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T. S. BAINES

MODELLING IN THE EVALUATION OF A MANUFACTURING STRATEGY

Supervisors: Prof. J. M. Kay & Prof. D. J. Hamblin

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ABSTRACT

This thesis describes research that has developed the principles of a modelling tool for the analytical evaluation of a manufacturing strategy.

The appropriate process of manufacturing strategy formulation is based on mental synthesis with formal planning processes supporting this role. Inherent to such processes is a stage where the effects of alternative strategies on the performance of a manufacturing system must be evaluated so that a choice of preferred strategy can be made. Invariably this evaluation is carried out by practitioners applying mechanisms of judgement, bargaining and analysis. This thesis makes a significant and original contribution to the provision of analytical support for practitioners in this role.

The research programme commences by defining the requirements of analytical strategy evaluation from the perspective of practitioners. A broad taxonomy of models has been used to identify a set of potentially suitable techniques for the strategy evaluation task. Then, where possible, unsuitable modelling techniques have been identified on the basis of evidence in the literature and discarded from this set. The remaining modelling techniques have been critically appraised by testing representative contemporary modelling tools in an industrially based experimentation programme. The results show that individual modelling techniques exhibit various limitations in the strategy evaluation role, though some combinations do appear to provide the necessary functionality. On the basis of this comprehensive and in-depth knowledge a modelling tool has been specifically designed for this task. Further experimental testing has then been conducted to verify the principles of this modelling tool.

This research has bridged the fields of manufacturing strategy formulation and manufacturing systems modelling and makes two contributions to knowledge. Firstly, a comprehensive and in-depth platform of knowledge has been established about modelling techniques in manufacturing strategy evaluation. Secondly, the principles of a tool that supports this role have been formed and verified.

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COMMONLY USED ABBREVIATIONS

1. **ABC: Activity Based Costing**
2. **BP: Business Planning**
3. **DES: Discrete Event Simulation**
4. **IEM: Integrated Enterprise Modelling**
5. **QT: Queuing Theory**
6. **SD: System Dynamics**

CHAPTER 1
INTRODUCTION

A successful manufacturing industry can make a significant contribution to the prosperity of a nation. For a manufacturing company to consistently realise success invariably requires the organisation to seek and achieve congruence between internal manufacturing capabilities and external market and financial environments. This approach to organisation design is often expressed as a manufacturing strategy, and there is a close association between the existence of an intended manufacturing strategy within a business, and prosperity.

A manufacturing strategy can be formed by a number of methods, but a particularly successful approach is practising managers being guided through strategy formulation by a formal planning process. Usually, such a process is a sequence of activities that secure recognition of a company's existing manufacturing capabilities, structure an expression of the associated financial and market environments, and stimulate the evolution of a sequence of actions to overcome any deficits that may exist.

During manufacturing strategy formulation it is usual to evaluate the affect of proposed actions on the capabilities of the manufacturing system under consideration. Such evaluation can be made through judgement of individual personnel, refined through bargaining between a number of personnel, and supported by analytical methods. One such analytical method is modelling. A model can be created of a manufacturing system, a number of modifications can be made to the model to reflect the strategy under consideration, and the ensuing model behaviour treated as a prediction of future manufacturing capabilities.

Modelling is often used in detailed design of manufacturing systems. However, manufacturing strategy formulation is different from detailed manufacturing system design, and hence demands specific characteristics of a modelling approach. Unfortunately, there is a scarcity of previous research that has critically appraised modelling approaches in the role of strategy evaluation, and a verified modelling solution to this task is needed. Therefore, to promote the application of the manufacturing strategy concept, this thesis investigates modelling in the evaluation of a manufacturing strategy, and makes an original and significant contribution to knowledge on this subject. The structure of this thesis is as follows and is summarised in Figure 1.1.

Chapter 2 performs a literature review that sets the terminology used in this thesis, and explores the issues that currently constrain the application of the manufacturing strategy concept. This chapter culminates in identifying research opportunities in manufacturing strategy evaluation and identifies modelling as a potential solution to this task.

Chapter 3 establishes the extent of current knowledge on modelling through a second review of the literature. Initially, this chapter develops a comprehensive taxonomy of models to expose the variety of modelling approaches available, and a number of representative modelling techniques are chosen. Direct evidence is then sought from the literature on the suitability of these modelling approaches to manufacturing strategy evaluation.

Chapter 4 builds on the knowledge gained from the manufacturing strategy and modelling literature respectively. This chapter argues for research that considers modelling for the task of manufacturing strategy evaluation and develops a precise research aim for this thesis. A five stage programme of research activities is then designed to realise this aim. The initial stages of this programme develop a comprehensive and in-depth platform of empirically derived knowledge that is essential to forming the foundations of a modelling tool, subsequently the principles of a modelling tool are established, and the later stages verify this modelling solution.

Chapter 5 presents the execution of the first stage of the research programme by defining the requirements of modelling in a manufacturing strategy evaluation, termed the requirement set. This is achieved through in-depth interviews with practitioners.

Chapter 6 presents the execution of the second stage of the research programme by identifying clearly unsuitable modelling approaches due to distinct limitations being apparent when considered against the requirement set. This screening is based on evidence from the literature, and discounts a number of modelling approaches from further consideration in this research.

Chapter 7 presents the execution of the third stage of the research programme and performs a critical appraisal of modelling approaches. This is achieved by the design and application of a set of industrially based experiments, to test contemporary modelling tools against the previously determined requirement set.

Chapter 8 presents the execution of the fourth stage of the research programme and forms the principles of a modelling tool. This is realised by establishing the most suitable modelling approach to manufacturing strategy evaluation on the basis of the results gained in Chapter 7.

Chapter 9 presents the fifth and final stage of this research programme and conducts tests to verify the principles of the modelling tool established in the preceding chapter. Experiments are conducted at a second manufacturing company and provide confidence for a future investment in the construction of a purpose built modelling tool.

Finally, Chapter 10 draws conclusions on the work described in this thesis, and highlights two main contributions to knowledge of this research. First, that a comprehensive and in-depth platform of knowledge has been established concerning the support modelling techniques give to manufacturing strategy evaluation. Second, that the principles of a modelling tool tailored to this task have been formed and primarily verified. The limitations and concerns are then aired and, in closing, recommendations are made for future work in the area of manufacturing strategy research.

