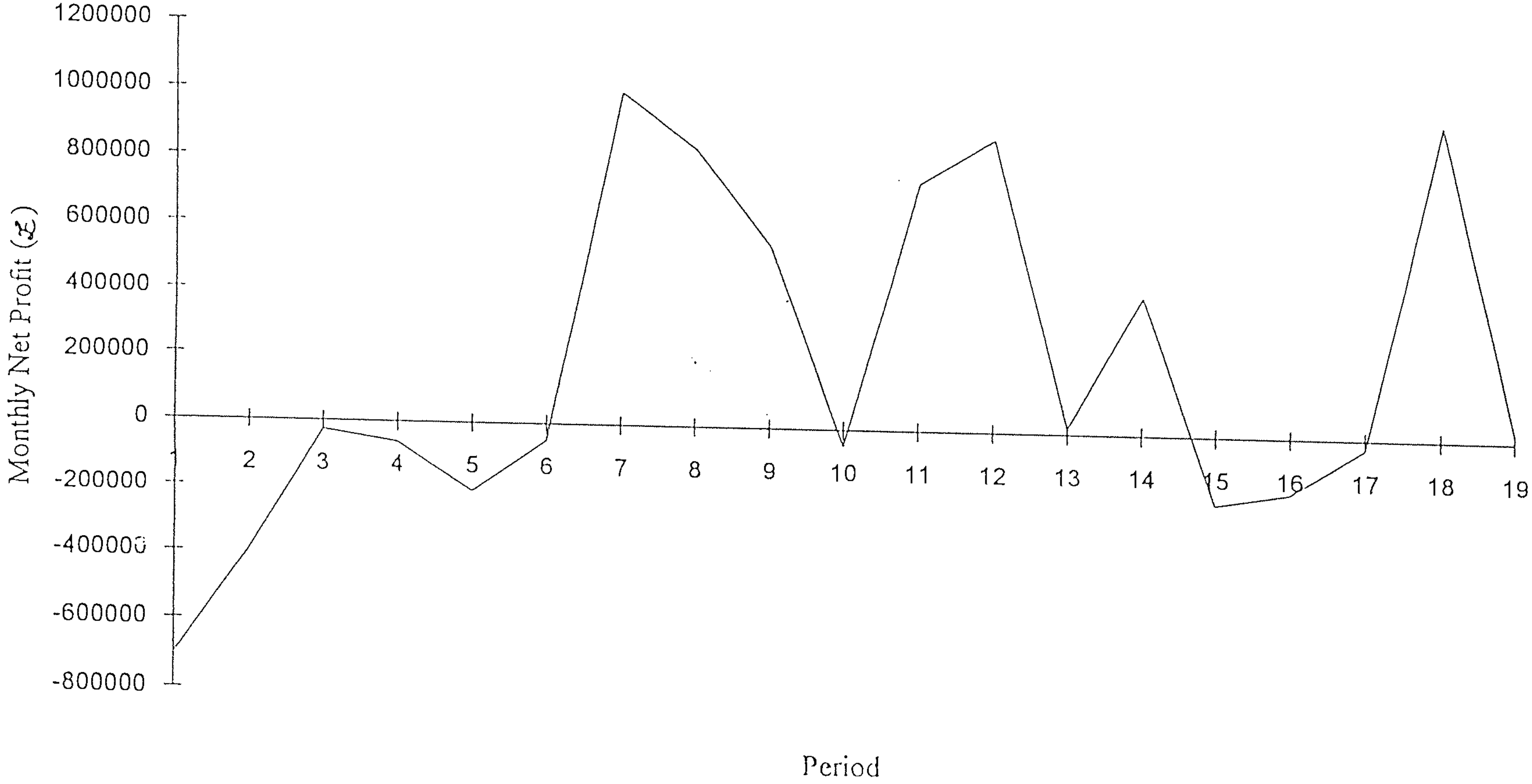
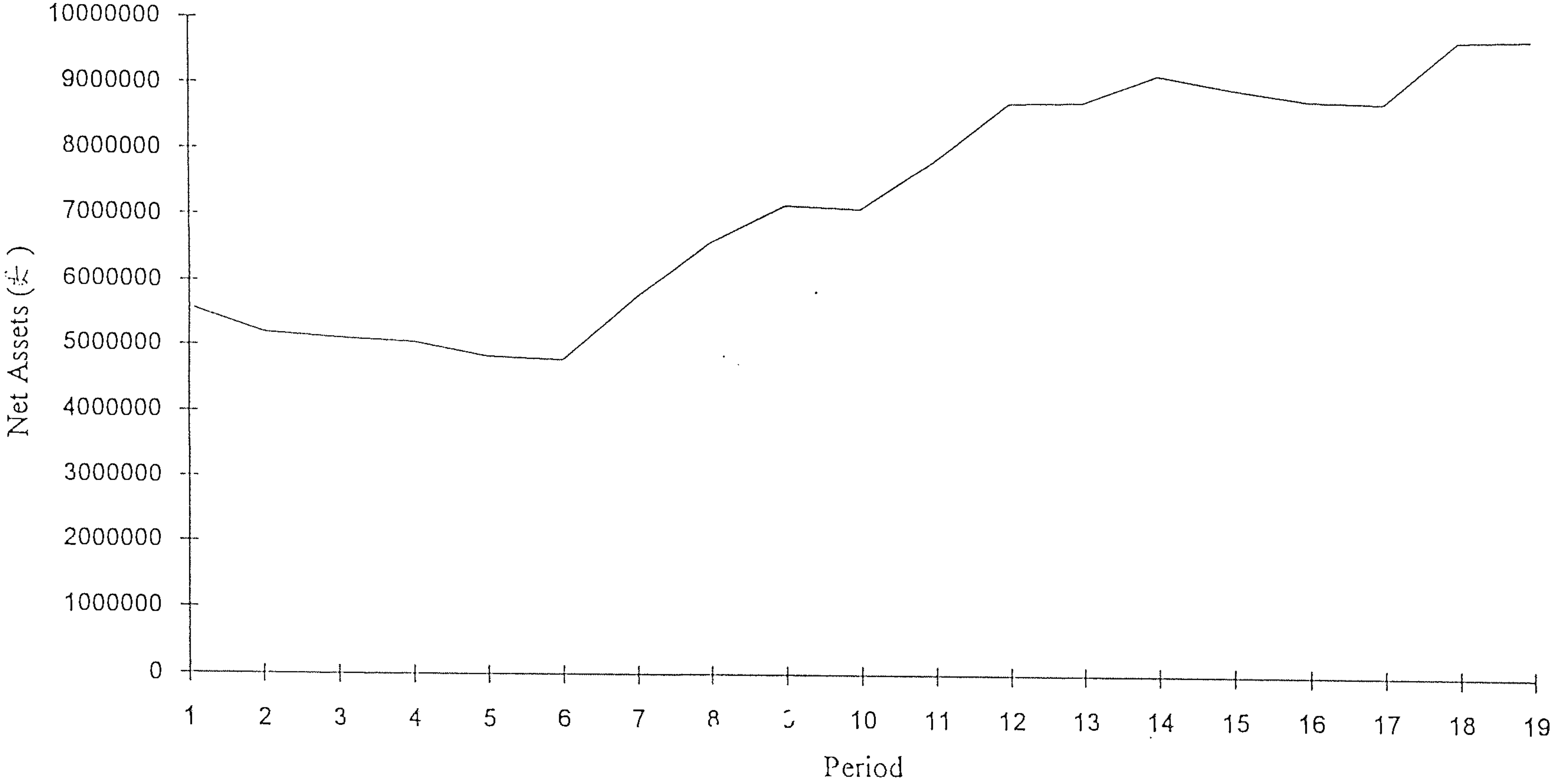


Figure 8.5 : Characterisation Model (Net Assets)



Given the difficulty in trying to determine the point at which the steady state position was reached from the raw data, it was decided to use Welch's procedure (Law & Kelton, 1991) to try and determine the transient period length. Welch's procedure is graphical in nature and relies on the use of a moving average. This moving average is given by:

$$Y_i(w) = \begin{array}{ll} \dfrac{\sum\limits_{s=-w}^{s=w} Y_{i+s}}{2w+1} & \text{if } i = w+1,\ldots, m-w \\ \\ \dfrac{\sum\limits_{s=-(i-1)}^{i-1} Y_{i+s}}{2i-1} & \text{if } i = 1,\ldots, w \end{array}$$

Figure 8.6 shows the application of Welch's procedure to the sales data using values of 2 and 4 for the window 'w'. This procedure smooths the data considerably and it is clear that steady state was reached at either simulation Period 11 or 12. Figure 8.7 shows Welch's procedure applied to net profit, again with the value of 'w' set to values of 2 and 4. From this plot it seems reasonable to propose a steady state position was reached in simulation Period 10 or 11. Finally, Figure 8.8 shows a similar plot for the level of net assets. Period 12 again seemed a reasonable point at which to conclude that steady state had been reached. From the three plots using Welch's procedure it was proposed to use simulation Period 12 as the start of steady state activity.

The **operational metrics** were taken from the BroomCo WBS model after **every week** of simulated activity for batch data and every two weeks for workstation and operator data. There was therefore between two and four times as much data for

Figure 8.6 : Characterisation Model (Sales Smoothed Using Welch's Technique)

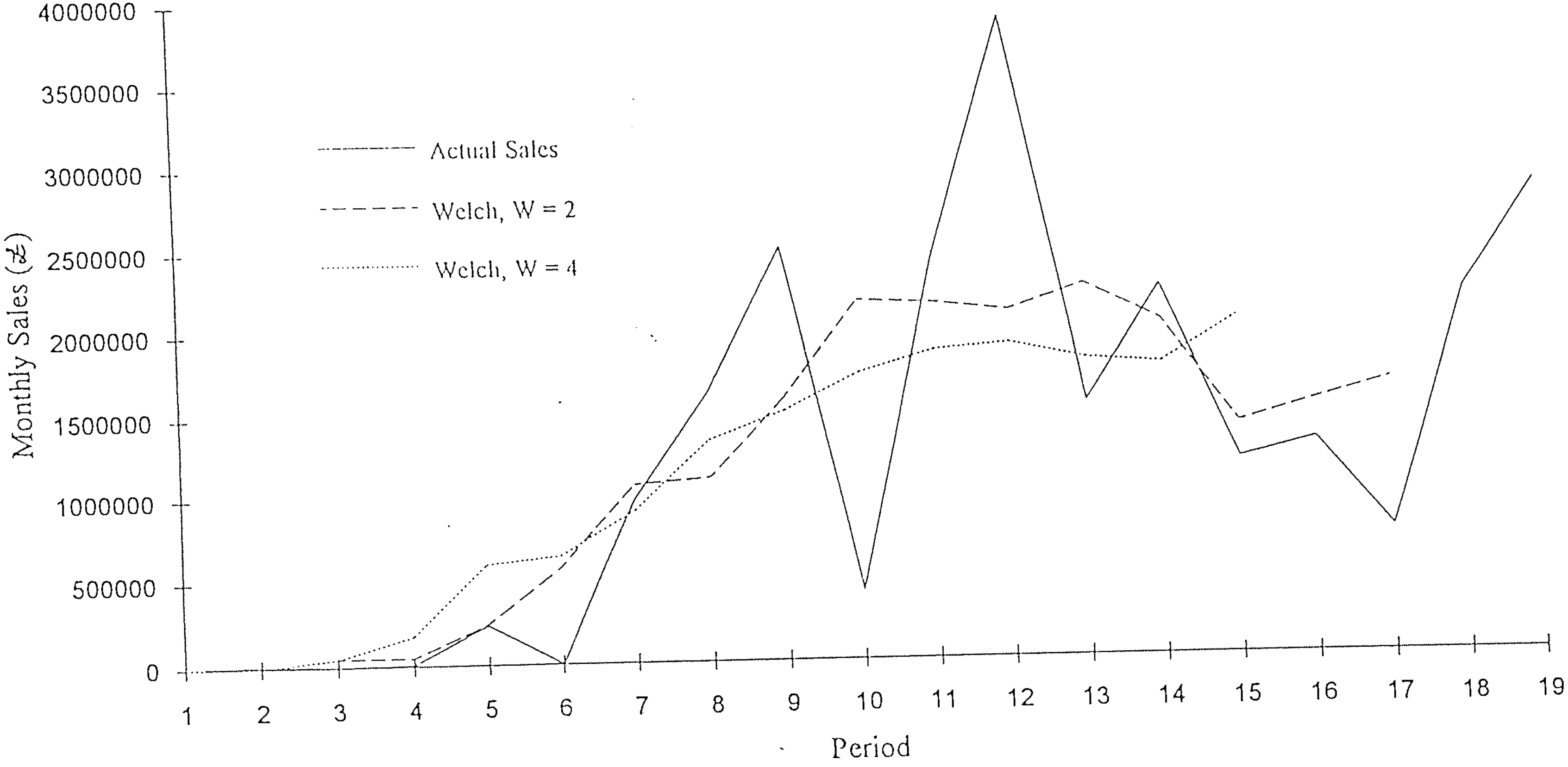


Figure 8.7 : Characterisation Model (Net Profit Smoothed Using Welch's Technique)

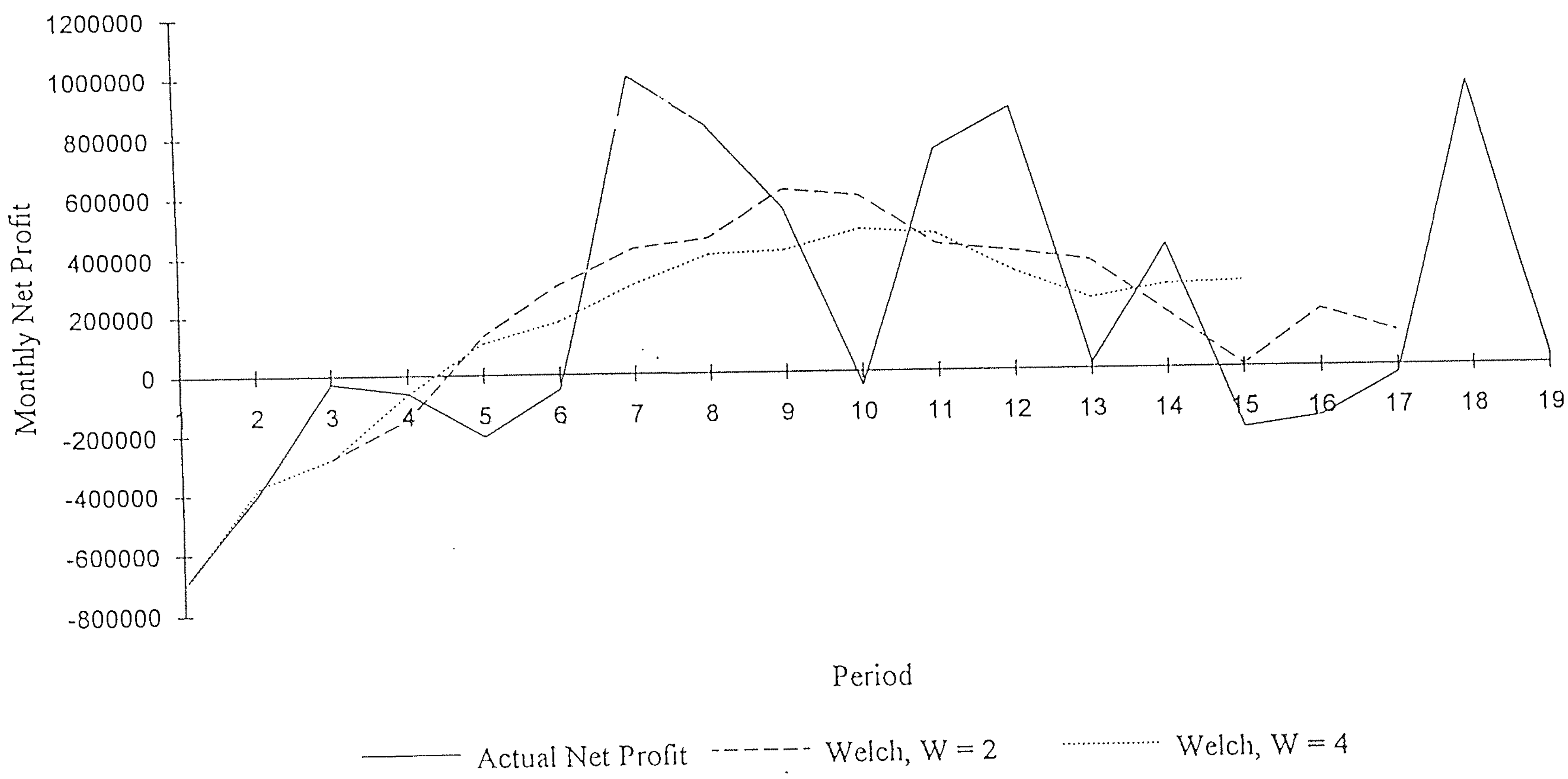
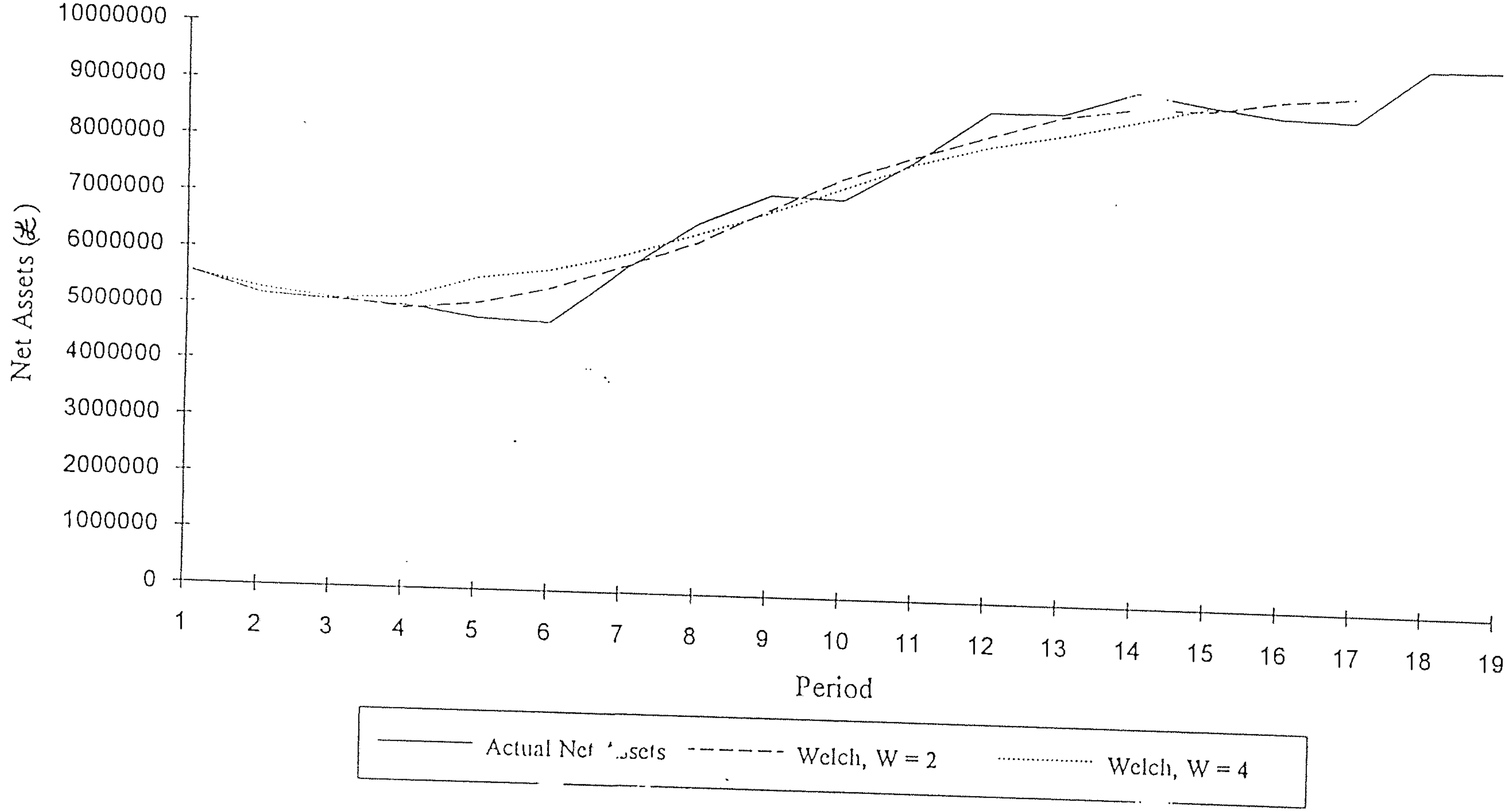