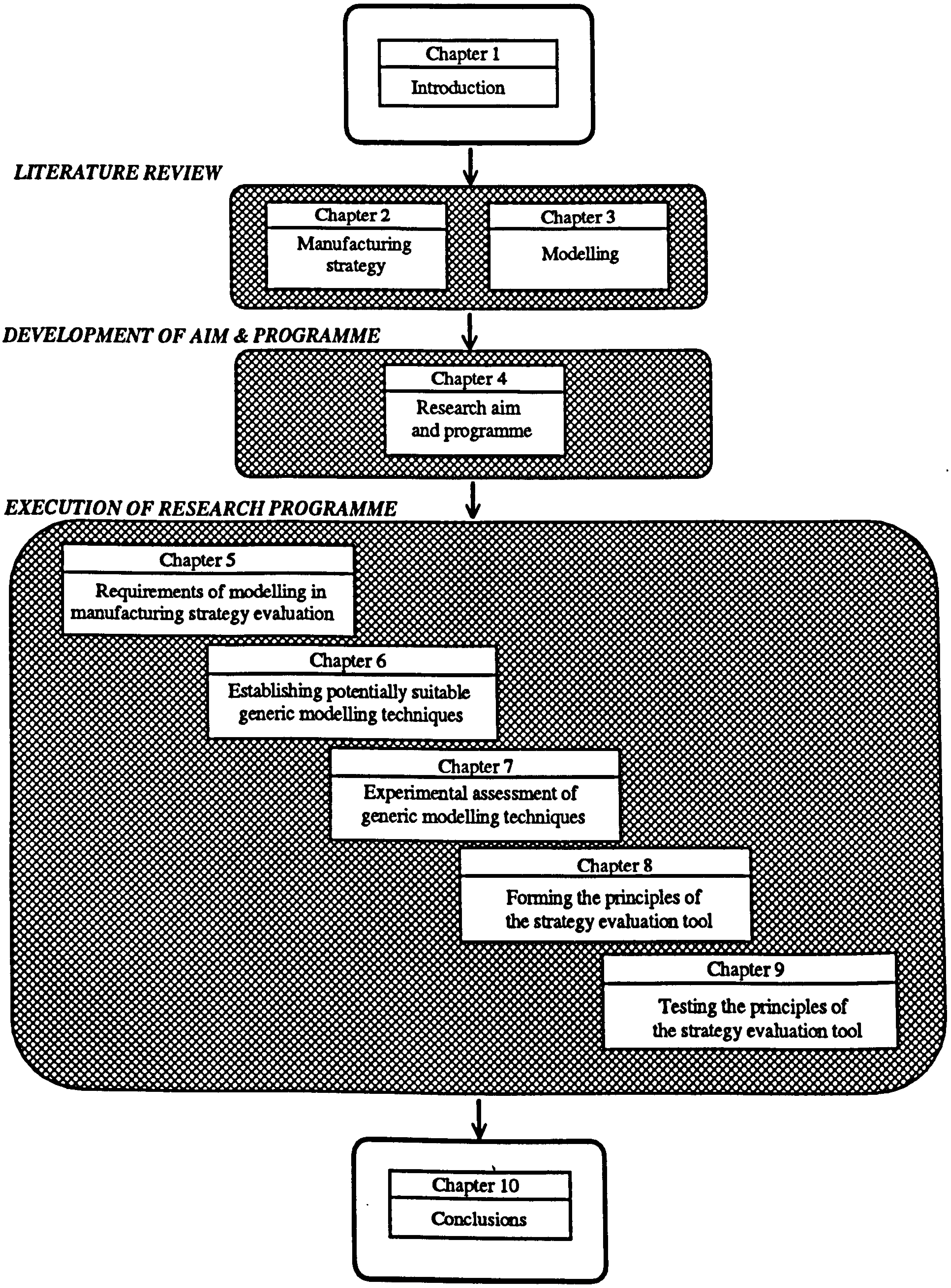

Figure 1.1: Thesis structure

CHAPTER 2

MANUFACTURING STRATEGY LITERATURE REVIEW

The motive of this research is to aid companies in the formulation of manufacturing strategy. The objectives of this chapter are to introduce manufacturing strategy, to set the terminology used in this thesis, and to explore the issues that currently constrain the application of this concept. These objectives are realised by addressing the following questions through a review of the literature that has made a valuable contribution to knowledge in this field[1].

1. What is a manufacturing strategy?
2. Why is manufacturing strategy important?
3. How can a manufacturing strategy be formed?
4. What are the current research issues that constrain the application of this concept?

From the literature it is apparent that a modelling mechanism is required that will support the evaluation of a proposed manufacturing strategy. Hence, this chapter concludes in identifying a need to carry out a similar review of the contributions in the modelling literature.

2.1 THE CONCEPT OF MANUFACTURING STRATEGY

Manufacturing strategy is a concept; it is a general notion about the organisation of a company's manufacturing activity. Probably because of this conceptual basis, there can be inconsistencies in the usage of terminology. Swamidass (1986) in a study of 35 manufacturing businesses noted that "...the term manufacturing strategy did not elicit uniform connotation in the minds of the executives...."; and Leong et al (1990) said that "...inconsistent terminology

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[1] There appears to be a recent trend to consider manufacturing strategy within the literature on operations strategy. According to Samson (1991) the distinction between these terms is that operations strategy and operations management encompass manufacturing and service activities. Likewise, Johnston et al (1993) consider operations to be a mix of goods and service; and Harrison (1993) suggests that 'operations' can be substituted for the word 'manufacturing' in many texts though the reverse is not necessarily true. Hence, appropriate operations strategy literature has been included in this review.

continues to be a problem in the manufacturing strategy literature". Misinterpretations can hinder research contributions. Evered (1983) argues that the "...quality of policy research will be influenced significantly by the care we take with conceptual clarity, particularly with regard to the praxis of strategic management". Therefore, this section explores the concept of manufacturing strategy and establishes through this a foundation of conventional terminology.

2.1.1 A definition of manufacturing strategy

The word 'strategy' has a Greek origin from around 550BC. Initially, the word referred to a role, for example a General, and later came to mean 'the art of the General' (Evered, 1983). More recently Chandler (1962), whilst discussing the planning and growth of an organisation, is generally accredited with probably the first definition of strategy in business. Chandler saw strategy as:

> "..the determination of the basic long-term goals and the objectives of an enterprise, and the adoption of courses of action and the allocation of resources necessary for carrying out these goals."

Later Ansoff (1969), in a business context, identified strategy as:

> "Strategy guides and directs a firm's growth and change."

Skinner (1969) is seen by authors such as Adam and Swamidass (1989), Anderson et al (1991), Sweeney (1991), and Probert et al (1993), as being the first to introduce the concept of manufacturing strategy. Skinner (in Skinner et al 1985) however, actually gives this credit to McLean in 1946, along with Miller and Rogers a decade later. According to Skinner, McLean observed that a number of companies may compete within an industry using entirely different approaches to manufacturing management. Irrespective of the actual origin, the literature considers the contribution of Skinner (1969) to be a milestone. In this work Skinner refers to strategy as:

> "...a set of plans and policies by which a company aims to gain advantage over its competitors."

The contribution of researchers such as Chandler, Ansoff and Skinner, amongst many others, can be clarified through viewing strategies at three tiers in an organisation. Hayes and Wheelwright (1984), define these levels as a hierarchical structure (Figure 2.1). The role that each strategy takes, they summarised as:

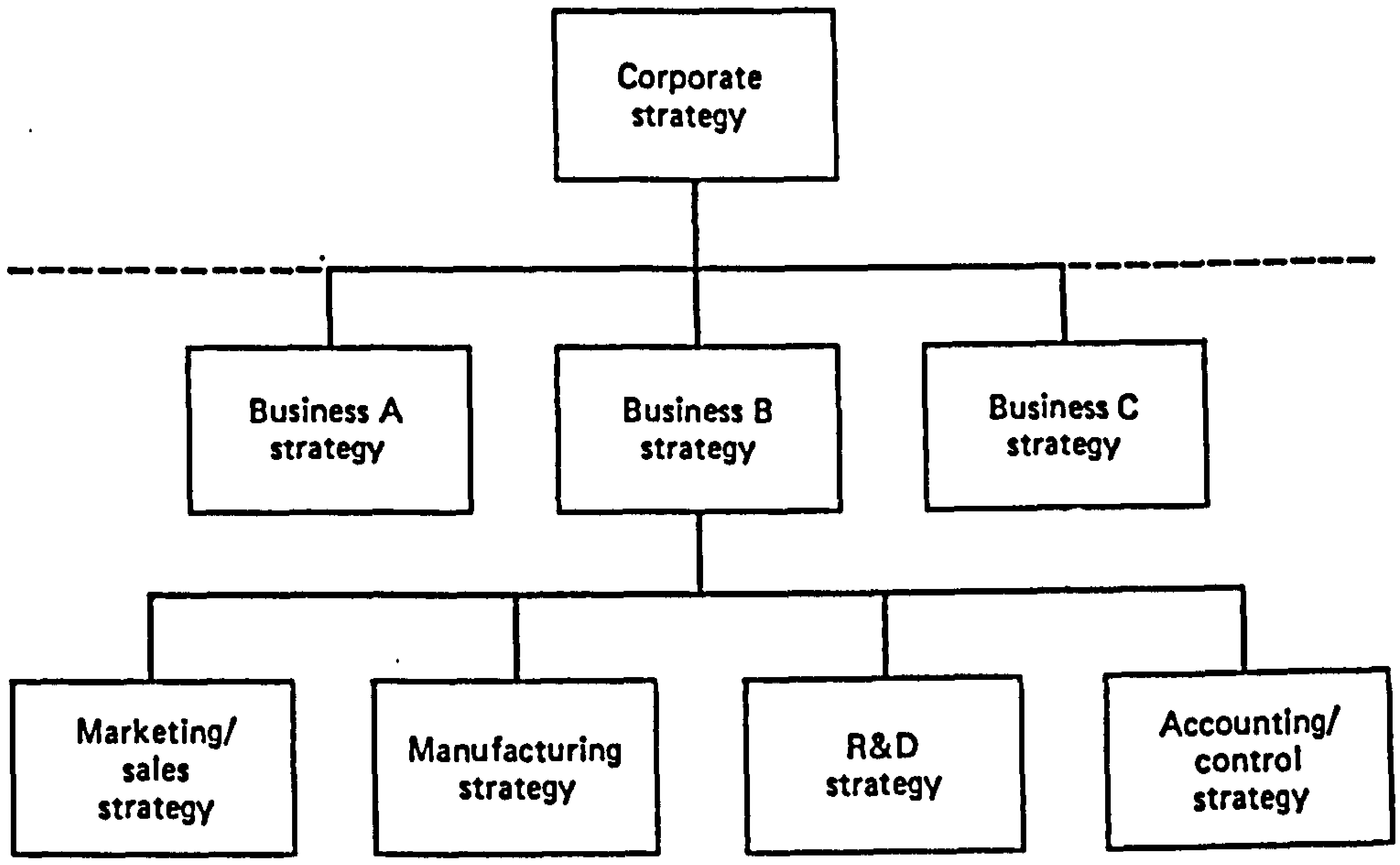

Figure 2.1: Levels of strategy in an organisation (Source: Hayes and Wheelwright, 1984)