Figure 8.8 : Characterisation Model (Net Assets Smoothed Using Welch's Technique))



operational metrics as there was for business metrics. Figure 8.9 shows the plot of the number of batches live in the system over time. This appears to reach a steady state in period 7 although there is significant variability in the middle of the simulation run. Figure 8.10 indicates the input number of batches, the output number of batches and the difference between the two. The output number of batches remained fairly constant, around the 140 level. Given this fact, the difference between the output and input is primarily influenced by the input, which is a function of the leadtimes and demands in the material planning system. Clearly, there are some major increases in this through the simulation period and towards the end of the simulation run. Figure 8.11 illustrates operator hours worked and this looks as if it reaches a steady state in about period 10. Figure 8.12 shows the queue for one of the key workcentres, welding. This appears to reach a steady state period around period 24, although the variability at the end of the run makes this conclusion unclear. As with the business metrics it is unclear at what point steady state behaviour is reached (although it is clearer than the business metrics, with less variability). Thus, Welch's procedure was used to smooth the number of live batches as shown in Figure 8.13. Using a window of 20, a steady state position appears to be reached after 24 periods of simulation

It is interesting to note that the business metrics take considerably longer to reach steady state than the operational metrics. This is illustrated by Figure 8.14 where there is a 3 to 4 month lag between the business metrics (sales in this case) and the operational metrics (number of batches in this case) reaching steady state (NB: Business metrics were recorded every month and operational metrics every week and therefore Period 1 of the business metrics is the same point in time as Period 4 of the operational metrics). The issue that this raises is whether a different transient period should be used for the operational and business metrics or whether it should be the same. This will be examined in the next section. The transient periods proposed (24 weeks for operational metrics and 52 weeks for business metrics) compare with an

Figure 8.9 : Characterisation Model (Work-in-Progress Batches)

Figure 8.10 : Characterisation Model (Input and Output Batches)

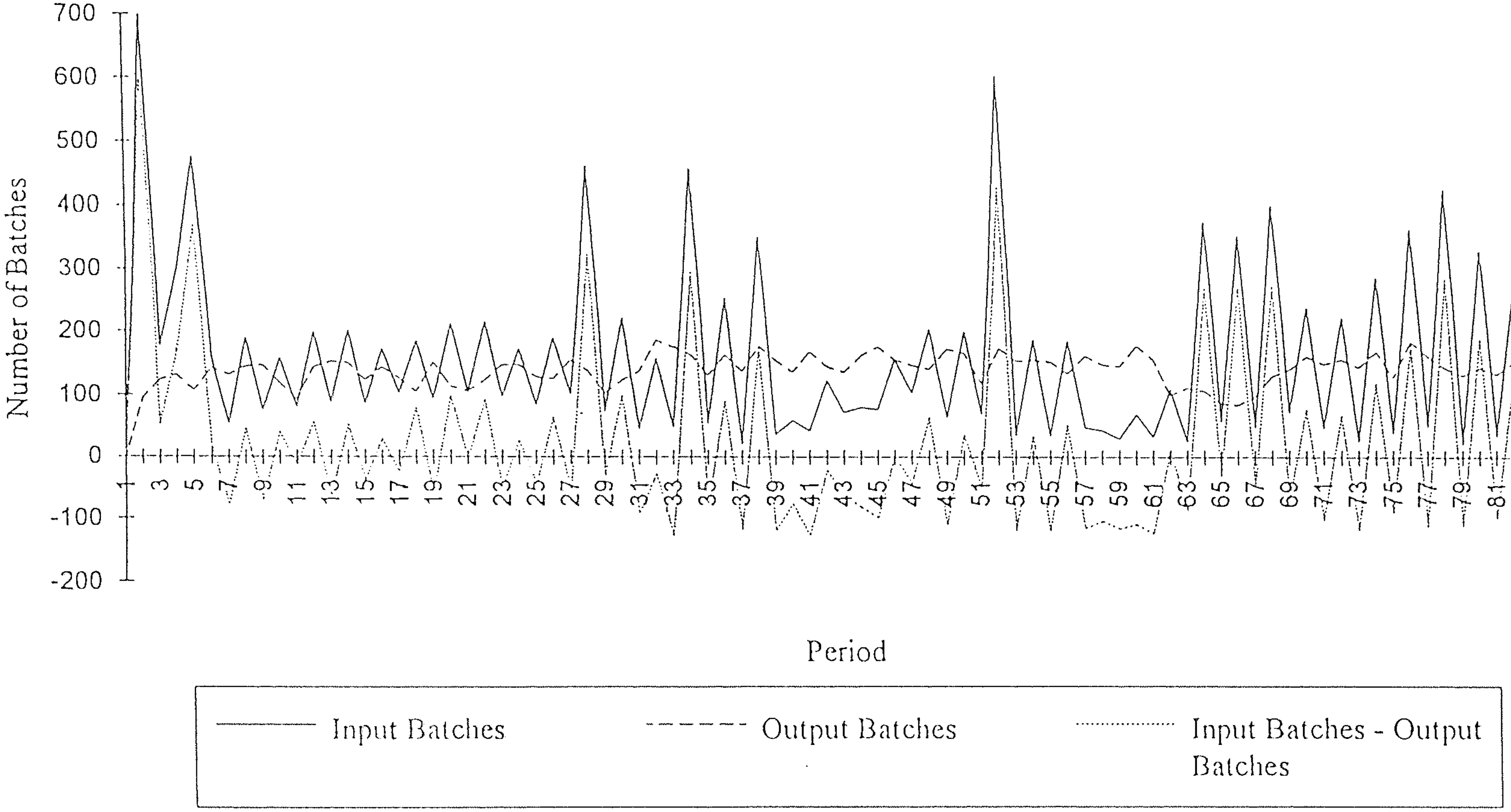


Figure 8.11 : Characterisation Model (Operator Hours)

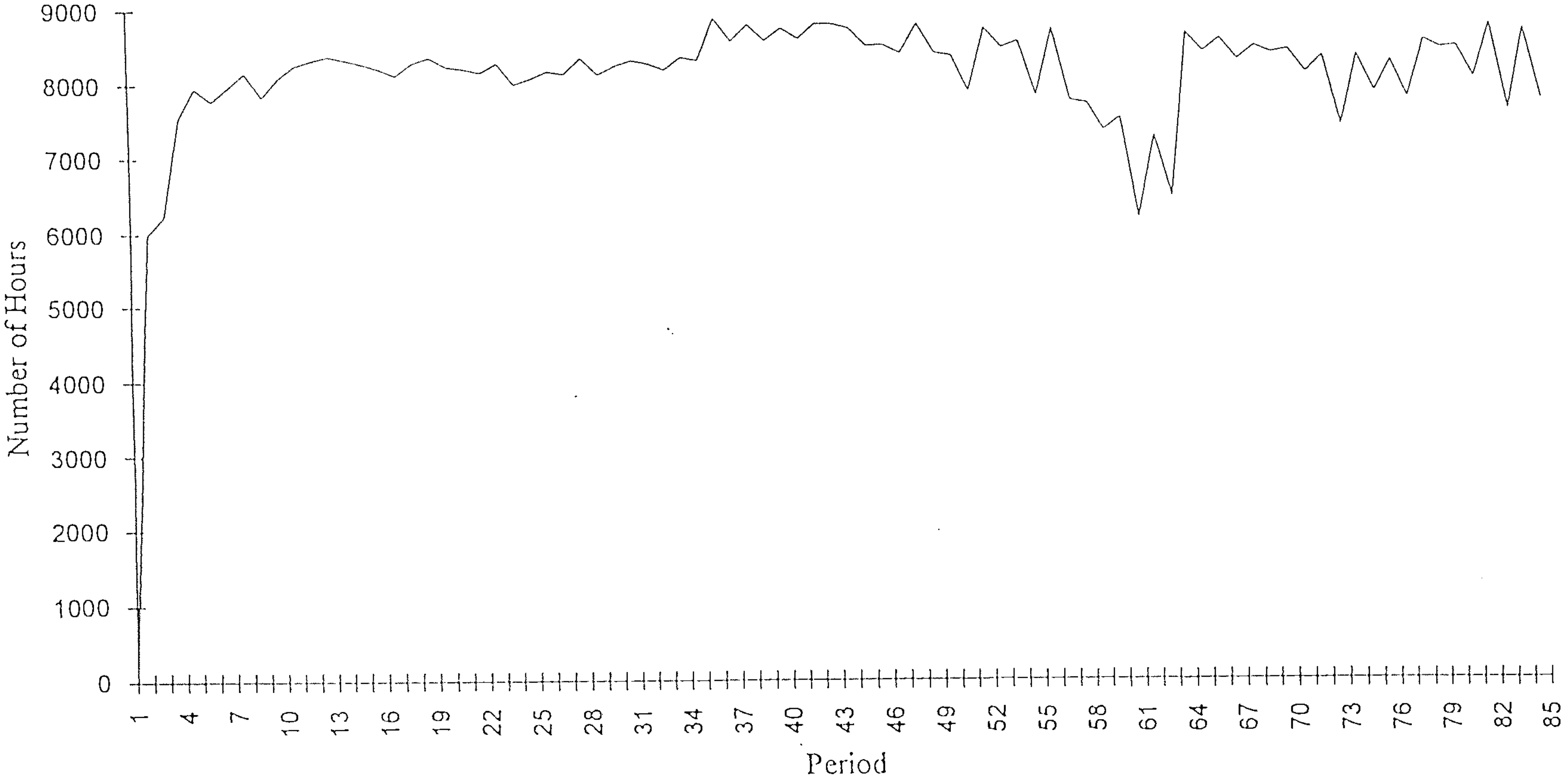


Figure 8.12 : Characterisation Model (Queue at WELD Workcentre)

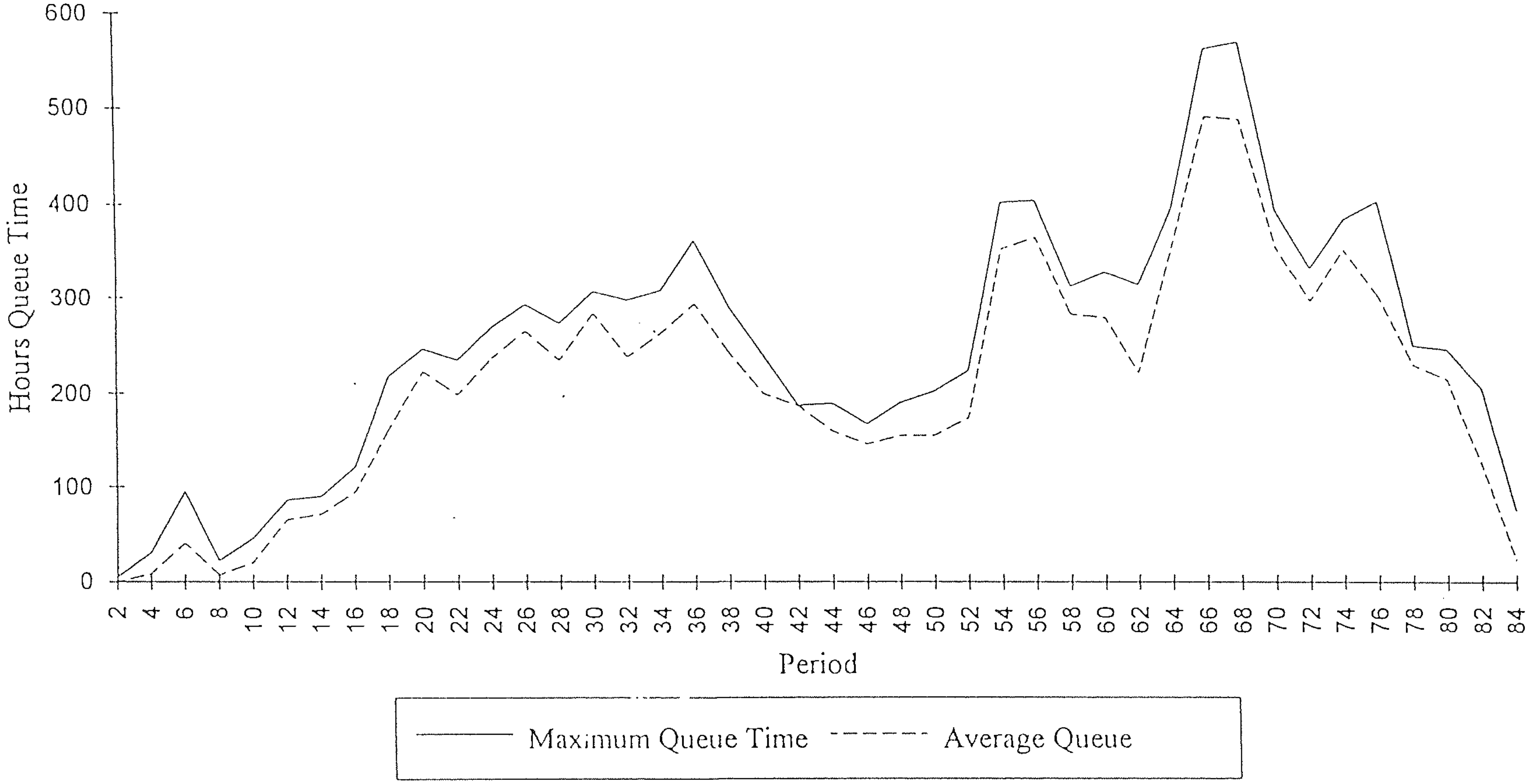


Figure 8.13 : Characterisation Model (WIP Batches Smoothed Using Welch's Technique)