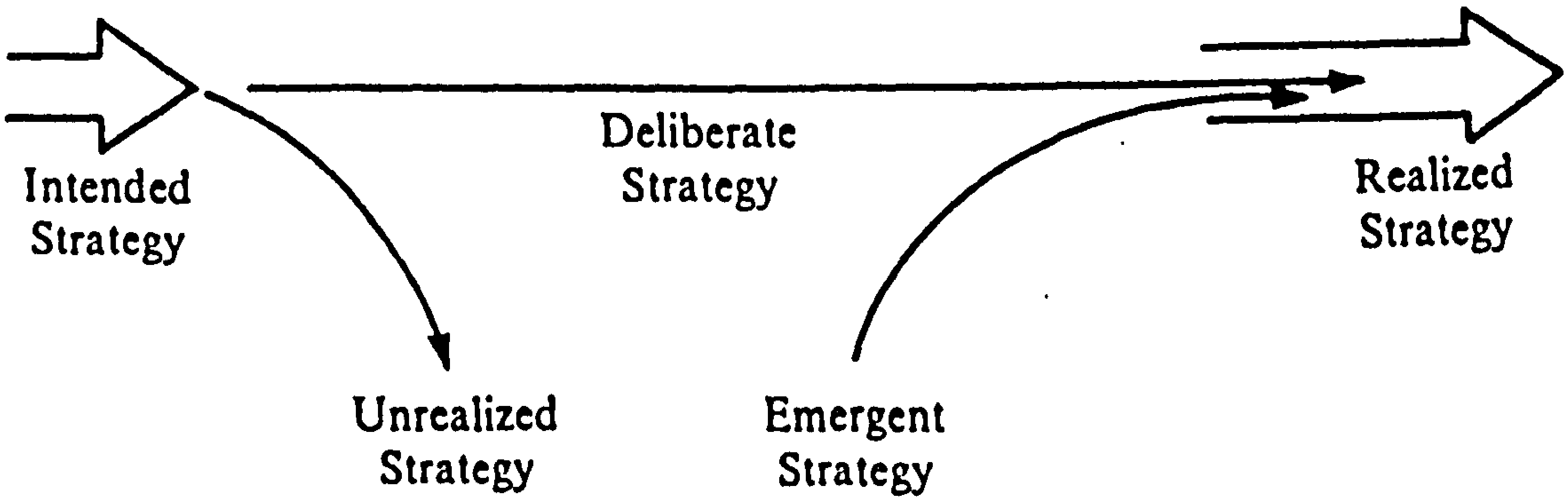

Figure 2.2: Forms of strategies (Source: Mintzberg, 1978)

> Corporate strategy : Definition of the businesses in which a corporation will participate, and the acquisition and allocation of key corporate resources to each of those businesses.
>
> Business strategy : The basis on which a business unit will achieve and maintain competitive advantage, in a way that links the strategy of the business to that of the corporation as a whole.
>
> Functional strategies : Providing support to the competitive advantage being sought by the business strategy.

Although the form of functional strategies other than manufacturing are outside the scope of this research, a brief insight assists in setting the context of manufacturing strategy. An overview of functional strategies proposed in the literature is given in Table 2.1. As illustrated in this table, functional strategies can be coarsely grouped into marketing, financial and manufacturing. Each of these strategies will have goals associated with their function. For example, the goals of a financial strategy can include Return On Investment (ROI) and profitability measures, while marketing goals include market share and growth (Pannesi, 1990). The functional strategies combine to form the basis of a company's business strategy (Anderson et al, 1991).

Since Skinner first promoted manufacturing strategy within an organisation, there have been numerous attempts to give a fuller and more precise definition of this specific functional strategy. An overview of such definitions is given in Table 2.2. Some differences in definitions appear to be semantic, for example Hayes and Wheelwright (1984) and Marucheck et al (1990), whilst other definitions represent a real alternative emphasis, such as Parnaby (1986) and Hill (1985). Anderson et al (1989) have observed a similar situation across a large sample of literature and call for a reduction in semantic differences and an understanding of emphasis. It appears that some research has fallen foul of a common criticism in this field, pointed out by Adam and Swamidass (1989), of creating new terms without materially adding to conceptual inventory. There is however a general agreement in the literature that manufacturing strategy has a long range thrust, and that there should be some competitive advantages defined (Schroeder, in Skinner et al, 1985). To support the practical application, and value to industry, of the manufacturing strategy concept, this thesis considers there to be two further attributes that should be explicit in a manufacturing strategy definition.

The first attribute is given by Evered (1983) who considers some definitions of strategy to be 'narrow' as the process of forming goals is excluded, other

	Source					
	Parnaby, 1986	Parnaby, 1988	New, 1989	Koelsch, 1989	Pannesi, 1990	Hax and Majluf, 1991
Functional strategies	Market	Market	Market	Marketing	Marketing	Marketing
	Product Engineering Manufacturing Systems Engineering Business Systems Engineering and Organisational	Product Engineering Manufacturing Systems Engineering Business Systems Engineering and Organisational Personnel Development and Training	Product Design Manufacturing	Product Manufacturing	Product Development Manufacturing	Human Resource Technology Procurement Manufacturing
	Financial Control	Financial Control		Financial	Finance	Financial

Table 2.1: Overview of functional strategies grouped into market, manufacturing, and financial categories

Author	Definition
Skinner, 1969	"Strategy is a set of plans and policies by which a company aims to gain advantage over its competitors."
Hayes and Wheelwright, 1984	"...consists of a sequence of decisions that, over time, enables a business unit to achieve a desired manufacturing structure, infrastructure, and a set of specific capabilities."
Cohen and Lee, 1985	"Manufacturing strategy is concerned with the development and implementation of plans which affect the firms choice of production resources, the deployment of these resources, and the design of the infrastructure to control operations activities."
Hill, 1985	"...a set of policies in both its process choice and infrastructure design...which are consistent with the existing way(s) that products win orders whilst being able to reflect future developments in line with changing business needs."
Parnaby, 1986	"The mix of machines, processes, people, control systems, computers information, organisational structure and job functions necessary to meet market needs at lowest manufacturing cost."
Swamidass and Newell, 1987	"...manufacturing strategy is viewed as the effective use of manufacturing strengths as a competitive weapon for the achievement of business and corporate goals."
Anderson et al, 1989	"...long range plan or vision for the operations function."
Miller and Hayslip, 1989	"...a projected pattern of manufacturing choices formulated to improve fundamental manufacturing capabilities, and to support business and corporate strategy."
Ghobadian, 1990	"The manner and extent by which the management puts the company's manufacturing resources at risk in order to support and achieve its chosen overall objective."
Marucheck et al, 1990	"Manufacturing strategy is a collective pattern of coordinated decisions that act upon the formulation, reformation and deployment of manufacturing resources and provide a competitive advantage in support of the overall strategic initiative of the firm..."
Schroeder and Lahr, 1990	"Manufacturing strategy provides a vision for the manufacturing organisation based on the business strategy. It consists of objectives, strategies and programs which help the business gain, or maintain, a competitive advantage."

Table 2.2: Overview of manufacturing strategy definitions

definitions give a 'broad' denotation of strategy that includes this process. Chandler (1962), for example, provides a broad definition of strategy. A narrow definition divorces the activities of goal and strategy formulation, enforcing a distinction between these two activities, and is felt to support practical application through allowing a more precise terminological foundation.

A second attribute in the strategy concept is provided by Mintzberg (1978) who defines strategy as "...a pattern in a stream of decisions", thus suggesting that strategies can evolve over time. Mintzberg argues that a 'realised' strategy may have 'intended' or 'emergent' origins, as illustrated in Figure 2.2 and discussed in Section 2.3.1, and that an emergent strategy can be observed when a non-intentional pattern can be recognised in past actions. Where an intended strategy is realised this can be termed a 'deliberate' strategy (Mintzberg, 1978; Mintzberg and Quinn, 1991). This appreciation of different strategy forms provides a broad potential research field. However, concentrating attention on prescribing how organisations should go about developing strategies is justified in Section 2.4.1 as being particularly valuable to industry. Hence, a definition of manufacturing strategy is favoured that reflects an intended strategy.

In conclusion, a definition of manufacturing strategy has been sought that combines the general views in the literature, and the specific characteristics given above. Such a definition is offered by Platts (1990), and is hence adopted in this thesis. In his work he forms an amalgam from several sources, to define manufacturing strategy as:

> " A pattern of decisions, both structural and infrastructural, which determine the capability of a manufacturing system and specify how it will operate in order to meet a set of manufacturing objectives which are consistent with overall business objectives."

2.1.2 The content of manufacturing strategy

The adopted definition of manufacturing strategy, as given by Platts (1990), mentions 'manufacturing objectives', and decisions about the 'structure' and 'infrastructure' of a manufacturing system. The specifics of what a strategy contains in each of these areas is generally referred to as the 'content'. The content focuses on the specifics of what was decided, whereas 'process' addresses how strategic decisions are reached in an organisational setting (Fahey and Christensen, 1986). To develop an appreciation of the nature of manufacturing strategy it is necessary to explore the generally accepted forms of content.

Subsequently in Section 2.3, a corresponding investigation into manufacturing strategy process is performed.

The manufacturing task, referred to by Platts as the manufacturing objectives, is seen by Skinner (1978) as a statement of what the manufacturing function must accomplish. Adam and Swamidass (1989) consider terms that are synonymous to manufacturing objectives to include 'manufacturing mission', and 'manufacturing criteria'. Platts defines the manufacturing objectives in terms of 'competitive criteria', as shown in Table 2.3. This is similar to New (1991) who uses 'competitive edge criteria'; Hill (1985) who uses 'order winning and order qualifying criteria[2]'; and Minor et al (1994) who use 'competitive priorities'. In each case these criteria are used to assess the contribution that a manufacturing activity makes to the saleability of a product. The literature however, holds a variety of opinions as to the actual dimensions of the competitive criteria. Table 2.4 is taken from Platts and indicates this variance.

Surprisingly vague in the dimensions of manufacturing objectives are measures that express the contribution that a manufacturing function makes, to the financial performance of a business. As Hill (1980) points out, corporate decisions are made by addressing marketing effectiveness, manufacturing implications and the financial considerations. Authors such as Platts (1990) and Pendlebury (1987) use measures that rigorously link manufacturing performance and market demands through manufacturing objectives in the earlier stages of strategy formulation. In their work financial implications are however only formally considered during a financial justification exercise at a much later stage in manufacturing strategy formulation. Conversely, Fine and Hax (1984) do formally recognise an earlier financial link in terms of such measures as capital productivity, inventory turnover, and unit costs. Likewise, Hill (1985) provides a conceptual model which links corporate objectives to manufacturing strategy formulation. The appropriate form of performance criteria for linking manufacturing and financial strategy appears to be a budding research area (Leong et al, 1990; Minor et al, 1994). Therefore, at this stage in this thesis it is appropriate to adopt the market based competitive criteria advocated by Platts, as these are generally representative of current literature, and be prepared to expand

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[2] In the context of a manufacturing contribution, order-winning criteria are factors which provide a distinct competitive advantage for a product. Order qualifying criteria are factors that must be provided, for a product to get into or to stay in the market place (Hill and Chambers, 1989).

Criteria	Function
Product features	Adding capability to the product, or choice to the customer.
Quality	Producing a product that performs well to specification.
Delivery lead time	Delivering the product within a short lead time.
Delivery reliability	Always delivering on schedule.
Design flexibility	Having the ability to produce products to customer specification.
Volume flexibility	Having the ability to supply fluctuating volumes without compromising lead time.
Price	Selling at the lowest price.

Table 2.3: Competitive criteria (Source: Platts, 1990)

	Source						
	Wheelwright, 1978	Hayes and Wheelwright, 1984	Fine and Hax, 1984	Buffa, 1984	Cohen and Lee, 1985	Haas, 1987	Hill, 1985
Performance criteria	Efficiency	Cost	Cost	Cost	Cost	Price	Price
	Dependability	Dependability	Delivery	Dependability	Service	Service	Speed
	Quality	Quality	Quality	Quality	Quality	Quality	Delivery reliability
	Flexibility	Flexibility	Flexibility	Flexibility /	Flexibility		Quality
				Service			Colour range
							Product range
							Design leadership

Table 2.4: Variance in goal dimensions (Source: Platts, 1990)

on this subset if more explicit links between financial and manufacturing strategy appear necessary.

The span of changes to a company that a manufacturing strategy is generally accepted to address is broad. As Skinner (1985) points out:

> "The entire factory must be planned and renovated as a unit lest any one element undermine the entire structure."

Likewise Buffa (1985) considers that:

> "All the activities in the line of material flow - from suppliers through fabrication and assembly and culminating in product distribution - must be integrated for manufacturing strategy formulation."

Such changes can be grouped as either structural or infrastructural. Furthermore, the notion of 'policy areas' (Platts, 1990); 'decision categories' (Hayes and Wheelwright, 1984) and 'manufacturing decisions' (Haas, 1987) can be applied to provide a detailed categorisation of structural or infrastructural changes. Whilst there is clearly some variance in opinion as to the appropriate name for this categorisation, for consistency, the term policy areas and associated categories of policy areas (Table 2.5), will be adopted here.

There is a variety of opinions on the policy area categories in the literature. Platts has previously surveyed this situation and provided a summary as shown in Table 2.6. There appears to be some discrepancy over the jurisdiction of policy areas and functional strategies. For example, Riedel and Pawar (1990) argue for a 'design strategy' as they are concerned not to exclude such developments as simultaneous engineering from the manufacturing strategy. Likewise New (1989) promotes a strategy formulation process with a separate 'product development strategy'. Adopting a broad selection of policy areas generally appears to reduce the number of functional strategies required. For example, Parnaby (1986) suggests five functional strategies and manufacturing is considered in terms of seven policy areas. It can be argued that a minimum number of functional strategies and a broad range of policy areas will promote a greater integration of strategic developments during strategy formulation. The policy areas adopted from Platts (1990) are broad and therefore allow the number of functional strategies to be kept to a minimum.

Decisions concerning policy areas and competitive criteria have mutual implications and constraints. Skinner (1969) is credited by New (1991) for identifying that there have to be trade-offs in a manufacturing strategy. Skinner

Policy areas	Description
Facilities	The factories, their number, size, location, focus.
Capacity	The maximum output of the factory.
Span of process	The degree of vertical integration.
Processes	The transformation processes (metal cutting, mixing, assembly, etc.) and most critically the way in which they are organised.
Human resources	All the people-related factors, including both the personal and the organisational level.
Quality	The means of ensuring that product, process and people operate to specification.
Control policies	The control policies and philosophies of manufacture.
Suppliers	The methods of obtaining input materials at the right time, price and quality.
New products	The mechanisms for coping with new product introduction, including links to design.