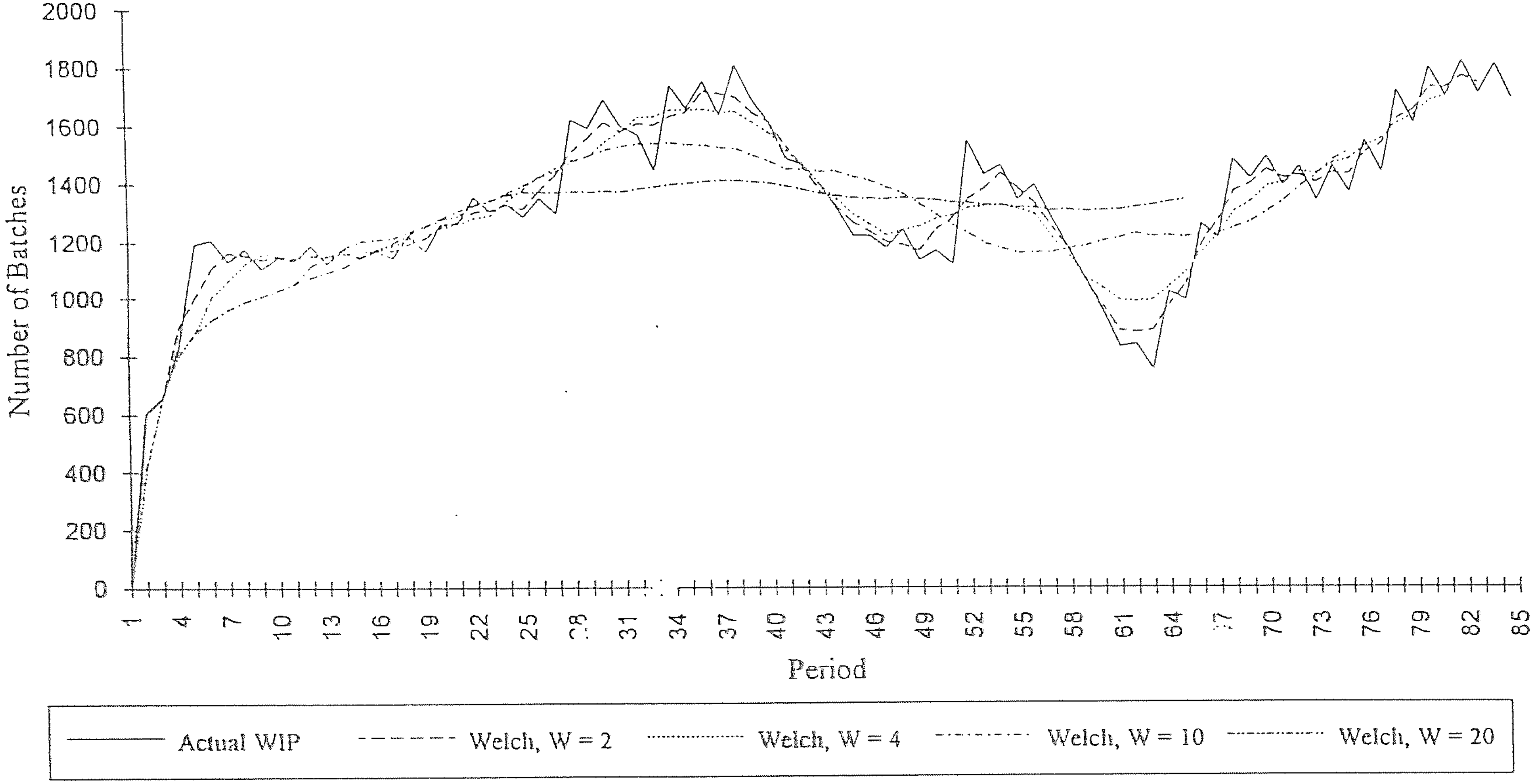
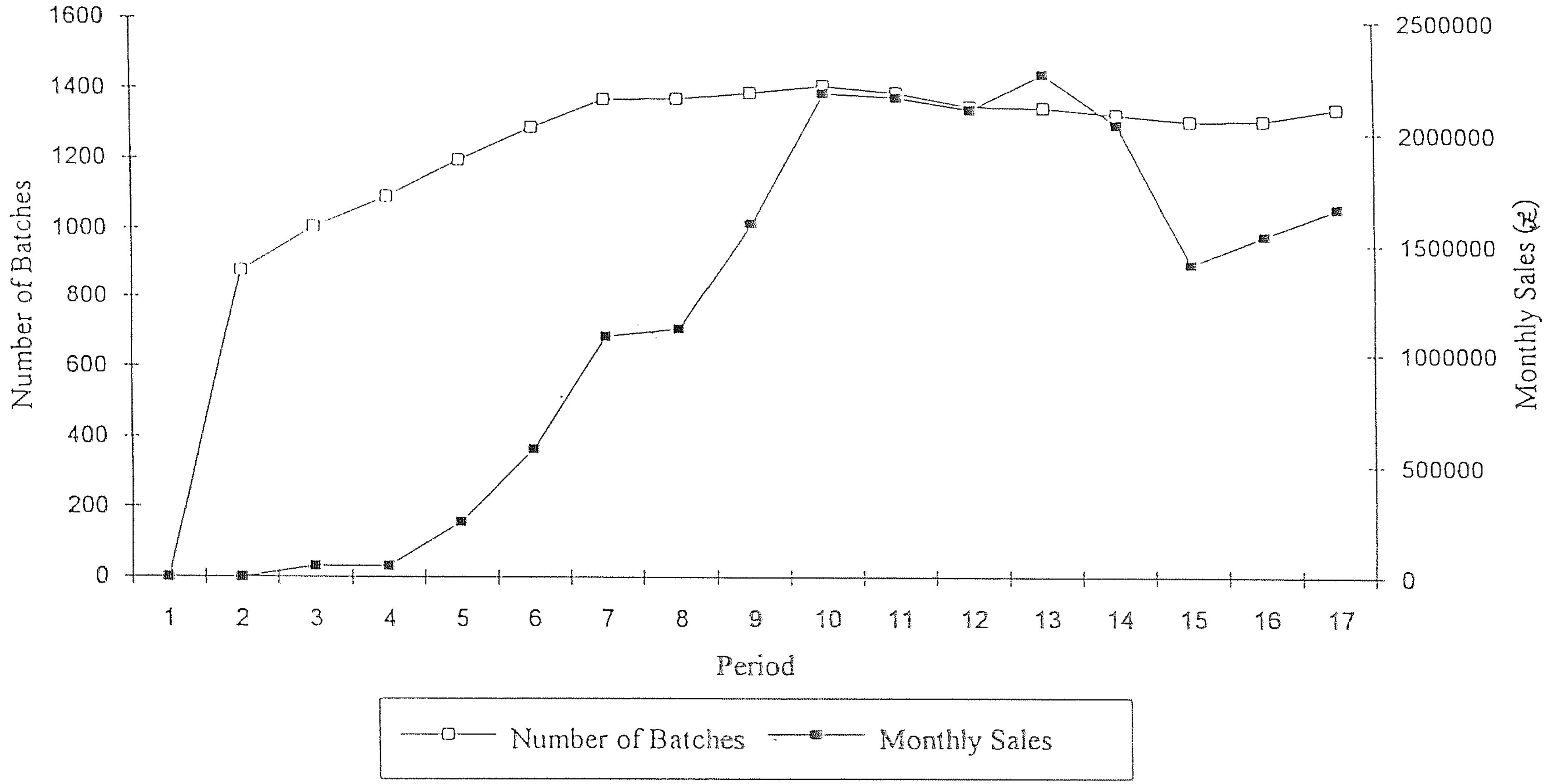


Figure 8.14 : Characterisation Model (Smoothed WIP Batches & Smoothed Monthly Sales)



average made-in leadtime of approximately 15 weeks and an average total leadtime (including purchases) of 21 weeks for the 11 end items.

8.3.3 Validating the Model

Once the point at which the model had reached steady state was determined, it was possible to calculate some average levels of business and operational performance by disregarding the data generated prior to the arrival of the steady state situation. Using the data given in Appendix 3 the following steady values were calculated. These were compared with the actual values as given in Section 8.2 :

Table 8.15 : BroomCo Actual Business Metrics and Model Business Metrics

Metric	Model	Actual
Average Monthly Sales	£2,002,323	£1,866,000
Average Monthly Net Profit	£237,855	£250,000
Average Monthly Net Assets	£9,128,741	£9,500,000
ROCE	31.3%	31.6%
Asset Turn	2.6	2.36
Net Margin	11.8%	13.4%

From Table 8.15, it can reasonably be concluded that the performance of the model is broadly similar to that of the actual business (They were of the same orders of magnitude). It would have been possible to track a particular business expense and compare this with the actual business expense as a lower level validation exercise.

As far as operational metrics were concerned, the level of WIP batches, the number of input batches, output batches, hours worked and operations completed was available. Using the data given in Appendix 4, the operational metrics given in Table 8.16 were calculated. At a lower level it would be possible to track the queues at individual workstations as shown in Figure 8.12.

Table 8.16 : BroomCo Actual Performance Metrics and Model Performance Metrics

Metric	Actual	Model 1*	Model 2*
WIP Batches	1,600	1,419	1,378
Input Batches	185	150	146
Output Batches	180	144	138
Hours Worked	8,700	8,272	8,080
Ops Completed	?	676	641

* Model 1 data is based on a 24 week transient and Model 2 data on a 52 week transient

The WIP level in the model was slightly lower than the actual level. One reason for this may have been the fact that by reducing the number of end items, the number (variety) of lower level parts required was reduced and therefore the number of batches ordered also decreased. This is illustrated in Table 8.17.

Table 8.17 : The Effect of Part Variety on the Number of Live Batches

End Items	Parts	Demand	Volume	Batchsize	No. of Batches
20	100	10	20000	20	2000
10	100	20	20000	20	1000

In the example given in Table 8.17, the number of end items required is reduced by 50% and the demand increased by 100% to give the same volume requirement (20,000). However, if there is a minimum batchsize of 20 then twice as many batches will be required in the situation where there are 20 end items. The difference in the level of input batches could be explained in the same way.

The difference in output batches and hours work can be explained by the use of overtime. Often, near the end of the month, considerable levels of overtime are worked, increasing batch output and total hours worked. Despite these differences the operational metrics presented are of broadly the same order of magnitude. It would be reasonable to conclude that the BroomCo WBS model was an adequate representation of the actual system, for the purposes of cellular manufacturing system design (i.e. it is valid for its purpose).

8.3.4 Conclusions on the Characterisation Model

This section has demonstrated that it is feasible to build a representative model of a manufacturing business. It has also been shown that this model can, broadly, be used to model the 'As Is' situation and generate business and operational metrics. However, two concerns raised themselves during this model building process. The first is the length of time needed to build the model. The second is the length of time taken for the model to reach steady state.

The BroomCo model discussed in this section took 1500 man-hours to build. This time does include all the data collection activities but excludes much of the time taken to debug and improve the WBS demonstrator software used for 'Cell 12'. Although the construction of a WBS model is shown to be feasible, the question that arises is whether it is practical. The model took some six weeks (including crashes etc.) running 24 hours a day, 7 days a week to reach steady state. This issue will be discussed in the next Chapter.

8.4 Experiment 2 : Boundary Definition

The objectives of this experiment were twofold. The first objective was to investigate the use of parts families in the 'make v buy' analysis. The second objective was to demonstrate that the boundary of a WBS characterisation model (BroomCo in this case) could be changed to reflect the results of the 'make v buy' analysis.

8.4.1 Make v Buy Analysis

BroomCo undertook a make v buy project as a strategic move to improve its competitive advantage, focus on its 'core' competencies and to determine the 'right' level of vertical integration. This project provided an opportunity to both influence the process (thus refining the methodology presented in Chapter 7) and to collect the data required to build the model discussed in Section 8.3.

The sample of 11 products detailed in Section 8.3 was used as the basis of the 'make v buy' analysis (NB : These products were themselves representative of product families). All the drawings of the parts in these products were examined and coded using a crude coding and classification system. The codes for all the parts were sorted and 18 component part and sub-assembly families formed.

A static analysis was undertaken, resulting in the number of production hours per family (split by process and therefore operator skill) and the number of part-numbers. This was used to calculate the effect on internal resources of proposing to make or to buy a parts family. In addition, a number of quotes were obtained for each parts family. These quotes were compared with a cost model that was built for the purposes of the exercise. This comparison enabled a view to be formed on the cost-benefits of outsourcing. In parallel, an exercise was undertaken to establish the key manufacturing processes to be retained in-house. Six scenarios were constructed, each with a particular combination of families made in and families made out. These scenarios were based on issues such as core competencies and cost. A cost calculation was then performed for each scenario using the cost model and assuming a constant raw material cost. From this analysis, a recommendation was made as to how the boundary of the business should be redrawn. Appendix 5 gives details of the families defined, the static cost assessment and the 'make v buy' scenarios evaluated.

8.4.2 Building the Boundary Model

In principle, any of the scenarios discussed in Section 8.4.1 could be modelled by the use of WBS. However, it was decided to model the effect of buying out one family of parts identified for outsourcing in Section 8.4.1. This allowed the consequences of one change to be investigated rather than confusing the situation with multiple interactions. The following steps were undertaken to change the model (for the parts family):

Step 1 : The structures on UNIPLAN were changed to make sure that any items to be bought out, were at the lowest level of the bill of material. This meant deleting raw materials (for which a program was written). For each part-number that was turned from a made-in item to a bought-out item on the bill of material, the stock record was changed. The supplier code, new planned leadtime, re-order size, re-order level and the buying price were added. The MRP low level code program was then re-run.

Step 2 : The material record in ATOMS was adjusted to indicate that the part was now bought out. The routing file was adjusted for the purposes of consistency.

Step 3 : A supplier account and nominal account for the proposed supplier of the parts families was created in DBFLEX. The WBS file with buying prices and leadtimes (supplier object) was amended. The WBS file cross referencing nominal codes was also adjusted.

Step 4 : A static analysis was undertaken to determine the adjustment required to the resources in the factory model. The number of 'directs' required under static conditions was calculated using spreadsheet analysis. The level of resource in the

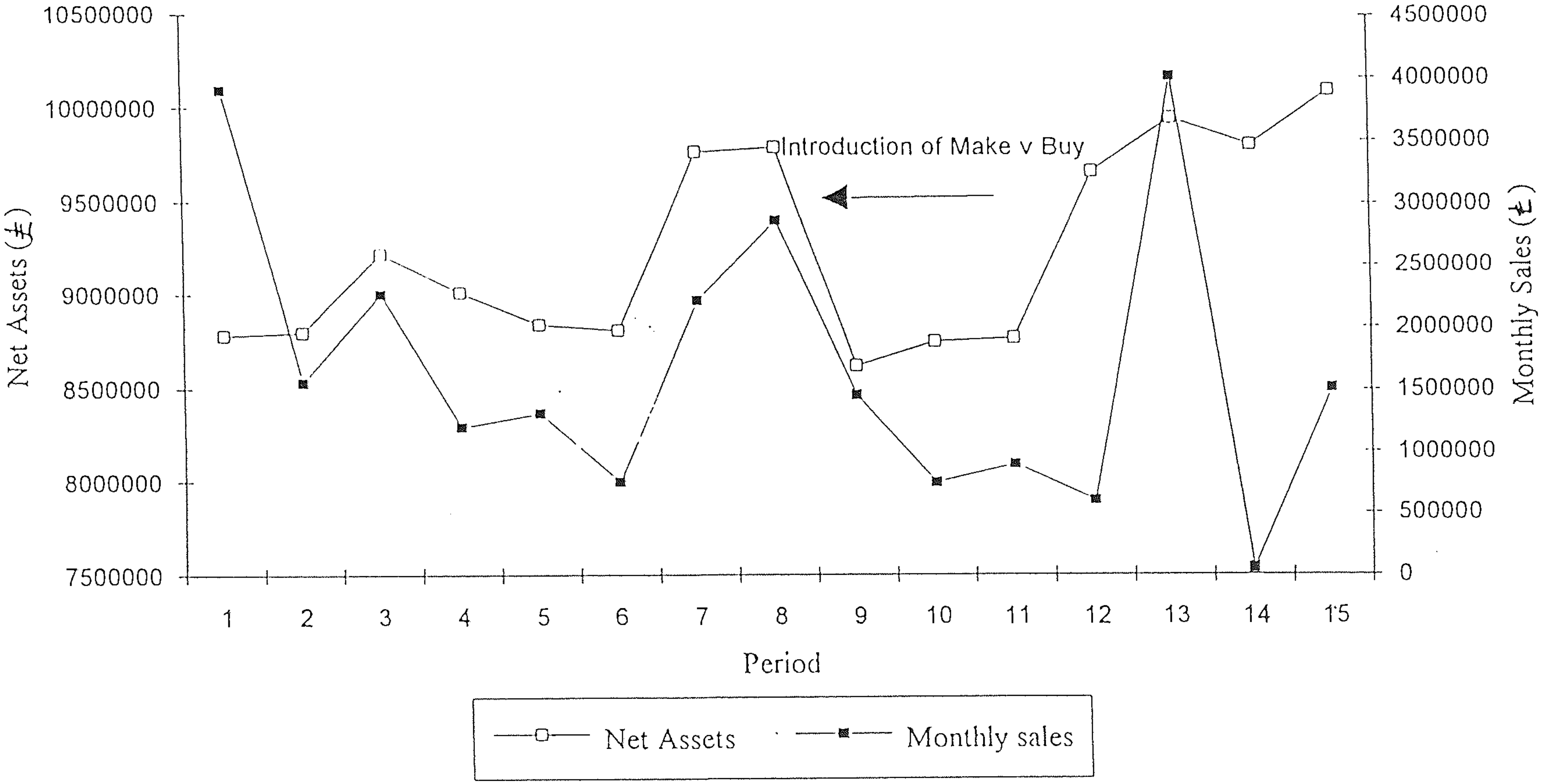
ATOMS model was adjusted accordingly. The asset base in terms of the number and value of plant was adjusted in ATOMS and DBFLEX.

The four steps were carried out for family 'A2' (presswork and machining sub-assemblies). The family consisted of 241 components with a load of approximately 60,00 hours. This static assessment of load led to the factory model operator resource being reduced by 50 across various machining, presswork and fitting operator groups. After all the changes to the model had been made, the simulation was started up again to see if the model would enable differences in operational and business metrics, as a consequence of changing the boundary of the business, to be detected.

8.4.3 Boundary Modelling Results

The experiments undertaken were not intended to be used for the prediction of future system behaviour. Rather they were used to demonstrate that the use of WBS was feasible and that system behaviour moved in a fashion that might be expected. Appendices 6 and 7 give the results of this experiment for business and operational metrics. It could be hypothesised that, given the changes made, that the boundary model would have lower WIP and a lower batch input. The effect on the business metrics is more difficult to speculate on. Figure 8.18 illustrates the effect of the model changes on the level of monthly sales and net assets. It is difficult to see any pattern to the output other than that it reduces between Periods 8 and 9 , increasing again between Periods 12 and 13 (all of which could be the result of usual variation in the system output). Table 8.19 gives the average of the business metrics and their associated ratios for the revised model against the averages for the original (characterisation) model. Clearly, there is a difference. However, this could be due to the effects of the transient between the steady states of the two system configurations, rather than an absolute difference between steady state performances.

Figure 8.18 : Boundary Model (Sales and Net Assets)



The results shown in Table 8.19 are not proposed as predictions of system performance. They are however, illustrative of what WBS could in practice be used for. The results of this type of analysis for 'make v buy' can also be taken to a lower level. Figure 8.20 for example, shows the turnover (taken from the DBFLEX accounting system), over the length of the simulation associated with the supplier of the parts family 'A2'. Associated with this was a small rise in the average purchase spend (as would be expected).

Table 8.19 : Comparison of Business Metrics Before and After the Model Boundary was Changed

Metric	Original Model	Revised Model
Average Monthly Sales	£2,002,323	£1,325,605
Average Monthly Net Profit	£237,855	£32,724
Average Monthly Net Assets	£9,128,741	£9,383,723
ROCE	31.3%	4%
Asset Turn	2.6	1.69
Net Margin	11.8%	2.4%

Differences in the operational metrics are more easily detectable. Figure 8.21 shows the effect of the change in the manufacturing boundary on the level of WIP batches and input batches (from UNIPLAN). Clearly, both the level of input and WIP reduces to a new steady state after approximately Period 92. Figure 8.22 tracks the number of hours worked and the number of operations completed. Again this response from the model is as might be expected with a reduction in both (as a result of less operator resource being resident in the model). Table 8.23 compares the average values for several operational metrics in the characterisation and boundary model after they have both reached steady state. The differences between the two sets of results are quite marked and move in the direction that might be expected.