Table 2.5: Policy areas (Source: Platts, 1990)

	Source						
	Wheelwright, 1978	Hayes and Wheelwright, 1984	Fine and Hax, 1984	Buffa, 1984	Cohen and Lee, 1985	Haas, 1987	Hill, 1985
Policy areas	Process	Technology	Technologies and Processes	System position, Product and Process technology	Process	Process design	Process
	Capacity	Capacity	Capacity	Capacity/ Location	included in Process		
	Plant	Facilities	Facilities	Facilities	Facility and Plant configuration		
	Vertical integration, Supplier control, Customer control, Interdependencies	Vertical integration	Vertical integration, Vendor relations	Supplier and Vertical integration	included in Product	Supplier roles and relationships	Process positioning
	Planning and control	Production planning, Material control, Organisation	Manufacturing infrastructure	Operating decisions	Control, Organisation	Information and Control systems	Manufacturing systems, Controls and procedures, Work structuring
	Work force	Work force	Human resources	Work force and Job design	included in Organisation	Organisation human resources	Organisation structure, Function support
	Quality control	Quality	Quality management		included in Product and Control		
			Scope/ New products		Product	Product design, Research and development	

Table 2.6: Variance in categories of policy areas (Source: Platts, 1990)

identified that compromises are necessary in the goals and decision areas of a production system. This view is supported by such authors as Buffa (1985), Fine and Hax (1985), Wheelwright (1978) and Whybark (1987). New (1991) criticises later authors, in particularly Schonberger (1986), for neglecting this concept. New goes on to say that a company that attempts to be the 'best' when measured against all strategic goals does not have a manufacturing strategy; rather they have "...a set of pious incompatible hopes".

Finally, the definition of strategy given by Platts does not explicitly consider the time taken to realise manufacturing capabilities and associated objectives. As recognised by Hayes and Wheelwright (1984) such time is an element of strategy. Time is taken for manufacturing capabilities to be realised, and hence forms a further trade-off in strategy formulation. The 'schedule' by which changes are brought about is recognised by this thesis to be an important aspect of the content of a manufacturing strategy.

In conclusion, the content of a manufacturing strategy can be viewed in terms of changes to the structure and infrastructure of a company, made with the intention of fulfilling manufacturing objectives. The manufacturing objectives can be categorised in terms of competitive criteria, and are focused at forming links between functional strategies. Changes to a company's structure and infrastructure, associated with manufacturing strategy, can be broadly categorised into policy areas. However, there are inevitable trade-offs that have to be made in decisions about competitive criteria, policy areas, and time schedule applied to realise the associated manufacturing capabilities.

2.2 A CASE FOR MANUFACTURING STRATEGY

The significance of research in this discipline is totally dependent on the value of the manufacturing strategy concept. Why promote this concept if there is little benefit to be gained by companies formulating and implementing manufacturing strategy? This section therefore, seeks evidence to support the manufacturing strategy concept by exploring the empirical case for manufacturing strategy and then, as this evidence is limited, constructing an argument that reasons why this is a valuable research discipline.

2.2.1 An empirical case for manufacturing strategy

To support the concept of an explicit manufacturing strategy it initially appears reasonable to search for empirical evidence. This evidence may be expected to be in the form of experimentation programmes that have sought to prove or disprove hypotheses about the value of manufacturing strategy to companies. Such work is however scarce and few studies have specifically evaluated the effect of manufacturing strategy on overall business performance (Minor et al, 1994).

The few empirical studies that have been performed are typified by Roth and Miller (1990) who in a 1988 survey of 193 executives from large North American companies, found evidence to tentatively support the perceived importance of manufacturing as a competitive weapon. Likewise, Marucheck et al (1990) cite similar supportive research by Richardson et al (1985) and Swamidass and Newell (1987). Richardson et al (1985) showed that improving the focus in both the corporate mission and the manufacturing tasks, and increasing congruence between the corporate and manufacturing objectives, resulted in each producing better corporate performance within the Canadian electronics industry. Swamidass and Newell (1987) demonstrated that an enhanced role for manufacturing managers in strategic decision making resulted in better business performance. On the basis of such work Marucheck et al (1990) conclude that:

> "The few empirical studies that have been done suggest that a stronger role for manufacturing within the hierarchy of corporate strategy formulation should improve performance."

The paucity of literature is felt to reflect the difficulty of conducting valid empirical research on this topic. Samson (1990), for example, highlights the difficulties of observation and control and the time lags between strategy formulation, implementation, and associated changes in business performance. A similar view is taken by Matthews and Foo (1990) who suggest that one reason for the lack of empirical research is due to problems of manageability, parsimony, and measurability. For example, questions arise as to whether the formal strategy was the cause of success, or was success gained from the company's exposure to a more strategic management role? Would the company have improved anyway?

It would be unsatisfactory to abandon the manufacturing strategy concept because of a failure to conveniently fit neatly into experimental procedures. Within the literature a number of researchers add their opinion to endorse manufacturing strategy. For example, Voss (1984) argues "...that appropriate manufacturing policies[3] are vital for the health of Britain's manufacturing

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[3] In this article the terms policy and strategy are introduced as being synonymous.

industry and that in many cases UK companies are following inappropriate policies"; and Hill (1985) believes that "...the building blocks of corporate success are to be found in creating effective, successful businesses where manufacturing supports the market requirements within a well chosen, well argued and well understood corporate strategy". Similar opinion comes from Anderson et al (1991) who stress that it is difficult to argue with the importance of having an effective manufacturing strategy.

There is not however a complete consensus amongst authors on the importance of manufacturing strategy. Indeed, there are many instances of manufacturing business success where an explicit strategy, in any guise, has been absent. A particularly pertinent example is the case of the motor cycle manufacturing company Honda, gaining dominance of American and British markets in the 1960s. At the time, their success was attributed to strategy, but as Pascale (1984) concludes from later discussions with the Japanese management, success was mainly circumstantial and no explicit strategies existed.

In conclusion, empirically derived support for the manufacturing strategy concept is limited. Furthermore, though the paucity of evidence can to some extent be contributed to the difficulty in conducting empirical studies, it has been demonstrated that a manufacturing strategy is not essential to business prosperity. However, the existing empirical evidence does indicate that a well formed and executed manufacturing strategy can be conducive to business success, and this finding is widely supported by the opinions of authors in the literature.

2.2.2 A dialectic case for manufacturing strategy

To complement the empirical evidence, an argument is constructed in this section that justifies why manufacturing strategy is a valuable research discipline. The process followed to form this argument begins with investigating how a manufacturing strategy is intended to characterise the manufacturing function of a company, the significance of the subsequent level of manufacturing capability to business performance is then explored, and finally the importance of such manufacturing businesses is stated.

The manner in which a manufacturing strategy is intended to characterise the manufacturing function of a company is succinctly summarised by Skinner (Skinner et al, 1985) who thinks of this concept in three ways:

1. That the manufacturing function should not operate in isolation from the main corporate focus of the company.

2. That developments are not allowed to take place without first considering their impact on manufacturing structure.
3. Manufacturing strategy is based conceptually on coherent, consistent, manufacturing structure which is underpinned with an appropriate infrastructure.

The significance of such manufacturing characteristics is determined by the intended contribution of the manufacturing function to the business performance of a company. Section 2.2.1 has presented apparently contradictory evidence, in that, it is considered to be important for a company to have a manufacturing strategy but examples exist where strategy has played no part in business prosperity. An explanation is that the role of a manufacturing function can vary between companies. Such a view is taken by Hayes and Wheelwright (1984, 1985) who provide a framework that indicates the various roles and associated levels of performance that the manufacturing function of a company can take. This framework consists of four stages, namely:

- Stage 1 - Minimise manufacturing's negative potential : Internally neutral
- Stage 2 - Achieve parity (neutrality) with competitors : Externally neutral
- Stage 3 - Provide credible support to the business strategy : Internally supportive
- Stage 4 - Pursue a manufacturing-based competitive advantage : Externally supportive

The characteristics of each of these stages are given in Table 2.7 and explained as follows.

Hayes and Wheelwright (1984) see that at stage 1 the manufacturing activity is passive and not sought to make any positive contribution to business strategy. They argue that such companies see the manufacturing system as a 'once and for all' design, only to be modified when absolutely essential, even then it is likely to be restrictive investments that do not constrain the production flexibility.

Hayes and Wheelwright see stage 2 companies as being predominantly traditional and operating in mature markets. In general, they see that the manufacturing function in such companies is not formally supportive of business strategy, rather developments are made to keep the company up with 'industrial practice', and investment patterns are set by competitors.