Figure 8.20 : Boundary Model (Purchases fo Boundary Definition Supplier)

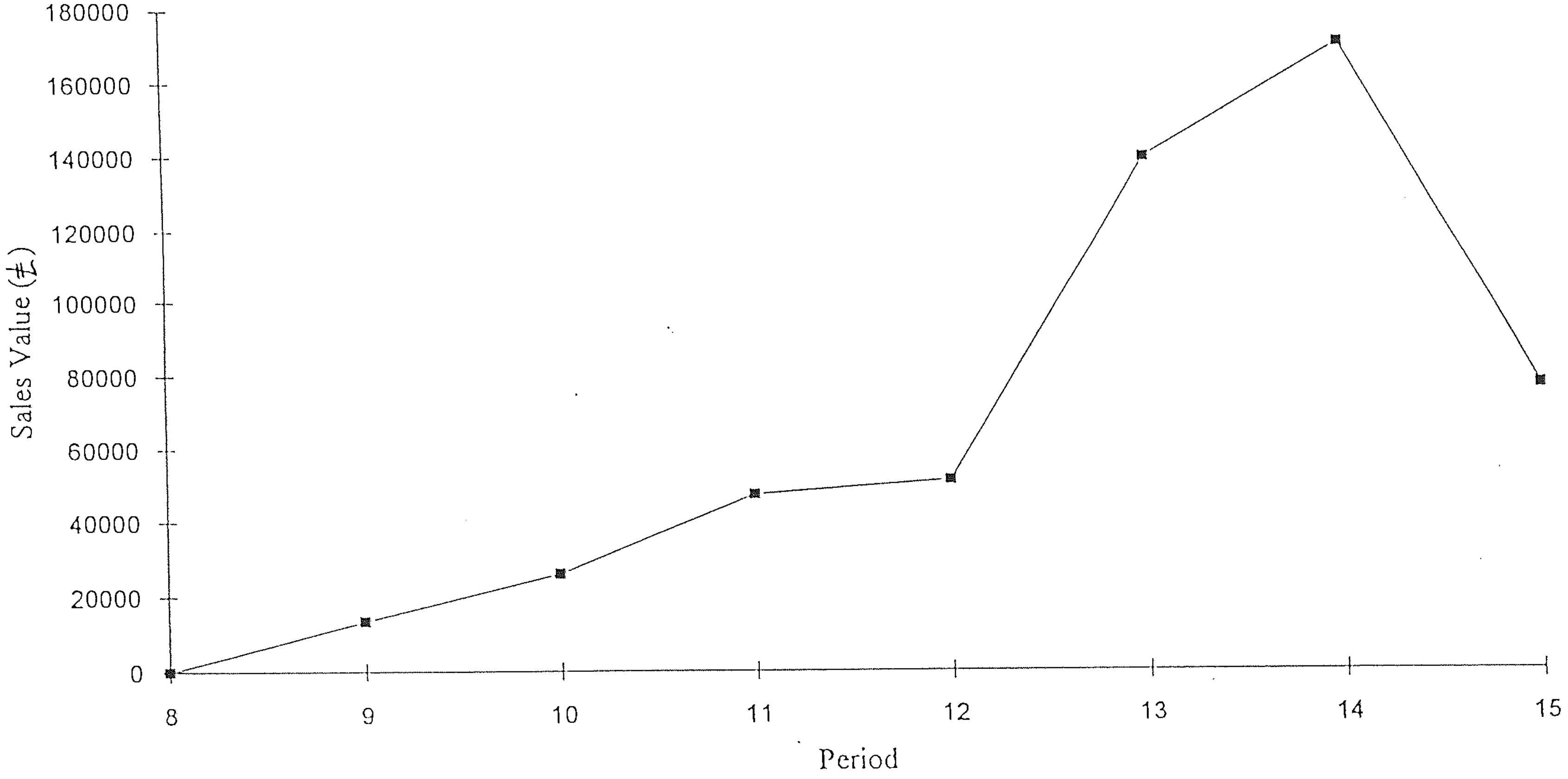


Figure 8.21 : Boundary Model (WIP Batches and Input Batches)

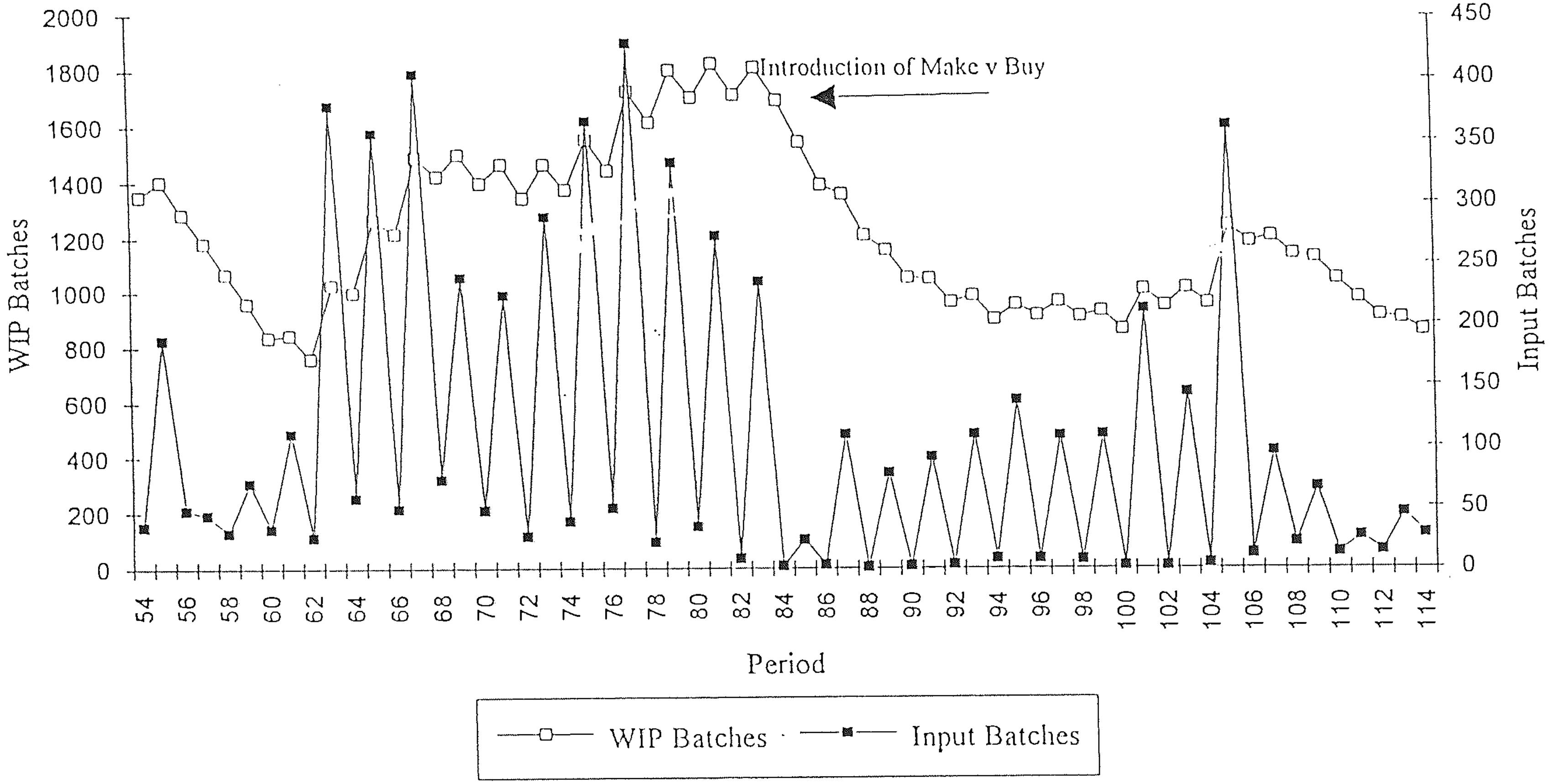


Figure 8.22 : Boundary Model (Hours Worked and Operations Completed)

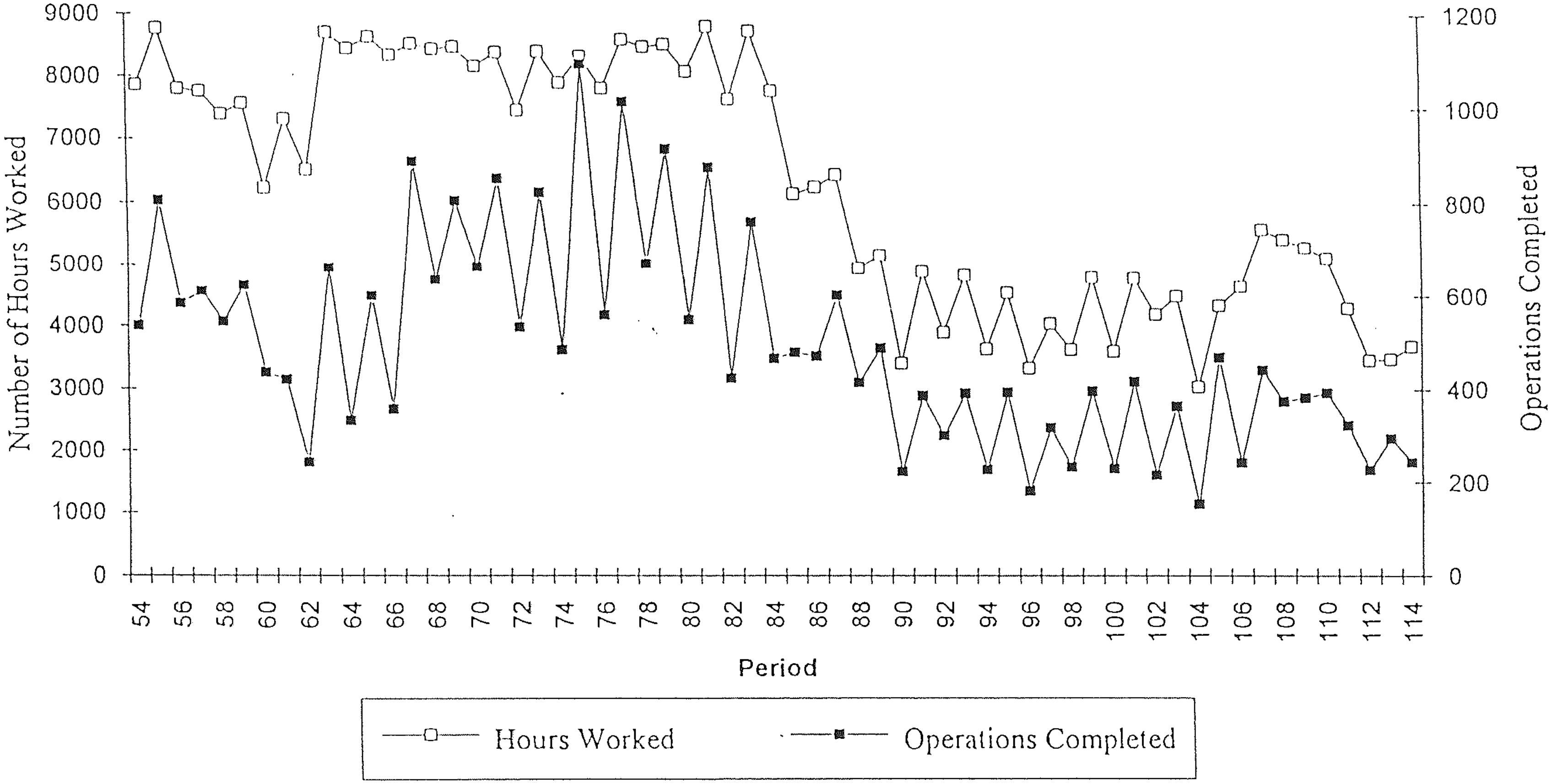


Table 8.23 : BroomCo Characterisation Model Operational Metrics and Boundary Model Operational Metrics

Metric	Boundary Model	Characterisation Model
WIP Batches	1,000	1,378
Input Batches	67	146
Output Batches	75	138
Hours Worked	4282	8,080
Ops Completed	314	641

The experiment in this section has not predicted the behaviour of BroomCo to the proposed changes in the manufacturing boundary. Rather, this experiment has demonstrated that the boundary of a WBS model can be changed and that the effect of these changes can be seen in metrics taken from the model. To be used for predictive purposes a much longer run would have to be undertaken.

8.5 Experiment 3 : Concept Design

After considering the definition of the boundary of the manufacturing system, manufacturing segmentation could be undertaken and a concept design produced (Phase 3). Given the methodology detailed in Chapter 7, this task involves the design of a cellular manufacturing system (or 'hybrid') for those parts families that are to be manufactured in-house. The manufacturing segmentation may or may not be based on the parts families. For example, if product or end item modules and cells were required then product rather than part families could be used.

8.5.1 Building the Concept Model

This experiment had the objective of demonstrating that a concept design, based on a revised manufacturing segmentation, could be modelled in WBS. Rather than implement a completely revised manufacturing segmentation into the model, it was decided to introduce one change to demonstrate that its potential effect may be modelled. A vertically integrated cell, manufacturing all of the made-in components and sub-assemblies (15 partnumbers) of the FCL product (see Table 8.2), was introduced into the factory model. Plant and labour were dedicated to the manufacture of this product, their level being determined by a static model. The plant and resource were not available for use by other products in the model. These changes were affected by altering routeing files, operator groups, workcentres and workstation allocations.

8.5.2 Concept Modelling Results

Once again, this experiment was conducted, not for use as a prediction of behaviour but to demonstrate feasibility and to assess if changes in performance seemed reasonable. Appendices 8 and 9 contain the results of the experiment. Figure 8.24 shows the effect of the changes on net profit when compared with the characterisation model. The monthly net profit is lower. This is to be expected as a consequence of the loss of 'pooling synergy' (see Chapter 6). The movement of resource from the main manufacturing facility to the cell has not been compensated for by set-up reductions (as none have been introduced into the model) and therefore output will reduce (reducing gross profit). Figure 8.25 shows the effect of the change on Sales of FCL. It can be seen that a more consistent pattern of sales is present in the concept model than in the characterisation model. Again this is to be expected, as more than sufficient resource was placed in the FCL product cell to ensure the schedule could be met. Figure 8.26 shows the effect of the introduction of the FCL product cell on the number of WIP batches. Again this shows a result that might be expected. WIP in the overall system is higher, although it is lower for the parts that go into the FCL product. This is an example of the sub-optimisation referred to in Chapter 6. This experiment showed that the WBS model could be used to study the effects (both at a business and operational level) of introducing product orientated

Figure 8.24 : Concept Model (Net Profit)

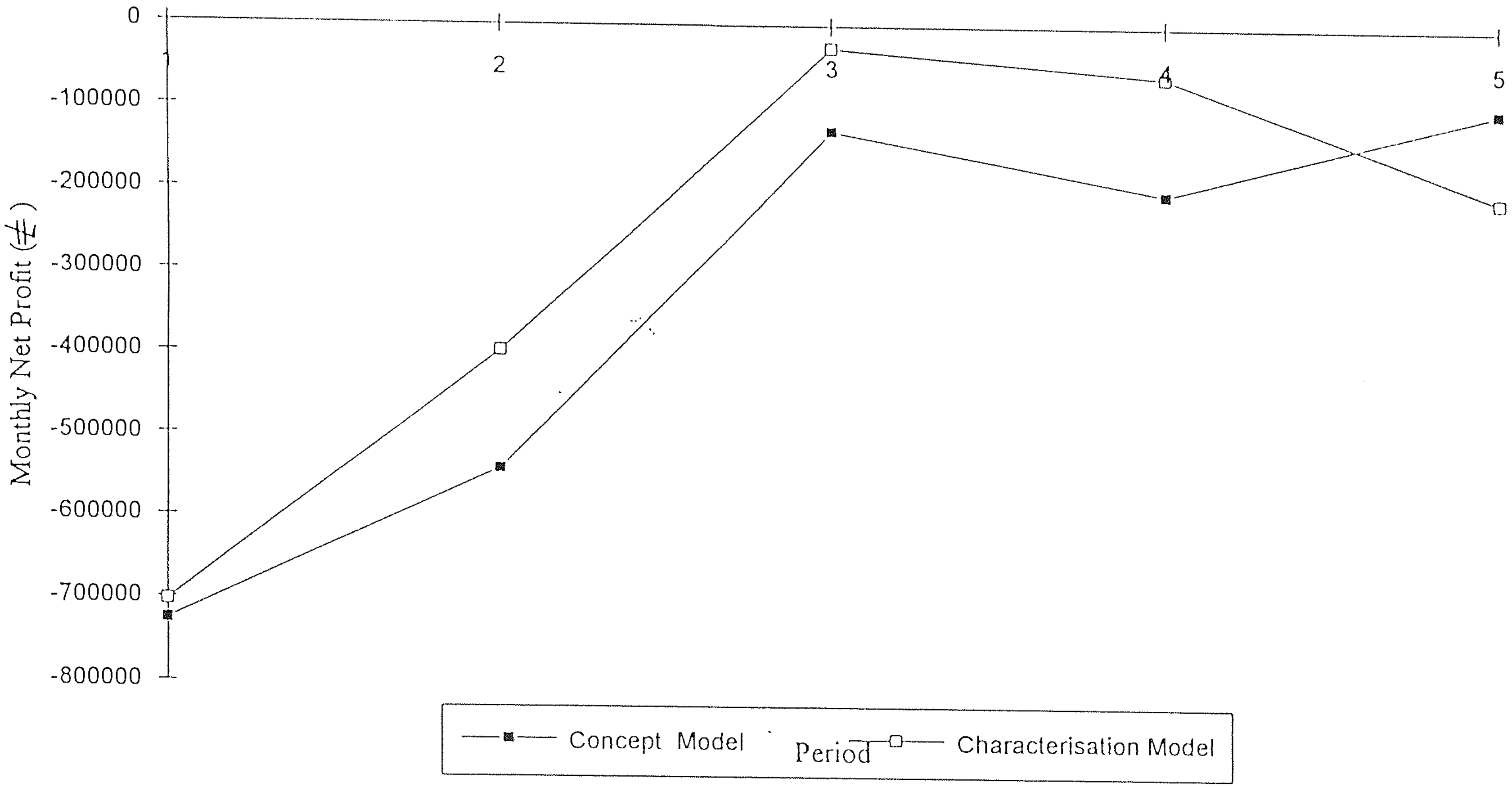


Figure 8.25 : Concept Model (FCL Sales)