Stage 1	**Minimize manufacturing's negative potential: "internally neutral"**	Outside experts are called in to make decisions about strategic manufacturing issues Internal, detailed, management control systems are the primary means for monitoring manufacturing performance. Manufacturing is kept flexible and reactive
Stage 2	**Achieve parity with competitors: "externally neutral"**	"Industry practice" is followed The planning horizon for manufacturing investment decisions is extended to incorporate a single-business cycle Capital investment is the primary means for catching up with competition or achieving a competitive edge
Stage 3	**Provide credible support to the business strategy: "internally supportive"**	Manufacturing investments are screened for consistency with the business strategy A manufacturing strategy is formulated and pursued Longer-term manufacturing developments and trends are addressed systematically
Stage 4	**Pursue a manufacturing-base competitive advantage: "externally supportive"**	Efforts are made to anticipate the potential of new manufacturing practices and technologies Manufacturing is involved "up front" in major marketing and engineering decisions (and vice versa) Long-range programs are pusued in order to acquire capabilities in advance of needs.

Table 2.7: Stages in the strategic role of manufacturing (Source: Hayes and Wheelwright, 1984)

Stage 3 companies are seen by Hayes and Wheelwright to exist where the manufacturing function provides credible and significant support to the overall competitive strategy of the business. In this case they expect business and manufacturing strategy to be mutually supportive, with manufacturing developments formally intended to take place over an extended time horizon.

Finally, at stage 4 of the Hayes and Wheelwright framework are companies where the competitive strategy is based to a significant degree on manufacturing capabilities. In this case long range business plans are developed, all functional strategies are equal partners, and manufacturing plays a major role in securing strategic objectives. Hayes and Wheelwright consider companies that exhibit stage 4 characteristics to be referred to as World Class Manufacturers (WCM). A WCM company is one that approaches:

> "....the development of the role of manufacturing into one which fully supports the marketing strategy of the business and, at the same time, provides the capability to establish a competitive advantage from the manufacturing activity itself."
>
> (Sweeney, 1990).

In the framework given by Hayes and Wheelwright it is plain that companies operating at stages 1 and 2 do not seek competitive advantage through manufacturing capabilities. Whilst manufacturing developments can occur, they will tend to be reactive and piecemeal. Conversely, the concept of an explicit manufacturing strategy can be associated with companies that operate at either stage 3 or 4, as manufacturing developments are expected to be integrated and supportive of the business strategy.

Having established how a manufacturing strategy is intended to characterise the manufacturing function of a company, and that such manufacturing capabilities play a key role in some companies, the case for manufacturing strategy is synonymous with the relative importance of companies at stage 3 and 4 of the Hayes and Wheelwright framework. Hayes and Wheelwright argue that many Japanese and German companies are at stages 3 and 4. A report by the Institution of Electrical Engineers (IEE, 1994) shows how the performance of UK manufacturing industry has not reached that of Japan and Germany, Figure 2.3. Furthermore, a Department of Trade and Industry report (DTI/PA 1989), states that to compete for this trade in world markets requires a strategic approach to manufacturing. Failure of manufacturing industry to compete in this arena risks

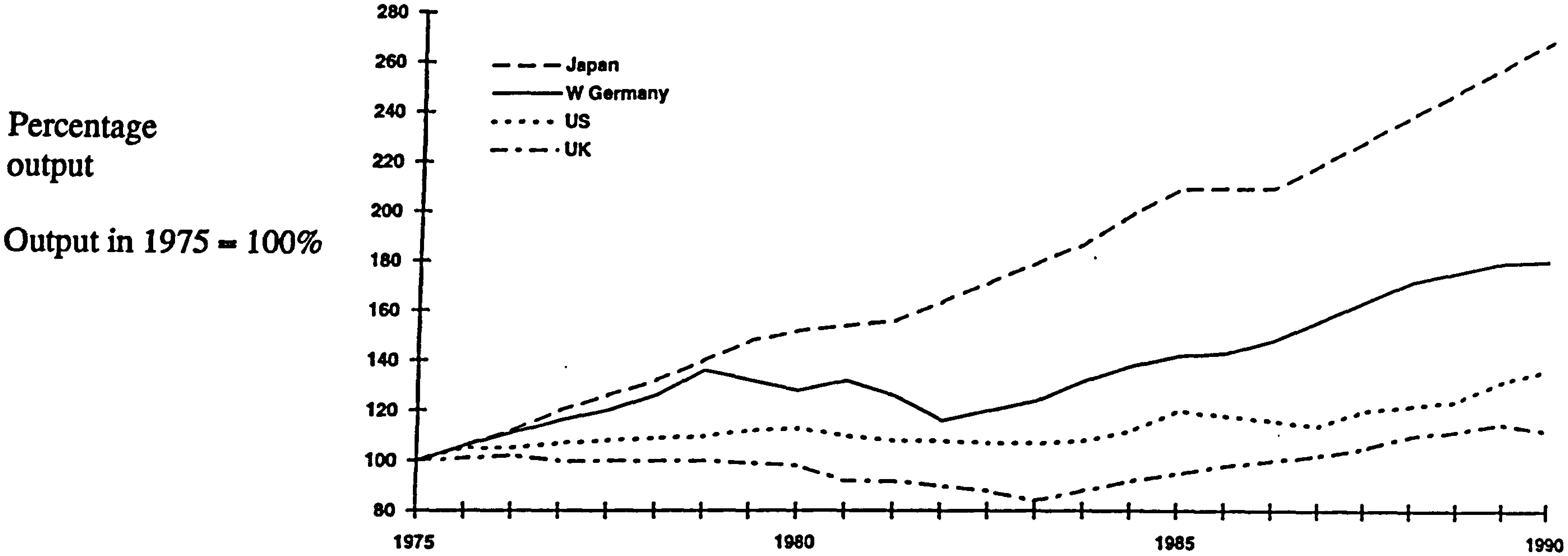

Figure 2.3: Overview of Japanese and German manufacturing output (Source: IEE, 1994)

the loss to the UK of 22% of gross domestic product and loss in employment of 21% of the UK workforce (Deasley and Collins, 1994).

By way of contrast, stages 1 and 2 can be associated with companies that have primarily sought success through marketing, financial and legal skills. Hayes and Wheelwright (1984) cite research, based on 72 successful American firms, which shows very disappointing long-run returns to share holders through this approach. In these cases an explicit manufacturing strategy is unlikely to exist, however such an approach to manufacturing appears to be relatively common. In a study of 40 American companies Schroeder (in Skinner et al, 1985) observed that only 37% had a well defined manufacturing strategy. Similarly, in a study of eight machine tool companies in the UK Barrar (1987) observes that:

> "There were few formal planning processes, or cohesive functional long-term plans or, indeed, structured procedures for dealing with change and its impact on the format of their production systems."

To conclude this line of reason, although not all companies require an explicit manufacturing strategy to succeed, there are those which use this concept to support, or even form the basis, for the competitive advantage being sought by the business strategy of a company. Such companies are particularly important to the UK economy, and it can therefore be deduced that the concept of manufacturing strategy is valuable.

2.3 MANUFACTURING STRATEGY PROCESS

The objective of this section is to establish how a manufacturing strategy can be formed in an organisation. Previously the term 'process' has been introduced as the mechanism through which strategic decisions are reached in an organisational setting (Section 2.1.2). Literature on processes can generally be viewed as focusing on either 'strategy formation' or 'strategy formulation'. Furthermore, an effective mechanism of strategy formulation is a 'formal planning process'. This section structures an investigation around these three distinctions.

2.3.1 Strategy formation

To fully appreciate the mechanisms of strategy formation it is necessary to return, for the duration of this subsection, to a definition of strategy that is not constrained to intended actions[4]. An appropriate definition is given by Mintzberg (1978) who defines strategy as:

"...a pattern in a stream of decisions."

Mintzberg (1978) argues that such a definition enables an appreciation that a strategy maker may formulate a strategy through a conscious process before making a specific decision, or a strategy may form gradually, perhaps unintentionally as decisions are made one by one. A similar view of strategy forms is implied by authors such as Ansoff (1969), from a business strategy perspective, who saw that strategic change takes place in most firms, with or without explicit strategy formulation by management. Porter (1980) agrees and says that every firm has a competitive strategy which has either been developed explicitly through a planning process or it may have evolved implicitly through the activities of various functional departments. Likewise, Ferdows (in Skinner et al, 1985) sees that there is always a strategy behind manufacturing decisions even though it might be unconscious, not good, inconsistent or unintended.