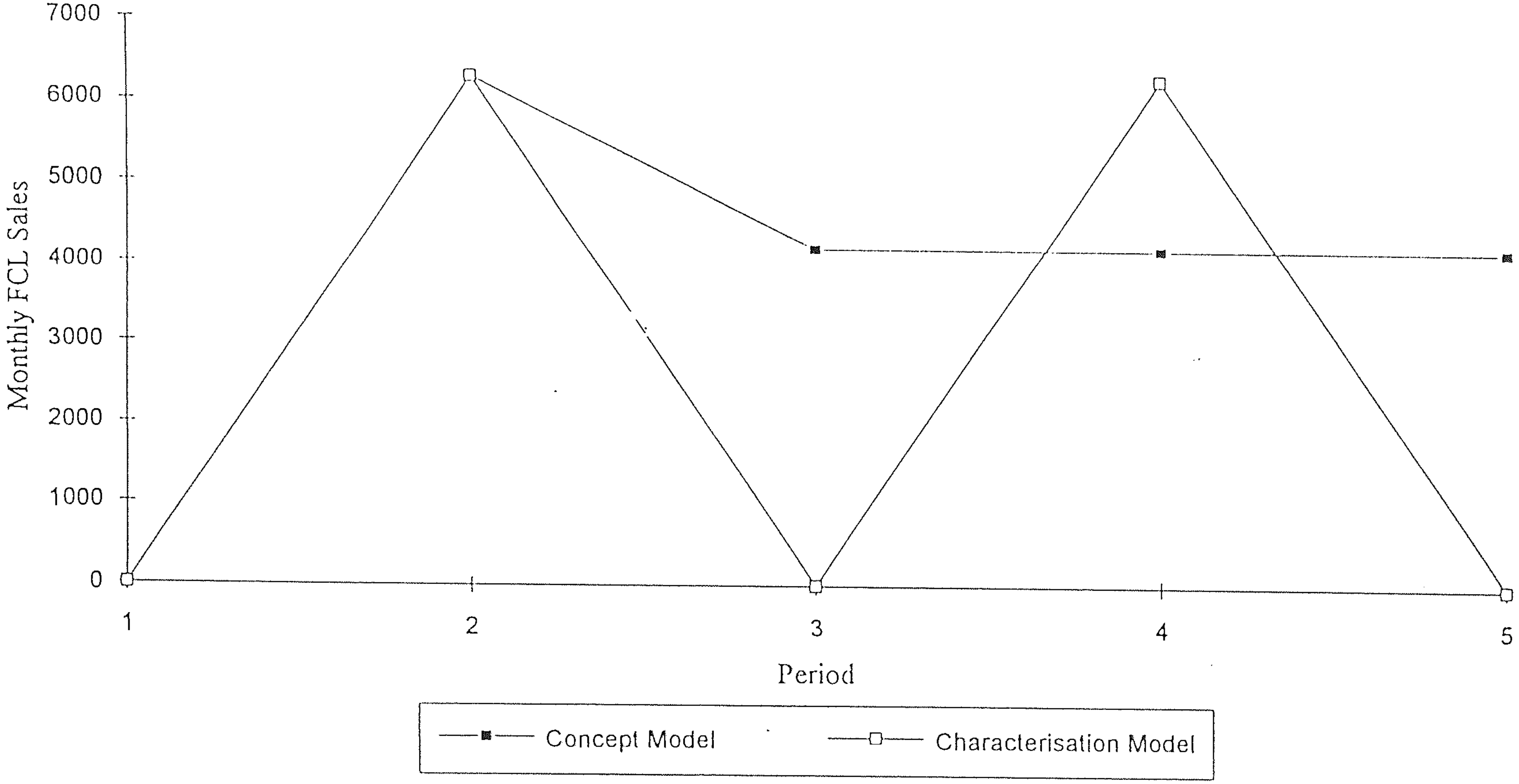
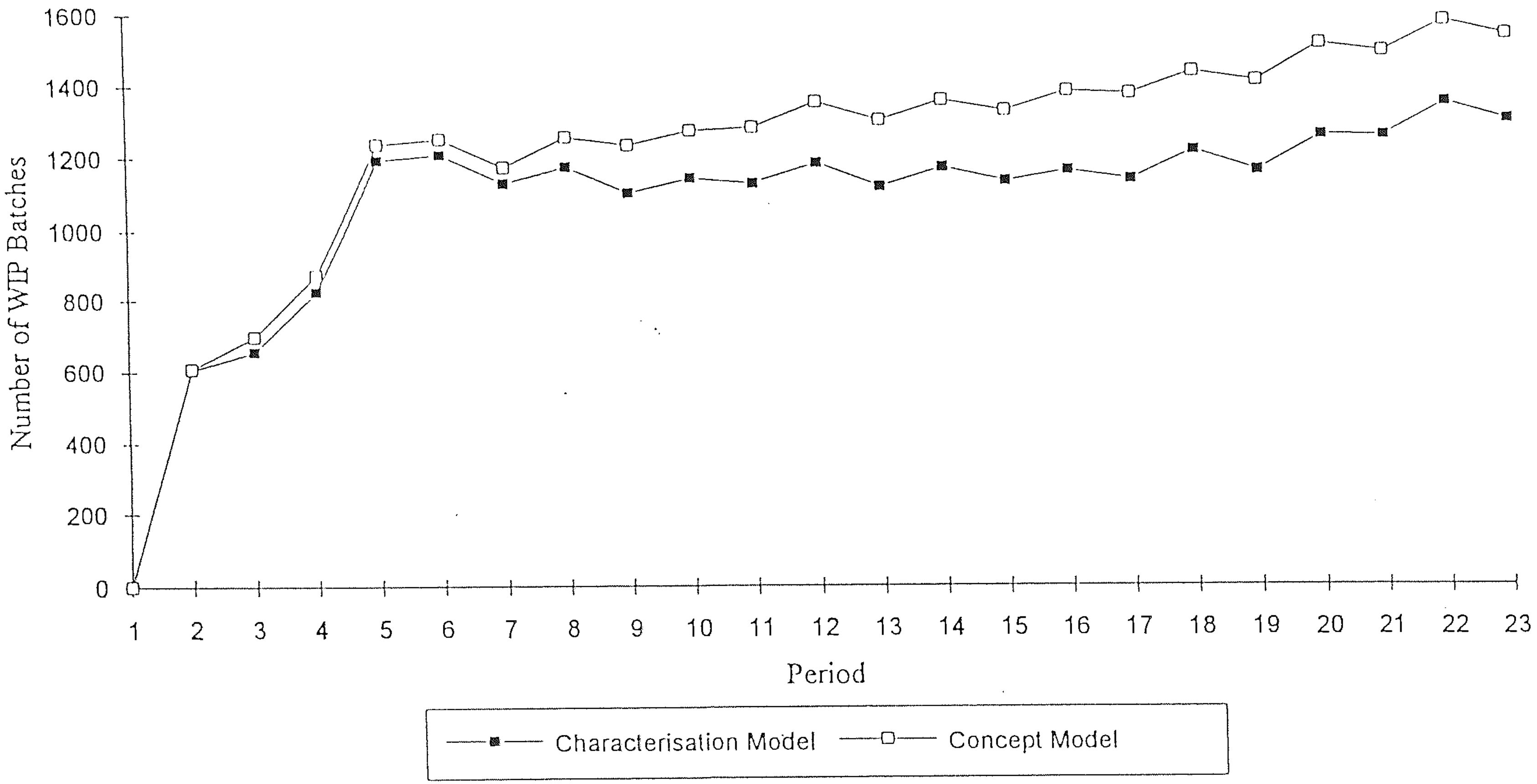


Figure 8.26 : Concept Model (WIP Batches)



cells. By extension therefore, it would be possible to model extensive changes to the manufacturing architecture of the model (either process or product).

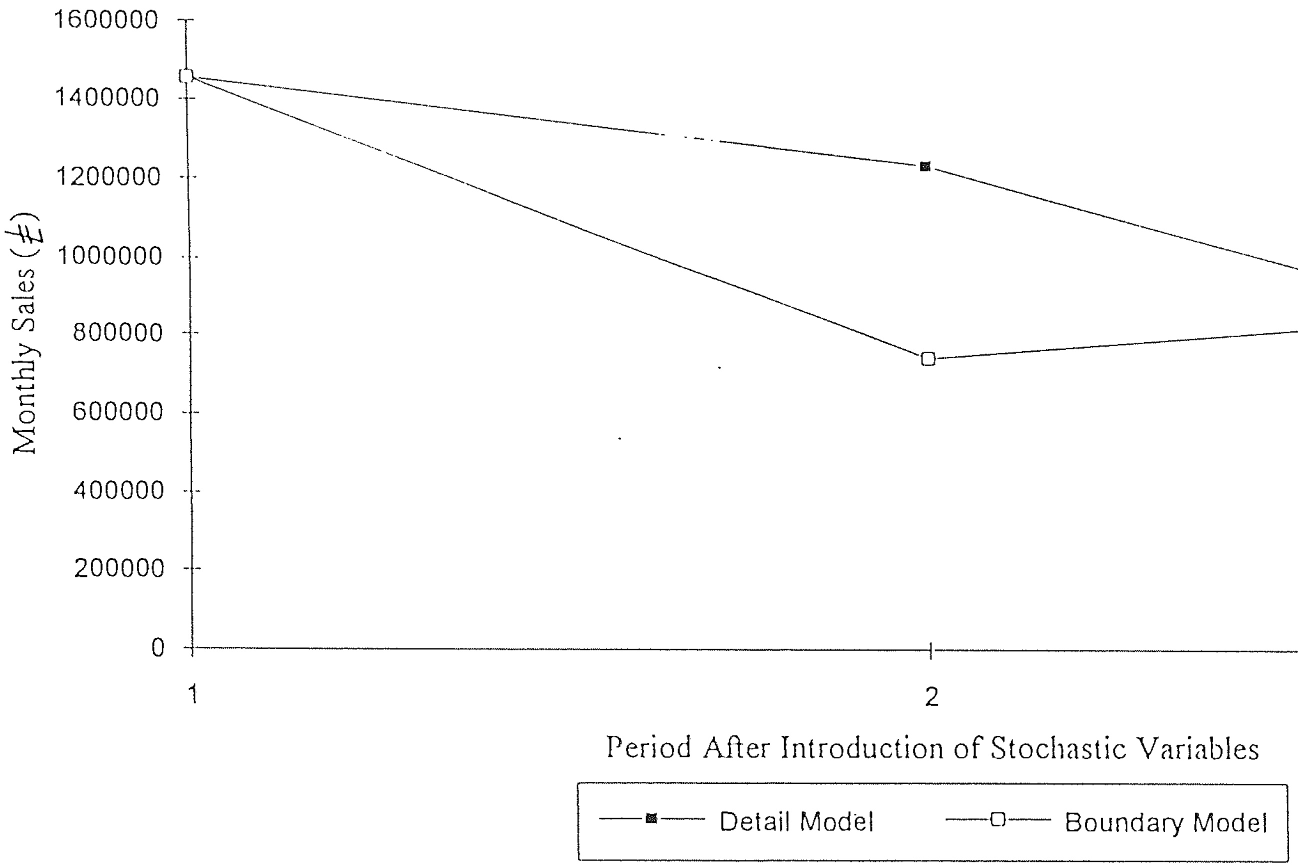
8.6 Experiment 4 : Detail Design

Having configured the overall manufacturing system, the next step in the methodology developed in Chapter 7 is to undertake the detail design. This phase includes the introduction of stochastic elements on key plant on a priority basis (i.e. adding the detail to bottlenecks first). This is achieved by adding data to the already existing configuration model. It is a process of incremental model building. The addition of this detail adds to the reliability of any model for making predictions about future system behaviour. The objective of the experiment was therefore to establish if such detail could be added to the WBS model and the effects seen in operational and business metrics.

It was decided to add stochastic data to one bottle-neck workcentre and investigate whether the WBS model would detect the effects of this change. A breakdown record was added to the workcentre in the factory model. Two simulation runs of 22 weeks were undertaken: one with the model unchanged (i.e. the deterministic boundary model) and one with a breakdown record for one of the bottle-neck workcentres introduced (i.e. a stochastic detail model). It was therefore possible to compare the results, to see if changes as a consequence of adding the breakdown record could be detected. (It should be noted that, as the boundary model was deterministic and therefore predictable (over a number of runs), any changes in the model performance would be due to the addition of stochastic detail).

A clear change was detected between the boundary and the detail model. Appendices 10 and 11 give the results of the experiment. Figure 8.27 shows the effect of the

Figure 8.27 : Detail Model (Sales)



addition of the breakdown record on monthly sales. This graph indicates that sales were initially the same in the boundary and detail model. Sales in both models then dropped, although less steeply in the detail model than the boundary model. Sales then increased for the boundary model, whilst continuing to decline in the detail model. Although no conclusions on future system behaviour could be drawn from such limited data, the graph does indicate why the dynamic evaluation of changes in a manufacturing system is necessary. Intuitively, one would expect the sales in the detail model to be lower than in the boundary model. This is because the addition of a breakdown record at a bottle-neck should reduce capacity there, and thus (eventually) reduce output. Figure 8.27 does not indicate an immediate reduction sales. This *could* be because a reduction in throughput at the bottle-neck may allow downstream labour to be utilised to manufacture parts required to complete a kit. The completion of more kits would allow sales to increase. The veracity of this hypothesis could be tested by further runs and the use of appropriate statistical analysis. Figure 8.28 shows net monthly profit, for which similar comments may be made.

At the operational level, one would expect the level of WIP in the detail model to be higher than that in the boundary model, as the queue behind the bottle-neck workcentre would increase as a consequence of reduced capacity (because of more breakdowns). Figure 8.29 illustrates this. Figure 8.30 illustrates the difference in the queue at the workcentre for which the breakdown record was added.

This experiment demonstrated that stochastic data could be added to the WBS model and the effects demonstrated. The experiment discussed in this section could not however, be used to predict future system performance, as a consequence of too little simulation performance data.

Figure 8.28 Detail Model (Monthly Net Profit)

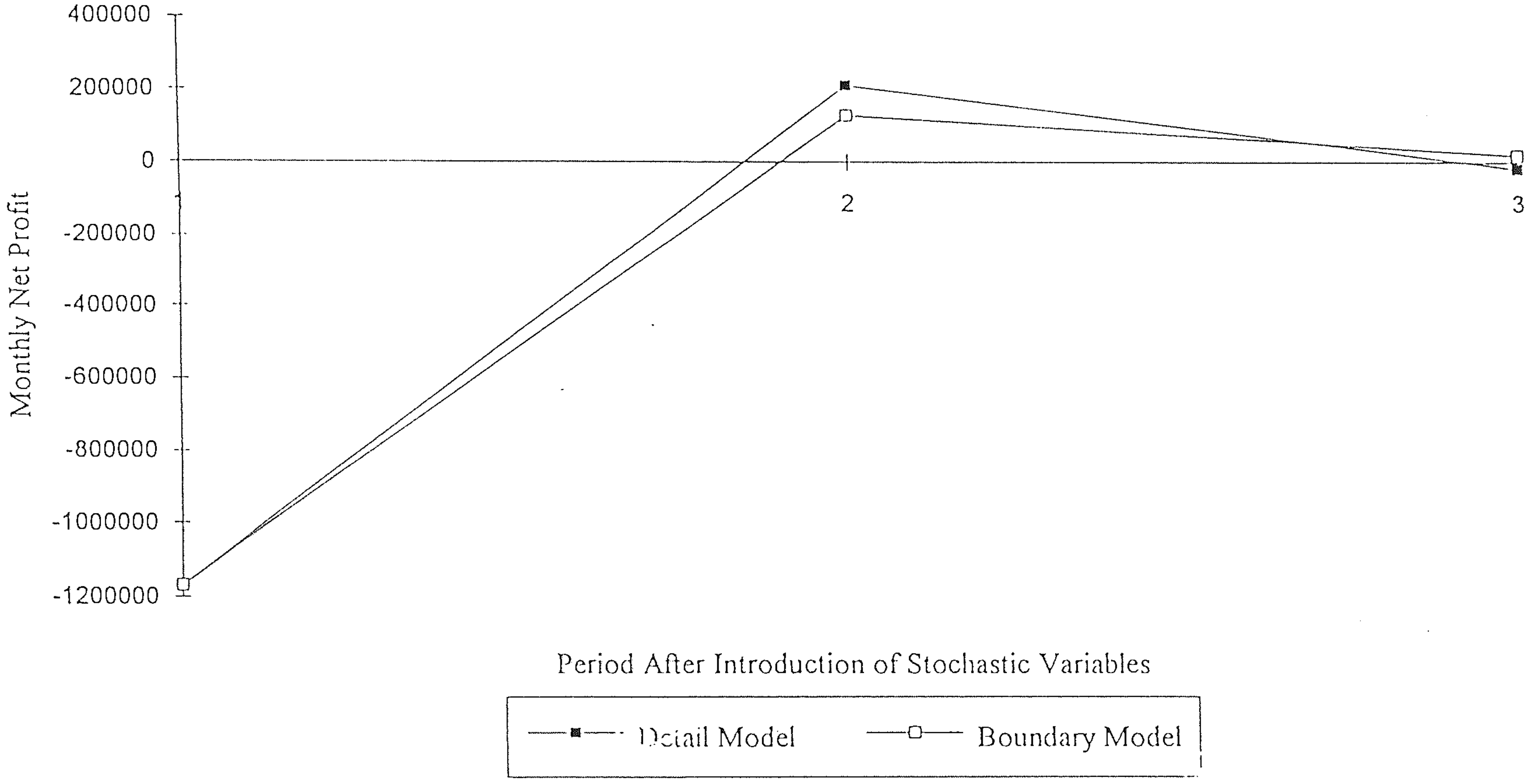


Figure 8.29 : Detail Model (WIP)