Mintzberg (1978) specifies this distinction between conscious and unintended actions more precisely. He identifies that a 'realised' strategy may have 'intended' or 'emergent' origins, as illustrated in Figure 2.2, and that an emergent strategy can be observed when a non-intentional pattern can be recognised in past actions. Mintzberg (1994) also reasons that even when a strategy is deliberately intended the resulting real-world strategy is often, because of such influences as learning, a mix of intended and emergent strategies. Quinn (1978) reinforces this view and argues that there is likely to be a significant difference between an intended strategy and a realised strategy because strategy deals with 'unknowable' factors.

The action of consciously forming a strategy can only be associated with an intended strategy and is termed formulation. In this sense strategy formulation can be thought of as a subset of strategy formation. Likewise, Mintzberg (1994) argues that only with an intended strategy does the distinction exist between strategy formulation and implementation, along with the notion of tactical actions, and a potential for dislocation of tactical and strategic thought. Tactics are short duration, adaptive, action-interaction re-alignments used to accomplish limited goals (Mintzberg and Quinn, 1991).

---

[4] The definition of manufacturing strategy chosen for this thesis in Section 2.1.1, reflects an explicit intention to improve the performance of a manufacturing system.

A summary of the mechanism of strategy formation is shown in Figure 2.4 and explained as follows. Initially, an intended strategy may be formulated but as implementation ensues, new knowledge is likely to be learnt about the system being addressed. This new knowledge may be taken into account in a number of ways. A purely emergent component of a realised strategy may arise if some form of subconscious action is taken. The intended strategy may be deliberately constrained by tactical actions, or alternatively, the new knowledge may be significant enough for the intended strategy to be fully revised. In practice all three components are likely to occur to a greater or lesser extent. The frequency of major revisions is likely to be company dependent. In a detailed study of six companies Marucheck et al (1990) found that in practice manufacturing strategy was usually formally reviewed and updated on a quarterly basis.

2.3.2 Strategy formulation

The depth of consideration given to the content of a strategy can vary in strategy formulation. At one extreme strategy formulation may be achieved through strategy formulators applying a relatively shallow decision making process with the resulting strategy content being largely adopted, this may be termed a prescriptive or generic strategy. Alternatively, a very detailed, full and lengthy consideration of strategy content may be performed. This second case is more usually associated with formal planning processes.

Mintzberg and Quinn (1991) see that generic strategies are not created for an individual company rather, they are selected from a limited set of options based on a systematic study of the firm and the industry conditions it faces. An apparent example of this case is Porter (1980, 1985) who proposes three generic business strategies which are 'overall cost leadership', 'differentiation' and 'focus'. Likewise, Sweeney (1991) explores an extension of Porters approach and gives generic competitive strategies that manufacturing businesses can adopt, these are 'world class competitor', 'market differentiator', 'least cost producer' and 'uncompetitive'. Furthermore, Skinner (1985) advocates a manufacturing strategy of a 'focused factory' and Burbidge (1979) promotes Group Technology (GT). The generic distinction can be extended down to individual policy areas, Wallace (1986) for example, sees Manufacturing Resource Planning (MRP II) as the solution to all control issues. However, some authors, such as Greenhalgh (1990), are concerned about generic approaches as each organisation is, or needs to be, unique in some way in order to survive long term.

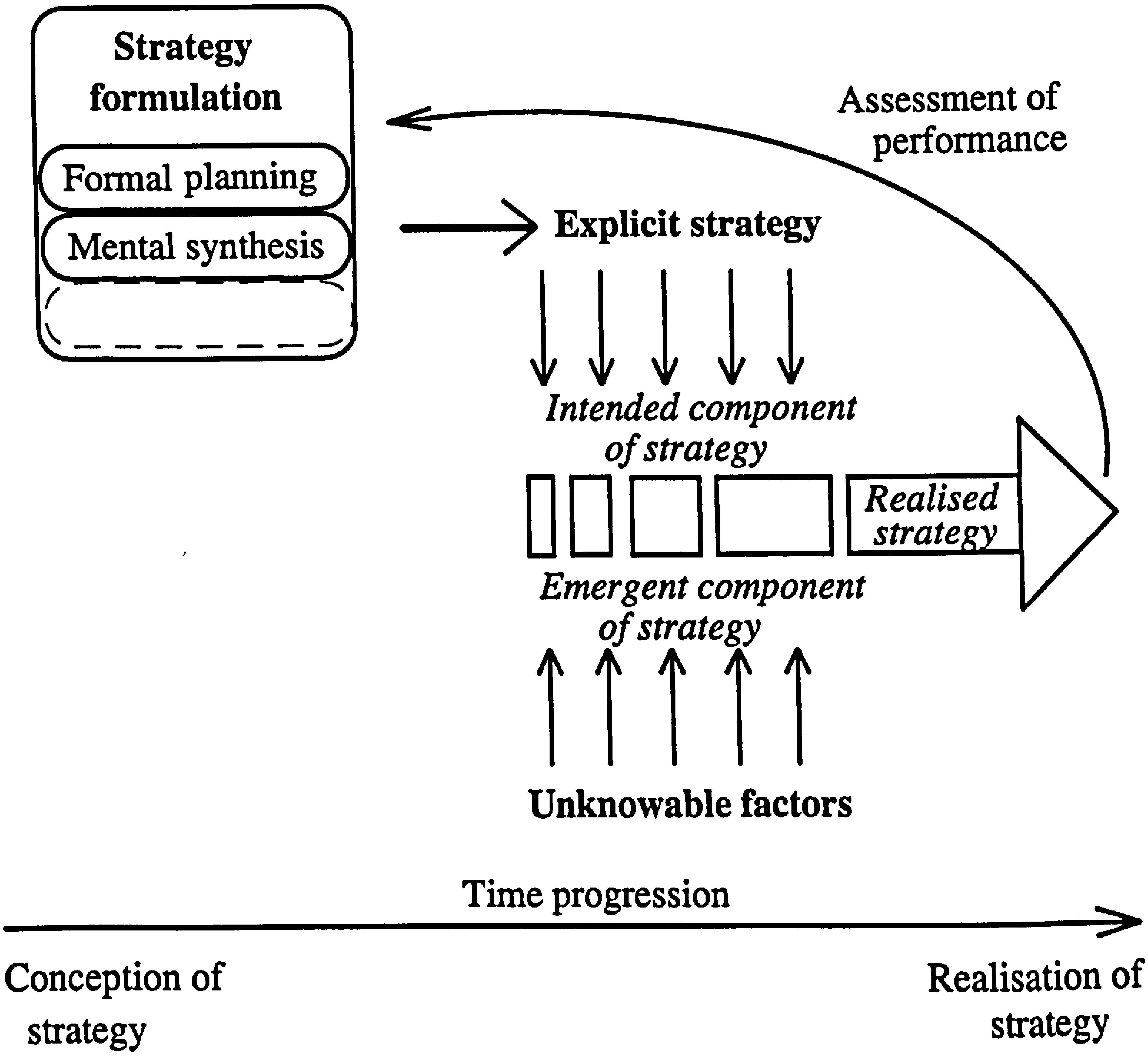

Figure 2.4: Process of strategy formation

The role of formal planning processes in strategy formulation, particularly in a corporate context, appears to be open to contention. Andrews (1971) suggests that a common form of strategy formulation is an individual executive responding to environmental pressure, competitive threat, or environmental opportunity. Hofer and Schendel (1978) stress that formal planning systems are not always required for effective strategy formulation. Likewise, Mintzberg (1994) sees that most successful strategies have been based to a large extent on formulation through mental synthesis. He argues that the appropriate process of strategy formulation is based on forms of synthesis, with formal planning processes supporting this role.

The benefits of formal planning processes in a supportive role are further endorsed by Quinn (1978), Adam and Swamidass (1989), and Schroeder and Lahr (1990). An overview of the opinions of these authors is given in Table 2.8. In particular, within the literature there is strong support for the contribution that formal planning processes can make to manufacturing strategy formulation, for example Hill (1985) and Skinner (1969, 1985). Likewise, Schroeder and Lahr (1990) found that in their experience of applying a formal planning process to develop manufacturing strategy in over 30 companies, that many of them undertake discussion at a general level, partly based on the belief that strategy is not detailed in nature. They observe however that in such situations the outcome, all too often, is superficial in nature.