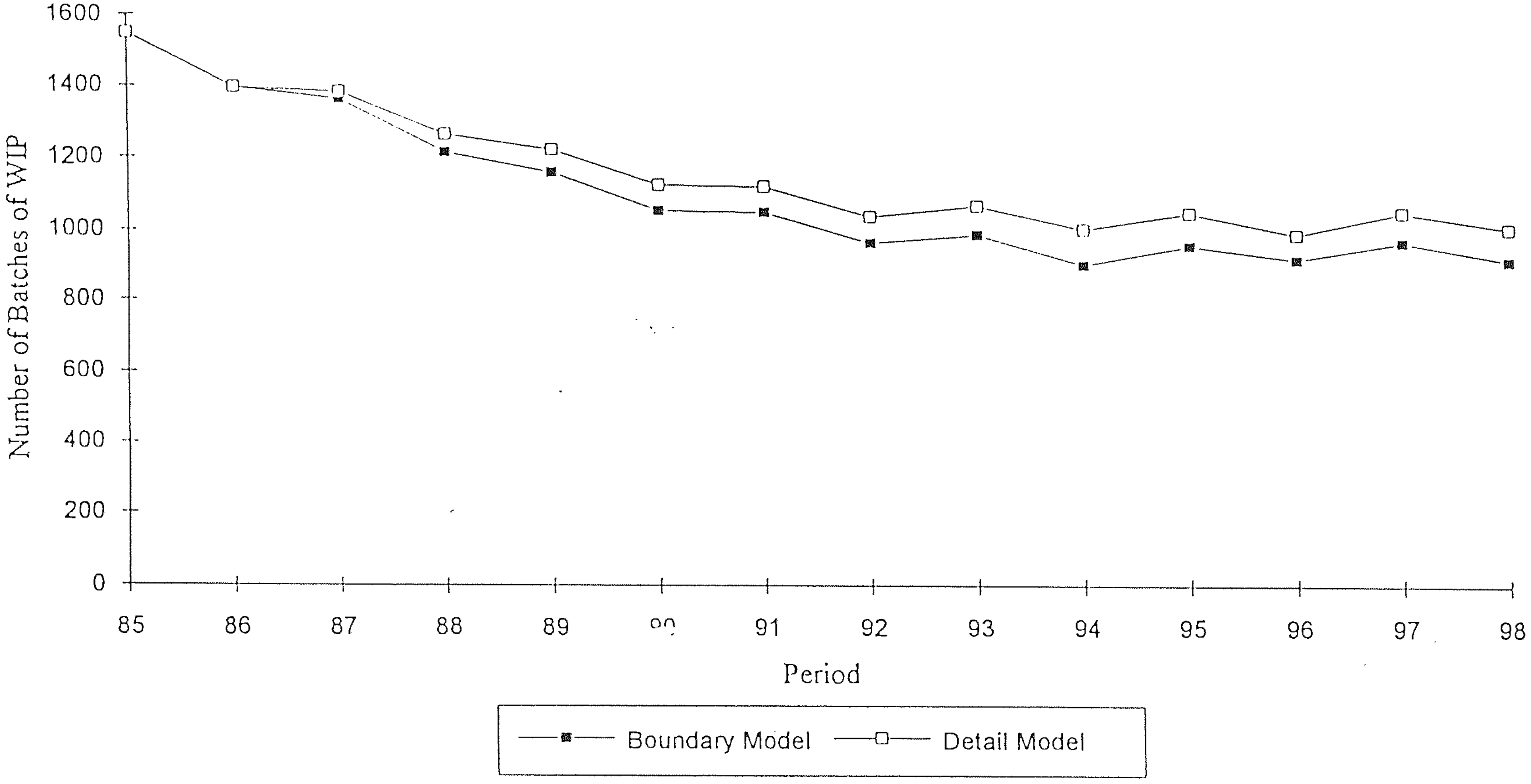
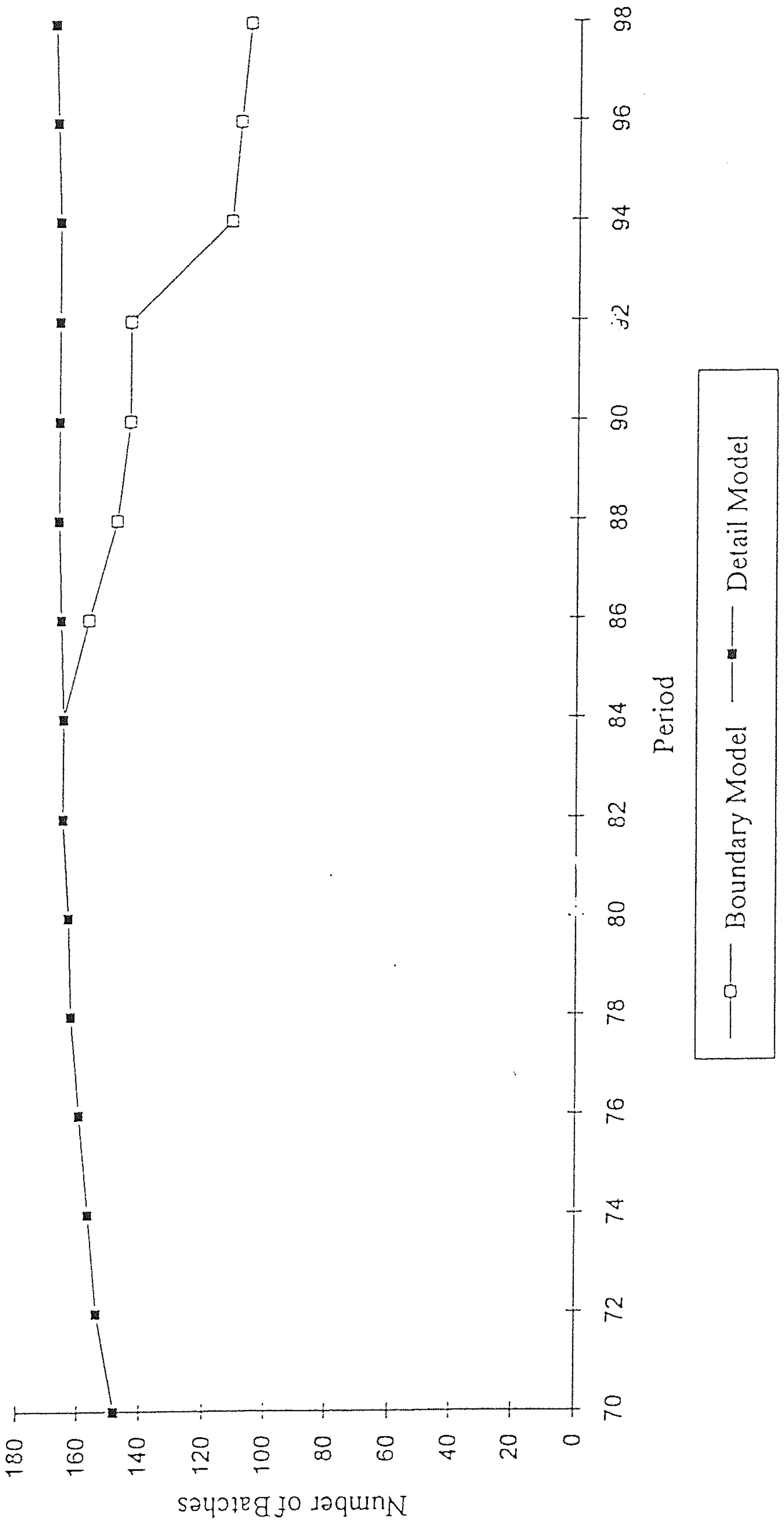


Figure 8.30 : Detail Model (Queue at 02VM Workcentre)



8.7 Summary

This chapter has explored the more contentious points of the methodology proposed in Chapter 7 for the design of cellular manufacturing systems. Experiments using industrial case-study data (in contrast to the studies, discussed in Chapter 6, which used synthetic data) were undertaken in each of the following areas :

System Characterisation : A complex manufacturing system was modelled using WBS. Its complexity was sufficient to indicate that WBS would be a capable tool to generally perform this activity.

System Boundary Definition : WBS was shown capable of modelling and demonstrating the effects of redefining the manufacturing systems boundaries after a 'Make v Buy' analysis.

System Concept Design : WBS was also able to model the introduction of a product orientated cell and show how the overall manufacturing systems performance was affected.

System Detail Design : WBS was capable of the creation of a stochastic detail model and of demonstrating the overall effects of introducing such changes.

The results of the analysis in all of the above experiments were not put forward as predictions of future system behaviour, though this could have been achieved with more simulation time and appropriate statistical analysis. Throughout the experiments, WBS was shown capable of evaluating performance not only in terms of operational but also business metrics. This chapter has shown that the methodology proposed in Chapter 7 is feasible. This chapter has not, however, shown that the application of the methodology produces 'better' results.

Chapter 9

Conclusions and Further Work

9.1 Introduction

The purpose of this chapter is to provide a summary of the conclusions reached in the project and to highlight the key conclusions amongst these. It also provides details of the further work that could be undertaken as a result of the findings of this project.

9.2 Summary of the Investigation Conclusions

This project has shown that manufacturing may be regarded as a system and, therefore, a framework based on systems ideas, may used to both design cellular manufacturing systems and analyse and evaluate the processes that are used to design them. An approach to designing cellular manufacturing systems based on systems concepts should exhibit **systematic** and **systemic** characteristics. Current approaches were categorised into the following taxonomy that was developed for the project :

Category 1 : Design Techniques and Procedures
Category 2 : Systematic Design Approaches
Category 3 : Integrated Modelling
Category 4 : Design Methodologies

Using the systems framework a number of deficiencies in first three categories were identified. Firstly, their scope was limited, and did not address the complete design problem. Typically, the scope was narrow and anything but 'holistic'. Secondly, the approaches did not evaluate alternative design proposals with respect to the criteria that most senior executives in industry would expect. Operational metrics were usually evaluated at the expense of business metrics. There was an implicit assumption that improvement in operational metrics would be reflected in business metrics. Thirdly, the performance of the whole system was commonly not considered when evaluating the introduction of cellular manufacturing.

Manufacturing Systems Engineering (MSE), which falls into the last category of the taxonomy appeared, if judged on the basis of the literature alone, to overcome many of the deficiencies identified for categories 1 to 3 in the taxonomy. It claims to be based on an understanding of system ideas and on the recognition of the complexity of manufacturing and the need to view it in its entirety. Consideration is given to overall objectives, the manufacturing system and the wider system of which it is part. Considerable emphasis is also given to control systems specification, with a number of underlying philosophical principles clearly stated.

However, when examined in a number of practical implementations, it was argued that the approach was not systemic in its application. There appears to be an over-emphasis on vertically integrated, product orientated structures with little evaluation of credible alternatives. Evaluation was often limited in nature with little analysis of the time varying behaviour of proposed design solutions. Shopfloor control systems were investigated well, but the 'top down' systems and their links with shopfloor systems were not analysed with the same degree of rigour. The 'residual' or 'remaining' process orientated manufacturing facility left after the introduction of cellular manufacturing systems was often ignored. In addition, the transient between the 'As-Is' and the 'To Be' position was also usually ignored. The methodology did however exhibit a number of strengths including the sophisticated use of cell formation techniques and computer tools, as well as strong consideration of shopfloor material control systems.

However, a potentially serious anomaly for the project thesis was revealed. Despite the weaknesses of the methodology, significant benefits were claimed from its application. The implication of this was that approaches to the design of cellular manufacturing systems did not have to be systemic in nature to be successful. However, longitudinal case-study investigations revealed possible explanations for the anomaly. It was argued that the improvements claimed were operational in nature and not reflected in business performance. Also the benefits given were quoted soon after implementation of redesigned cellular manufacturing systems and were not evaluated over a longer time period. The longitudinal case-studies indicated that the shortcomings (of both a systemic nature and of a more practical nature) did indeed result in the implementation of cellular manufacturing systems that did not bring the business benefit expected of them.

A systemic methodology was developed to overcome these deficiencies. This methodology was based on the systems lifecycle and incorporated a three stage design process. It also addressed a number of the issues raised by the investigations discussed in Chapters 4 and 5. Whole Business Simulation (WBS) was embedded within this methodology. The feasibility of the methodology was demonstrated by testing the most contentious and speculative elements. This was achieved by applying these elements to a substantial and complex industrial case-study. This investigation proved effective for this application which was of sufficient generality to suggest that these results may be replicated elsewhere.

9.3 Key Conclusions

The thesis of this project was that to be effective, cellular manufacturing systems must be designed not only *systematically* but also *systemically*. Analysis of the most promising of the existing approaches to the design of cellular manufacturing systems, MSE, using a series of case-studies, suggested that the reason why current approaches are not effective is because, although they are systematic, they are not systemic.

The results of this analysis were instrumental in facilitating the synthesis of a systemic design methodology. The methodology developed has six phases (detailed below), each with three dimensions (system design, WBS modelling and performance metrics). One particular strength of the methodology includes its ability to ensure that the complete design problem is addressed, not a partial problem. All the physical manufacturing system is considered, as are all key aspects of the material control and financial systems. These aspects are considered simultaneously, not sequentially. The focus of the methodology is not merely the solution of the cell formation problem, but is much wider in scope. A second particular strength of the methodology is its ability to evaluate design alternatives in terms of **both operational metrics** (such as labour and machine utilisation) **and business metrics** (such as net profit and return on capital employed). Key stages in the methodology include:

System Characterisation and Diagnostic : This phase of the methodology has the objective of characterising the current situation, diagnosing the reasons for any problems and setting targets for improvement. A complete WBS model of the 'As-Is' situation is built in this phase.

System Boundary Definition : This phase establishes the manufacturing envelope that is appropriate to the needs of the company. If this envelope is different from the existing situation, the effect of the proposed changes on operational and business metrics can be determined.

System Concept Design : The overall concept manufacturing system design that allows the business to become effective within the manufacturing envelope determined in the boundary definition phase is synthesised and evaluated.

System Configuration : Here, the focus is on determining and configuring proposed changes to the manufacturing system in the WBS model. This phase forms a 'bridge' between concept design and detail design, a step found to be missing in many approaches to the design of manufacturing systems. It is similar in nature to what Pahl and Beitz (1988) have termed 'Embodiment' in product design.

System Detail Design : The detail of the proposed manufacturing system design is finalised in this phase and detailed dynamic modelling and evaluation undertaken.

System Implementation : This phase includes pre-implementation planning. There is a particular focus on the management of the transient and planning how changes to material control systems are phased in.

Each of the above system design phases are accompanied by a WBS modelling dimension and associated performance metrics. The aspects of the methodology outlined above are key strengths of the approach when compared to existing approaches to the design of cellular manufacturing systems.

The most contentious aspects of the methodology were shown to be feasible for a substantial and complex industrial enterprise. Whole Business Simulation enabled this to be undertaken and its feasibility has been demonstrated. To this extent the project thesis can be said to have been supported. What has not been demonstrated however is that the systemic methodology is more effective than any other existing approaches by a direct comparison between the two. Therefore, the superiority of the proposed methodology rests on a combination of its inherent systemic nature (when compared to current approaches to the design of cellular manufacturing systems) and its feasibility.

9.4 Further Work

As a result of this thesis, three of areas of further work can be identified:

- The testing of the effectiveness of the methodology.
- Improving the WBS software to make it more robust and user friendly.
- Investigation of the link between the operational and business metrics in the design of cellular manufacturing systems.

Methodology Effectiveness - This thesis has not demonstrated that the methodology developed is more effective than existing methodologies, all that has been shown is that it is feasible. By identifying the strengths and weaknesses of existing approaches a new methodology has been developed. As strengths have been built on and weaknesses eliminated, it is possible to hypothesise that the proposed methodology will be more effective. This hypothesis needs to be tested. This will require the parallel running of a project concerned with designing a cellular manufacturing system, with one team designing it using the existing approach and another designing it using the proposed approach.

It should also be recognised that *a* systemic methodology rather than *the* systemic methodology has been proposed. The methodology detailed in Chapter 7 is based on a certain amount of postulation and prescription. Clearly, use of the methodology in an industrial situation, in an 'action research' mode (as undertaken for the 'make v buy' analysis), will lead to its improvement.

Improving WBS - A number of issues concerning WBS need to be improved. Firstly, the model building time was significant in the case-study. This was identified as a problem for simulation in Chapter 6 and WBS has not solved this problem, despite using ATOMS and proprietary systems. This is because of the sheer scale of the model. However, given that much of the development work was undertaken for the first time in this project, the building of the second whole business model should incur significantly less development time. This is because the data required has been more clearly identified, error checking, data loading and editing routines have been written and the WBS software debugged. Thus, a further model should be built to get a more realistic view on the model development time and how it might be improved.

The second problem that needs to be addressed is the length of the model runtime. Given that WBS requires the use of discrete event simulation, significant aggregation over and above that used in the BroomCo model is unlikely to be useful. The application of more advanced technology therefore seems an appropriate avenue to go down. This might include using Pentium PC technology or Workstation based technology. Parallel processing may also be a potential avenue of investigation.

The third issue that needs to be addressed is the robustness of WBS. It is prone to collapse for no apparent reason. Model packages such as DBFLEX sometimes create unpredictable memory problems in the computer hardware. This causes the both the package itself and the WBS software to terminate prematurely. Of the packages used in the experiments, DBFLEX was the most likely package to cause premature simulation run termination. Perhaps, the use of Object Orientated Programming techniques may make the software more robust and it should therefore be investigated.

Linking Operational and Business Metrics - WBS provides a tool that enables operational and business metrics to be simultaneously evaluated. This is a major step forward. This thesis has illustrated that this is possible, but has only touched on the insights which can be obtained. This capability is given even greater significance when viewed in the light of a recent report written by Oliver and Hunter (1994) at the University of Cambridge. They suggest that :

> '..significant improvements in manufacturing efficiencies can be made through the use of Japanese methods by UK companies. However, translating these manufacturing improvements into enhanced financial performance is much more problematic, and it may be here that the real challenge lies in the years ahead.'

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Appendix 1

Publications and Reports Produced During the Project

External Papers and Reports

Manufacturing Systems Redesign, 1992, Published by Hobsons Scientific as part of The Higher Education - Enterprise Link Series, (Reproduced in part (Fordhouses casestudy element) in Manufacturing Systems Design and Analysis (2nd Edition), Wu, 1994, Chapman and Hall, ISBN 0 412 58140 X, pp395 - 411)

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Lewis, P.A., and Love, D.M., 1993, The use of generic elements for the design of kanban systems, Advances in Manufacturing Technology VII, pp67 - 72, Bath University Press

Internal Reports Produced

Introduction to the Design of Kanban Systems (1989)

Cell Formation and Rank Order Clusterng (1990)

Cell Definition Structured Help (1990)

Material Flow Management : An Application To the Reduction of Stock and Arrears at LAPEC (1992)

Clustering and Sorting Techniques Application Guide (with G Black) (1992)

Appendix 2

Business Model Used for WBS

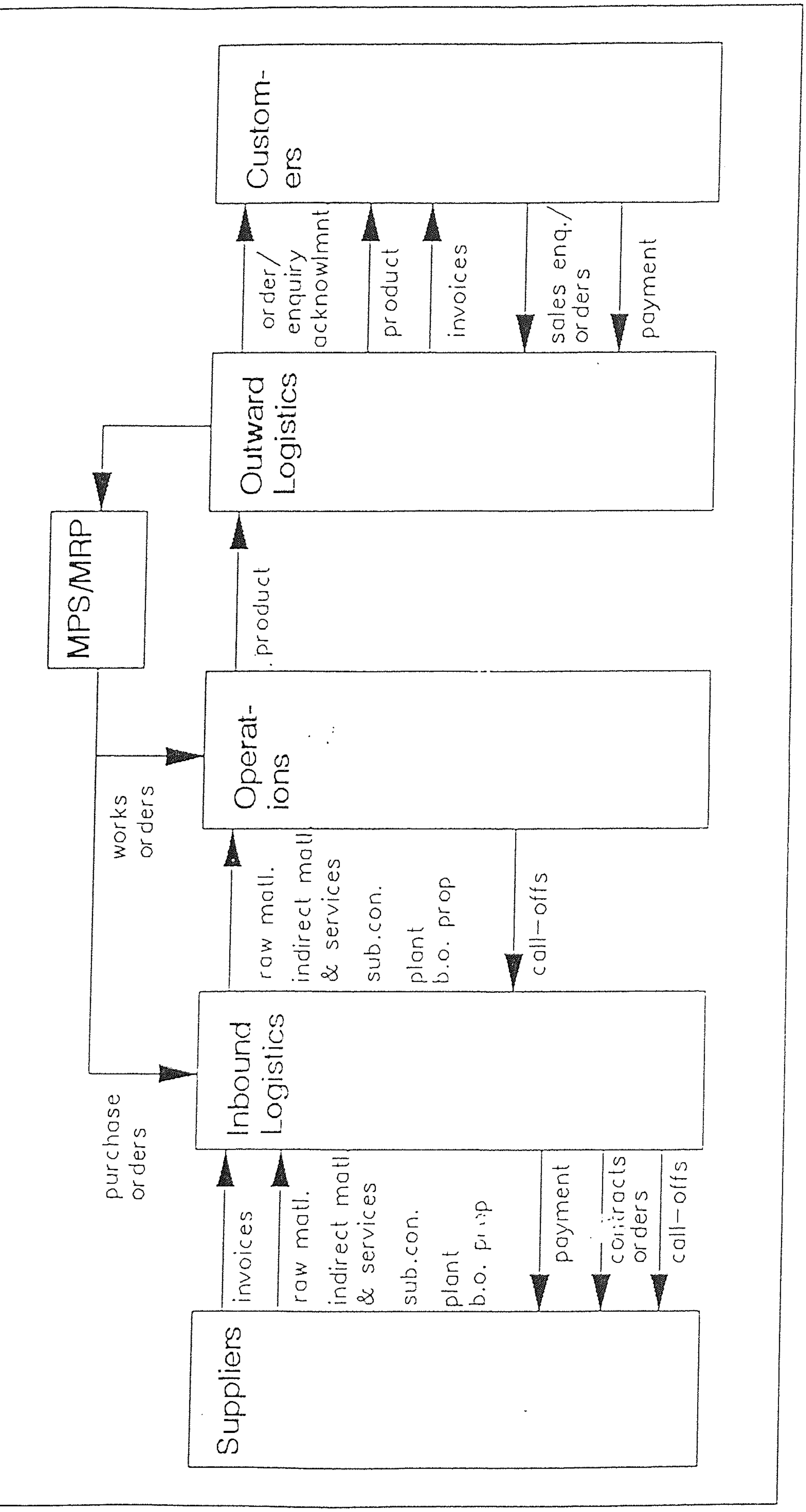


Figure A2.1 Major Interfaces

Figure A2.2 Major Processes

Outbound Logistics

- enquiry process
- s. order process
- product out process
- money in process

Operations

- manufacturing
- w. order launch
- w. order close

Inbound Logistics

- enquiry process
- p. order placement
- product in process
- money out process

Support

financial accounting : B/S/PL/funds/ratios

All

salaries

Figure A2.3 Sales Order Process

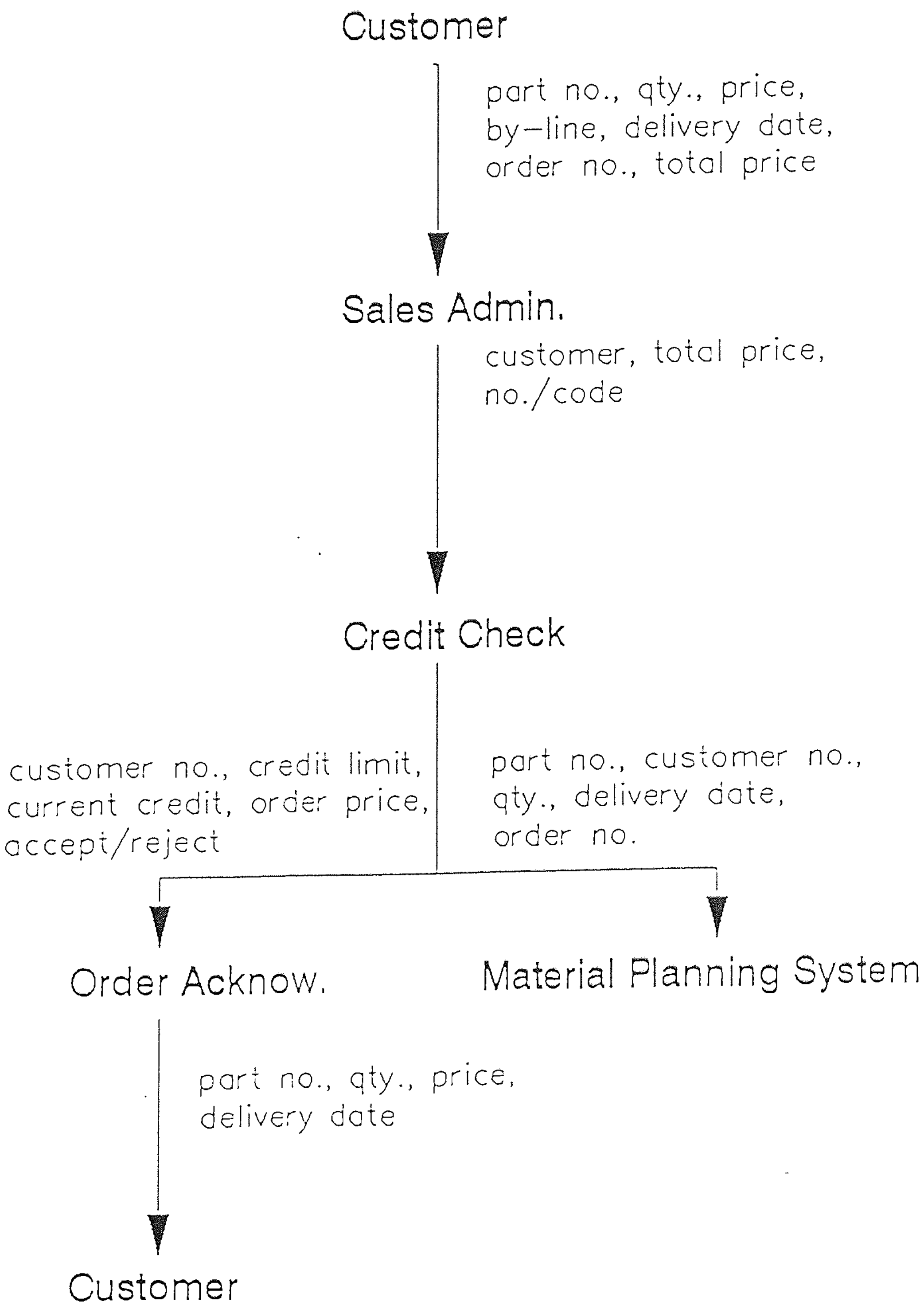


Figure A2.4 Payment in Process

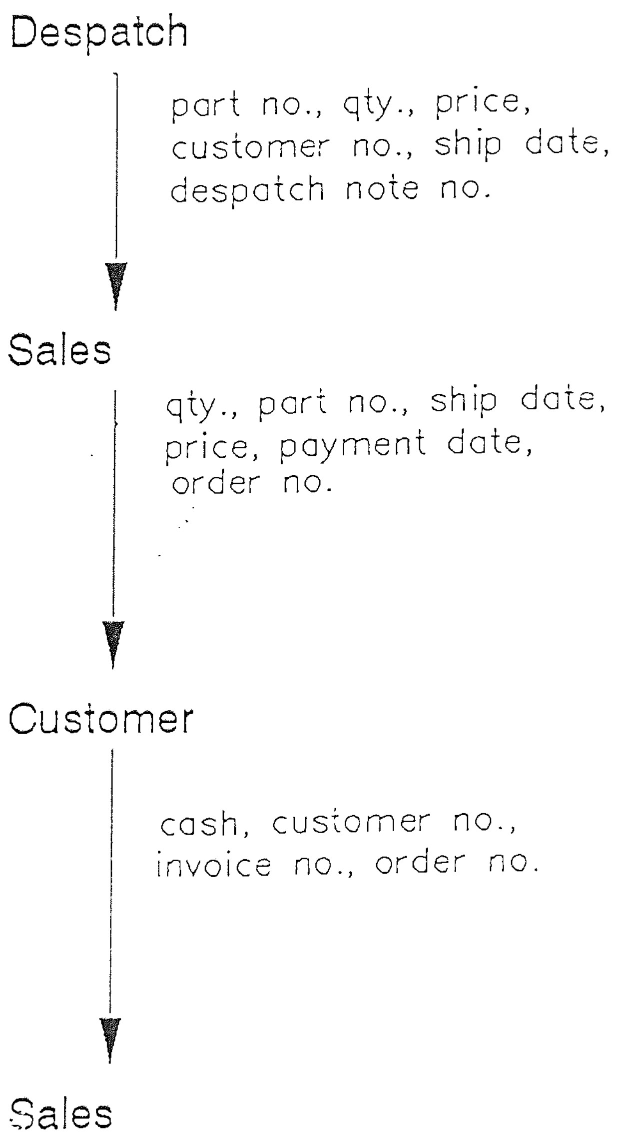


Figure A2.5 The Product Out Process

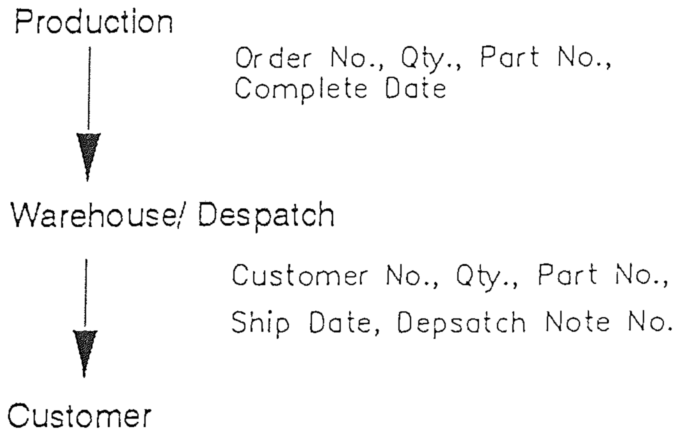


Figure A2.6 The Money Out Process

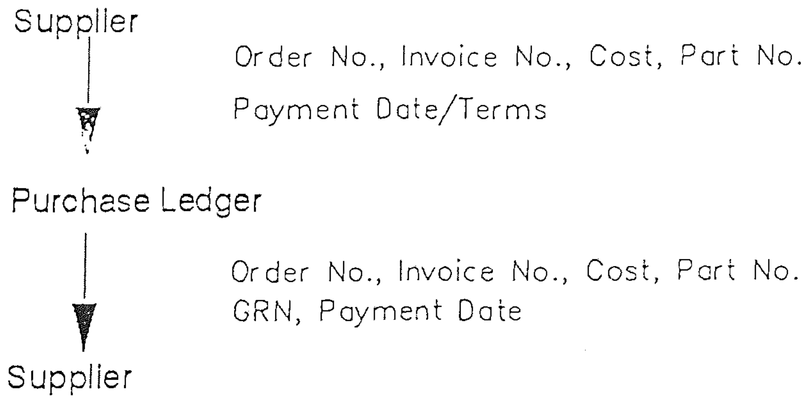


Figure A2.7 The Purchase Order Out Process

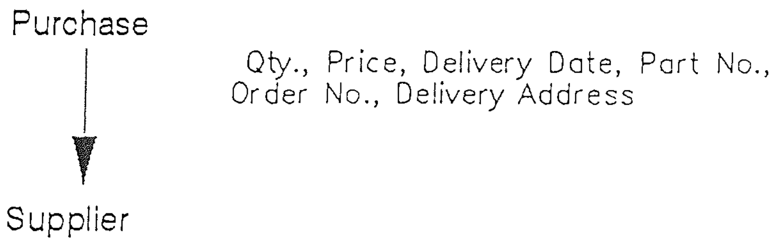
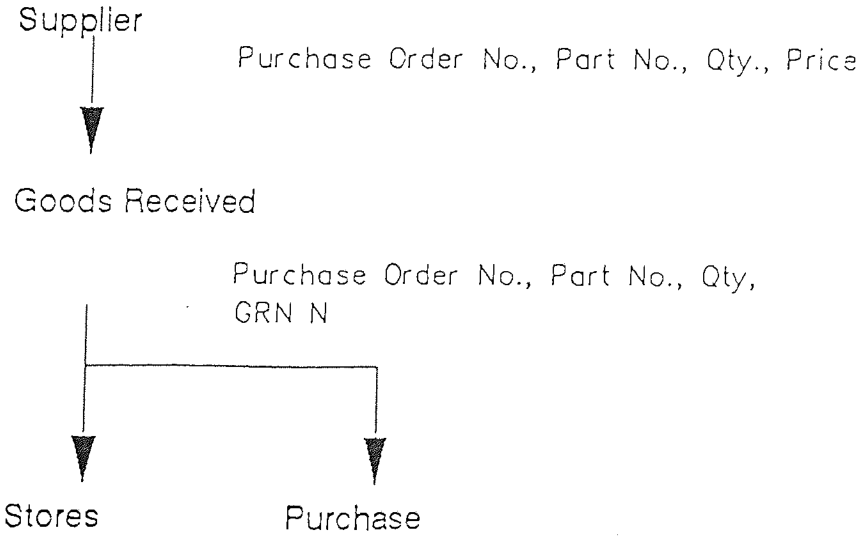


Figure A2.8 The Product In Process



Appendix 3

Characterisation Model (Business Metrics)

Model Data - Steady State			
	sales	net margin	net assets
june	0	-702923	5588077
july	6300	-396558	5191519
august	0	-27034	5109674
sept	6300	-61054	5048620
oct	234500	-207525	4841094
nov	2100	-50551	4790543
dec	982490	1002541	5793085
jan	1636330	840665	6633750
feb	2515812	555674	7189425
mar	407852	-48646	7140778
april	2432070	751390	7892168
may	3892960	887986	8780154
june	1548536	17142	8797296
july	2251952	423212	9220509
august	1193024	-207854	9012655
sept	1307656	-170412	8842242
oct	752604	-29402	8812840
nov	2211014	956383	9769223
dec	2860838	25792	9795015

Steady State Model (Welch, W = 2)			
	sales	net margin	net assets
June	0	-702923	5588077
July	2100	-375505	5296423
August	49420	-279019	5155797
Sept	49840	-148544	4996290
Oct	245078	131275.4	5116603
Nov	572344	304815.2	5421418
Dec	1074246	428160.8	5849579
Jan	1108917	459936.6	6309516
Feb	1594911	620324.8	6929841
Mar	2177005	597413.8	7527255
April	2159446	432709.2	7959964
May	2106674	406216.8	8366181
June	2263708	374375.2	8740556
July	2038826	190014.8	8930571
Aug	1410754	6537.2	8937108
Sept	1543250	194385.4	9131494
Oct	1665027	114901.4	9246395

Steady State Model (Welch, W = 4)			
	sales	net margin	net assets
June	0	-702923	5588077
July	2100	-375505	5296423
August	49420	-279019	5155797
Sept	175956	-63301	5194659
Oct	598204	105915	5576199
Nov	643520	178612	5748721
Dec	913050	306162	6048793
Jan	1345602	407831	6456624
Feb	1516961	416520	6873144
Mar	1741122	486601	7359745
April	1873447	469123	7828869
May	1909577	338795	8167664
June	1811385	242121	8409785
July	1777519	286644	8696429
Aug	2050073	294915	8991345

Appendix 4

Characterisation Model (Operational Metrics)

Period	WIP	INPUT	OUTPUT	STD HRS	OPS
0	0	0	0	0	0
1	604	699	95	5994.3	975
2	656	175	123	6224.09	591
3	825	300	131	7550.81	960
4	1194	476	107	7947.09	926
5	1209	157	142	7779.08	700
6	1131	53	131	7968.13	660
7	1177	190	144	8157.27	665
8	1106	75	146	7833.39	573
9	1146	158	118	8094.85	537
10	1133	80	93	8258.59	488
11	1189	199	143	8327.36	750
12	1125	88	152	8386.6	676
13	1177	202	150	8332.85	744
14	1140	86	123	8284.28	586
15	1169	172	143	8219.93	669
16	1145	103	127	8124.25	652
17	1225	185	105	8290.91	630
18	1168	94	151	8371.6	692
19	1267	213	114	8240.61	679
20	1265	104	106	8219.76	603
21	1358	216	123	8169.69	744
22	1308	97	147	8290.34	661
23	1334	173	147	8011.32	691
24	1290	84	128	8089.05	641
25	1354	190	126	8187.43	682
26	1300	101	155	8152.33	693
27	1625	463	138	8365.29	966
28	1595	73	103	8143.39	564
29	1694	222	123	8261.76	752
30	1602	45	137	8334.54	692
31	1574	158	186	8291.09	850
32	1447	48	175	8211.94	707
33	1743	459	163	8374.78	895
34	1666	54	131	8333.19	579
35	1757	254	163	8899.02	905
36	1640	20	137	8592.76	683
37	1815	352	177	8817.35	954
38	1696	36	155	8606.02	674
39	1619	59	136	8770.03	684
40	1493	42	168	8629.63	649
41	1471	123	145	8827.77	712
42	1407	72	136	8826.25	669
43	1325	80	162	8764.35	664
44	1226	77	176	8537.18	626
45	1227	157	156	8546.43	682
46	1184	104	147	8431.74	696
47	1248	205	141	8821.33	681
48	1139	64	173	8437.28	602
49	1174	201	166	8402.06	710
50	1125	69	118	7918.5	527
51	1556	605	174	8766.33	1034
52	1437	35	154	8511.4	603
53	1470	188	155	8594.32	797

Period	WIP	INPUT	OUTPUT	STD HRS	OPS
54	1351	34	153	7860.42	534
55	1403	186	134	8770.22	804
56	1288	47	162	7797.02	582
57	1183	43	148	7759.46	609
58	1067	29	145	7391.84	543
59	958	69	178	7569.34	622
60	834	32	156	6222.17	435
61	844	110	100	7321.83	419
62	757	25	112	6504.32	242
63	1027	377	107	8704.36	660
64	997	57	87	8452.2	332
65	1268	355	84	8628.96	599
66	1218	48	98	8340.34	356
67	1491	403	130	8524.13	886
68	1423	72	140	8436.36	635
69	1500	238	161	8478.42	804
70	1398	47	149	8167.2	663
71	1465	223	156	8395.28	851
72	1347	26	144	7463.21	531
73	1466	288	169	8410.64	822
74	1376	38	128	7911.59	484
75	1556	365	185	8329.5	1094
76	1444	49	161	7825.58	558
77	1729	428	143	8603.89	1015
78	1618	21	132	8490.23	670
79	1807	332	143	8521.21	914
80	1708	34	133	8092.57	548
81	1829	273	152	8817.83	875
82	1718	8	119	7659.98	424
83	1818	235	135	8747.64	762
84	1699	2	121	7788.61	467

Appendix 5

Make v Buy Analysis

KEY TO FAMILY CODING

CODE	SHORTHAND	DESCRIPTION
	COMPONENTS	
C1	SMW	sheet metalwork
C2	SMW & M/C	sheet metalwork & machining
C3	PRESS	presswork
C4	PRESS & M/C	presswork & machining
C5	M/C	machining
C6	M/C & HT	machining with heat treatment
C7	M/C OF CASTINGS	machining of castings & pressings
C8	FLEX CONNECTIONS	flexible connections
	ASSEMBLIES	
A1	M/C	machining only
A2	PRESS & M/C	presswork & machining
A3	SMW & M/C	sheet metalwork & machining
A4	M/C, SMW & PRESS	machining, sheet metalwork & presswork
A5	PRESS	presswork only
A6	PRESS & SMW	presswork & sheet metalwork
A7	SMW	sheet metalwork only
A8	TANKS & HEAVIER	tanks & heavier engineering
C	CUSTOMISED	customised parts

Comparison of Made In vs Bought Out Costs

	IN	OUT
SMW	£626,347	£657,452
SMW & M/C	£104,256	£107,100
PRESS	£597,909	£439,925
PRESS & M/C	£282,300	*
M/C	£1,420,813	£1,187,282
M/C & HT	£62,116	£48,034
M/C OF CASTINGS	£248,337	£222,973
FLEX CONNECTIONS	£2,215	*
<u>ASSEMBLIES</u>		
M/C	£232,774	£201,457
PRESS & M/C	£504,665	*
SMW & M/C	£914,309	£771,907
M/C, SMW & PRESS	£238,651	*
PRESS	£138,292	£99,591
PRESS & SMW	£45,764	*
SMW	£452,483	£508,232
TANKS & HEAVIER	£752,924	£755,274
CUSTOMISED	£99,741	*

The bought out cost assumes that no space is saved for individual families and that there are no extra acquisition costs

* = it has not been possible to obtain a reliable external quote

	1	2	3	4	5	6
SMW	IN	OUT	OUT	IN	IN	OUT
SMW & M/C	IN	OUT	OUT	IN	IN	OUT
PRESS	IN	OUT	IN	OUT	OUT	OUT
COMPLEX M/C	IN	OUT	IN	IN	OUT	OUT
M/C OF CASTINGS	IN	OUT	OUT	OUT	OUT	OUT
SIMPLE M/C	IN	OUT	OUT	OUT	OUT	OUT
M/C & HT	IN	OUT	OUT	OUT	OUT	OUT
PRESS & M/C	IN	IN	IN	IN	IN	IN
FLEX CONNECTIONS	IN	IN	IN	IN	IN	IN
<u>ASSEMBLIES</u>						
SMW & M/C	IN	OUT	OUT	IN	OUT	IN
SMW	IN	OUT	OUT	IN	IN	IN
PRESS	IN	OUT	IN	OUT	OUT	IN
M/C	IN	OUT	OUT	OUT	OUT	IN
TANKS & HEAVIER	IN	OUT	OUT	OUT	OUT	IN
PRESS & SMW	IN	IN	IN	IN	IN	IN
M/C, SMW & PRESS	IN	IN	IN	IN	IN	IN
PRESS & M/C	IN	IN	IN	IN	IN	IN
CUSTOMISED	IN	IN	IN	IN	IN	IN

For assembly families only :

IN = only the assembly process is in-house and the components are sourced as the appropriate component family, except for tanks & heavier engineering where the components would remain in-house

OUT = both the components and the assembly process are sourced outside

Appendix 6

Boundary Model (Business Metrics)

	Boundary Business Metrics		
	sales	net profit	net assets
june	0	-702923	5588077
july	6300	-396558	5191519
august	0	-27034	5109674
sept	6300	-61054	5048620
oct	234500	-207525	4841094
nov	2100	-50551	4790543
dec	982490	1002541	5793085
jan	1636330	840665	6633750
feb	2515812	555674	7189425
mar	407852	-48646	7140778
april	2432070	751390	7892168
may	3892960	887986	8780154
june	1548536	17142	8797296
july	2251952	423212	9220509
august	1193024	-207854	9012655
sept	1307656	-170412	8842242
oct	752604	-29402	8812840
nov	2211014	956383	9769223
dec	2860838	25792	9795015
jan	1455570	-1169141	8625874
feb	744524	128700	8754634
mar	894824	18649	8773284
april	603104	895512	9668796
may	4012112	282424	9951220
june	55000	-139732	9811488
july	1514100	212657	10100767

Appendix 7

Boundary Model (Operational Metrics)

PERIOD	WIP	INPUT	OUTPUT	STD HRS	OPS
0	0	0	0	0	0
1	604	699	95	5994.3	975
2	656	175	123	6224.09	591
3	825	300	131	7550.81	960
4	1194	476	107	7947.09	926
5	1209	157	142	7779.08	700
6	1131	53	131	7968.13	660
7	1177	190	144	8157.27	665
8	1106	75	146	7833.39	573
9	1146	158	118	8094.85	537
10	1133	80	93	8258.59	488
11	1189	199	143	8327.36	750
12	1125	88	152	8386.6	676
13	1177	202	150	8332.85	744
14	1140	86	123	8284.28	586
15	1169	172	143	8219.93	669
16	1145	103	127	8124.25	652
17	1225	185	105	8290.91	630
18	1168	94	151	8371.6	692
19	1267	213	114	8240.61	679
20	1265	104	106	8219.76	603
21	1358	216	123	8169.69	744
22	1308	97	147	8290.34	661
23	1334	173	147	8011.32	691
24	1290	84	128	8089.05	641
25	1354	190	126	8187.43	682
26	1300	101	155	8152.33	693
27	1625	463	138	8365.29	966
28	1595	73	103	8143.39	564
29	1694	222	123	8261.76	752
30	1602	45	137	8334.54	692
31	1574	158	186	8291.09	850
32	1447	48	175	8211.94	707
33	1743	459	163	8374.78	895
34	1666	54	131	8333.19	579
35	1757	254	163	8899.02	905
36	1640	20	137	8592.76	683
37	1815	352	177	8817.35	954
38	1696	36	155	8606.02	674
39	1619	59	136	8770.03	684
40	1493	42	168	8629.63	649
41	1471	123	145	8827.77	712
42	1407	72	136	8826.25	669
43	1325	80	162	8764.35	664
44	1226	77	176	8537.18	626
45	1227	157	156	8546.43	682
46	1184	104	147	8431.74	696
47	1248	205	141	8821.33	681
48	1139	64	173	8437.28	602
49	1174	201	166	8402.06	710
50	1125	69	118	7918.5	527
51	1556	605	174	8766.33	1034
52	1437	35	154	8511.4	603
53	1470	188	155	8594.32	797

PERIOD	WIP	INPUT	OUTPUT	STD HRS	OPS
54	1351	34	153	7860.42	534
55	1403	186	134	8770.22	804
56	1288	47	162	7797.02	582
57	1183	43	148	7759.46	609
58	1067	29	145	7391.84	543
59	958	69	178	7569.34	622
60	834	32	156	6222.17	435
61	844	110	100	7321.83	419
62	757	25	112	6504.32	242
63	1027	377	107	8704.36	660
64	997	57	87	8452.2	332
65	1268	355	84	8628.96	599
66	1218	48	98	8340.34	356
67	1491	403	130	8524.13	886
68	1423	72	140	8436.36	635
69	1500	238	161	8478.42	804
70	1398	47	149	8167.2	663
71	1465	223	156	8395.28	851
72	1347	26	144	7463.21	531
73	1466	288	169	8410.64	822
74	1376	38	128	7911.59	484
75	1556	365	185	8329.5	1094
76	1444	49	161	7825.58	558
77	1729	428	143	8603.89	1015
78	1618	21	132	8490.23	670
79	1807	332	143	8521.21	914
80	1708	34	133	8092.57	548
81	1829	273	152	8817.83	875
82	1718	8	119	7659.98	424
83	1818	235	135	8747.64	762
84	1699	2	121	7788.61	467
85	1549	23	173	6157.14	480
86	1397	3	155	6264.45	472
87	1365	110	142	6460.5	602
88	1216	1	150	4965.4	416
89	1162	78	132	5174.17	489
90	1057	2	107	3429.23	223
91	1054	91	94	4913.34	387
92	968	3	89	3914.3	302
93	991	110	87	4859.24	392
94	904	8	95	3656.56	227
95	959	138	83	4562.99	395
96	919	8	48	3345.41	181
97	970	109	58	4058.49	319
98	916	7	61	3642.36	234
99	935	110	91	4820.22	397
100	868	2	69	3621.98	230
101	1016	212	64	4805.92	418
102	955	2	63	4205.66	216
103	1019	144	80	4501.87	365
104	963	4	60	3047.33	152
105	1251	362	74	4355.08	469
106	1192	12	71	4660.43	243
107	1212	96	76	5600.01	442

108	1145	21	88	5437.49	375
109	1132	66	79	5304.1	383
110	1052	13	93	5127.19	394
111	982	26	96	4306.51	324
112	917	14	79	3473.85	227
113	906	45	56	3491.29	296
114	863	28	71	3694.84	244

Appendix 8

Concept Model (Business Metrics)

	Concept Model		
	Sales	Net Assets	Net Profit
june	0	5565491	-725508
july	6300	5024677	-540813
aug	4200	4896390	-128286
sept	4200	4693845	-202544
oct	82040	4594033	-99812

Appendix 9

Concept Model (Operational Metrics)

PERIOD	WIP	INPUT	OUTPUT	STD HRS	OPS
0	0	0	0	0	0
1	609	699	90	5512.1	976
2	697	175	87	5632.08	591
3	871	299	125	7000.04	946
4	1238	476	109	7213.66	885
5	1253	157	142	7033.58	713
6	1175	53	131	6950.85	593
7	1260	190	105	7195.34	634
8	1237	75	98	7106.44	551
9	1278	157	116	7153.29	545
10	1288	80	70	7105.73	429
11	1359	198	127	7413.38	751
12	1309	88	138	7429.78	626
13	1364	203	148	7585.08	792
14	1336	86	114	7278.87	468
15	1389	173	120	7071.03	566
16	1383	103	109	7031.28	481
17	1444	182	121	7587.97	745
18	1419	93	118	7167.41	515
19	1521	218	116	7262.84	614
20	1500	104	125	7062.27	491
21	1585	216	131	7223	625
22	1546	97	136	7091.03	522

Appendix 10

Detail Model (Business Metrics)

	Detail Business Metrics		
	sales	net profit	net assets
june	0	-702923	5588077
july	6300	-396558	5191519
august	0	-27034	5109674
sept	6300	-61054	5048620
oct	234500	-207525	4841094
nov	2100	-50551	4790543
dec	982490	1002541	5793085
jan	1636330	840665	6633750
feb	2515812	555674	7189425
mar	407852	-48646	7140778
april	2432070	751390	7892168
may	3892960	887986	8780154
june	1548536	17142	8797296
july	2251952	423212	9220509
august	1193024	-207854	9012655
sept	1307656	-170412	8842242
oct	752604	-29402	8812840
nov	2211014	956383	9769223
dec	2860838	25792	9795015
jan	1455570	-1169141	8625874
feb	1239524	211310	8837184
mar	729824	-18636	8818548

Appendix 11

Detail Model (Operational Metrics)

PERIOD	WIP	INPUT	OUTPUT	STD HRS	OPS
0	0	0	0	0	0
1	604	699	95	5994.3	975
2	656	175	123	6224.09	591
3	825	300	131	7550.81	960
4	1194	476	107	7947.09	926
5	1209	157	142	7779.08	700
6	1131	53	131	7968.13	660
7	1177	190	144	8157.27	665
8	1106	75	146	7833.39	573
9	1146	158	118	8094.85	537
10	1133	80	93	8258.59	488
11	1189	199	143	8327.36	750
12	1125	88	152	8386.6	676
13	1177	202	150	8332.85	744
14	1140	86	123	8284.28	586
15	1169	172	143	8219.93	669
16	1145	103	127	8124.25	652
17	1225	185	105	8290.91	630
18	1168	94	151	8371.6	692
19	1267	213	114	8240.61	679
20	1265	104	106	8219.76	603
21	1358	216	123	8169.69	744
22	1308	97	147	8290.34	661
23	1334	173	147	8011.32	691
24	1290	84	128	8089.05	641
25	1354	190	126	8187.43	682
26	1300	101	155	8152.33	693
27	1625	463	138	8365.29	966
28	1595	73	103	8143.39	564
29	1694	222	123	8261.76	752
30	1602	45	137	8334.54	692
31	1574	158	186	8291.09	850
32	1447	48	175	8211.94	707
33	1743	459	163	8374.78	895
34	1666	54	131	8333.19	579
35	1757	254	163	8899.02	905
36	1640	20	137	8592.76	683
37	1815	352	177	8817.35	954
38	1696	36	155	8606.02	674
39	1619	59	136	8770.03	684
40	1493	42	168	8629.63	649
41	1471	123	145	8827.77	712
42	1407	72	136	8826.25	669
43	1325	80	162	8764.35	664
44	1226	77	176	8537.18	626
45	1227	157	156	8546.43	682
46	1184	104	147	8431.74	696
47	1248	205	141	8821.33	681
48	1139	64	173	8437.28	602
49	1174	201	166	8402.06	710
50	1125	69	118	7918.5	527
51	1556	605	174	8766.33	1034
52	1437	35	154	8511.4	603
53	1470	188	155	8594.32	797

PERIOD	WIP	INPUT	OUTPUT	STD HRS	OPS
54	1351	34	153	7860.42	534
55	1403	186	134	8770.22	804
56	1288	47	162	7797.02	582
57	1183	43	148	7759.46	609
58	1067	29	145	7391.84	543
59	958	69	178	7569.34	622
60	834	32	156	6222.17	435
61	844	110	100	7321.83	419
62	757	25	112	6504.32	242
63	1027	377	107	8704.36	660
64	997	57	87	3452.2	332
65	1268	355	84	8628.96	599
66	1218	48	98	8340.34	356
67	1491	403	130	8524.13	886
68	1423	72	140	8436.36	635
69	1500	238	161	8478.42	804
70	1398	47	149	8167.2	663
71	1465	223	156	8395.28	851
72	1347	26	144	7463.21	531
73	1466	288	169	8410.64	822
74	1376	38	128	7911.59	484
75	1556	365	185	8329.5	1094
76	1444	49	161	7825.58	558
77	1729	428	143	8603.89	1015
78	1618	21	132	8490.23	670
79	1807	332	143	8521.21	914
80	1708	34	133	8092.57	548
81	1829	273	152	8817.83	875
82	1718	8	119	7659.98	424
83	1818	235	135	8747.64	762
84	1699	2	121	7788.61	467
85	1549	23	173	6157.14	480
86	1397	3	155	6264.45	472
87	1384	110	123	6431.09	599
88	1266	1	119	5138.5	423
89	1224	78	120	5258.33	533
90	1128	2	98	3883	258
91	1124	91	95	5255.12	438
92	1042	3	85	3963.11	332
93	1073	110	79	4628.22	349
94	1006	8	75	3336.26	199
95	1052	138	92	5429.67	429
96	992	8	68	4305.61	297
97	1053	109	48	5095.07	379
98	1008	7	52	3275.8	142