2.3.3 Formal planning process

As this thesis is concerned with an intended manufacturing strategy (Section 2.4.1), and that formal planning processes offer a valuable contribution to strategy formulation, it is appropriate to further explore such processes.

A distinction can be made about formal planning processes through using the internally and externally supportive classifications (stages 3 and 4) given by Hayes and Wheelwright (1984), and explained in Section 2.2.2. If a manufacturing function pertains to being internally supportive, the result of strategy formulation need only underpin the business strategy of a company. Whereas with an externally supportive manufacturing function, the business strategy is based to a large extent on the competencies of the manufacturing function, and this will need to be reflected in the strategy formulation process. Hence, strategy formulation processes can be classed according to the manufacturing capabilities with which they can be associated.

	Source		
	Quinn, 1978	Adam and Swamidass, 1989	Schroeder and Lahr, 1990
Comment	1. Provide a discipline forcing managers to take a careful look ahead periodically. 2. Require rigorous communications about goals, strategic issues, and resource allocations. 3. Stimulate longer-term analysis that would otherwise be made. 4. Generate a basis for evaluating and integrating short-term plans. 5. Lengthen time horizons and protect long-term investments such as R&D. 6. Create a psychological backdrop and an information framework about the future against which managers can calibrate short-term or interim decisions.	1. Identifying upcoming strategic issues and problems. 2. Formalizing the leadership role of top executives in strategic planning. 3. Provides specific analytic tools and techniques for formulating strategy.	1. Helps the business compete successfully. 2. Guides tactical decision making in manufacturing. 3. Helps to cope with a changing environment. 4. Provides a long-run view of manufacturing. 5. Enhances communication with other functions. 6. Puts manufacturing in a proactive mode.

Table 2.8: Benefits of formal planning

An example of a formal planning process that can be termed an internally supportive process for strategy formulation is shown in Figure 2.5. Such a process is applied through a mechanism of company based meetings of personnel, typically orchestrated by a number of worksheets (Figure 2.6). Similar and associated mechanisms are offered by, for example, Hill (1985), Fine and Hax (1985), Pendlebury (1987), DTI (1988), Bennett and Forrester (1990)(DRAMA), Danzyger (1990), Pannesi (1990), Maull and Hughes (1990)(STRATAGEM), Schroeder and Lahr (1990), and Barker (1992).

New (1989) and Baines et al (1993a) (Figure 2.7), both give conceptual planning processes that could be termed externally supportive. These processes are intended to be applied in generally the same manner as internally supportive approaches. However, they are distinctive because a hierarchical order of strategies has been dissolved. This reflects an intention during strategy formulation to evolve a company's business strategy through gaining balance and co-ordination across functional strategies.

Generally, the application of formal planning processes, whether internally or externally supportive, is intended to follow, though not necessarily procedurally, a number of stages. Cohen and Cyert (1973) identify from a variety of sources, nine stages that constitute the strategic planning process. Later Hofer and Schendel (1978) identified seven stages that are included implicitly or explicitly in major strategy formulation processes, these are:

1. Strategy identification: Assessment of current strategy.
2. Environment analysis: Identification of opportunities and threats.
3. Resource analysis: Assessment of principal skills and resources available.
4. Gap analysis: Comparison of the organisation's objectives, strategy and resource against the environment opportunities and threats to determine the extent of change required in the current strategy.
5. Strategic alternatives: Identification of the options upon which a new strategy may be built.
6. Strategy evaluation: Evaluation of the strategic options to identify those that best meet the values and objectives of all stakeholders, taking into account the environmental opportunities and threats and the resources available.

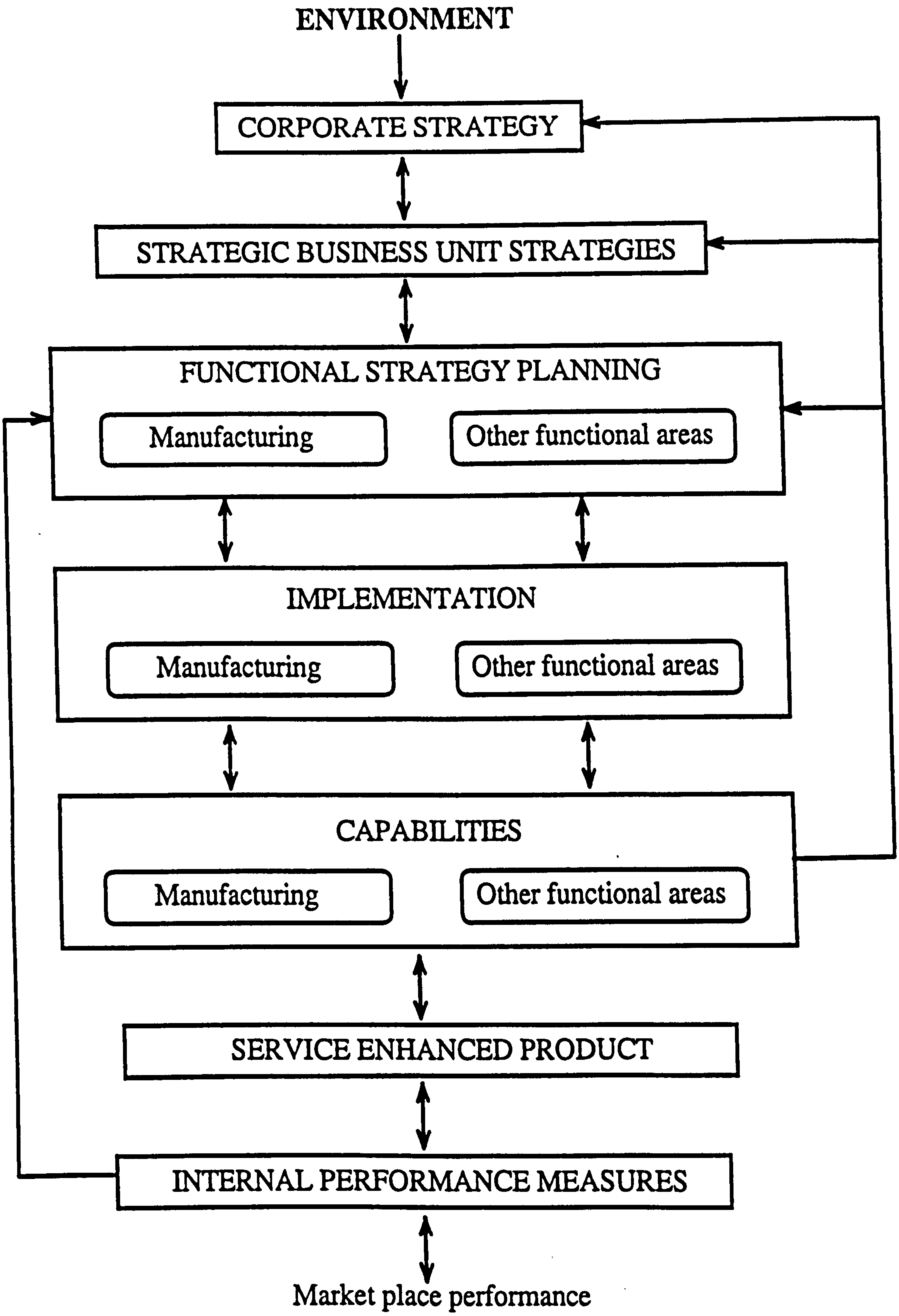

Figure 2.5: A process model of manufacturing strategy (Source: Ward, Leong and Snyder, 1990)

Competitive criteria							
Product * family	Features	Quality	Delivery		Flexibility		Price
			Lead-time	Reliability	Design	Volume	
Standard couplings	-	Q	Q(ex-stock)	-	-	-	100
Customised standard design	-	Q	30(short)	20	40	-	10
Customer special	50	Q	-	10	40	-	-

* = Examples of typical product families within a manufacturing company.
\- = Value not perceived as significant.
Q = Denotes an order qualifying criteria.
Numerical values = These signify the relative importance (taken as a percentage of 100%) of order winning criteria.

Figure 2.6: Example of a worksheet (Source: DTI, 1988)

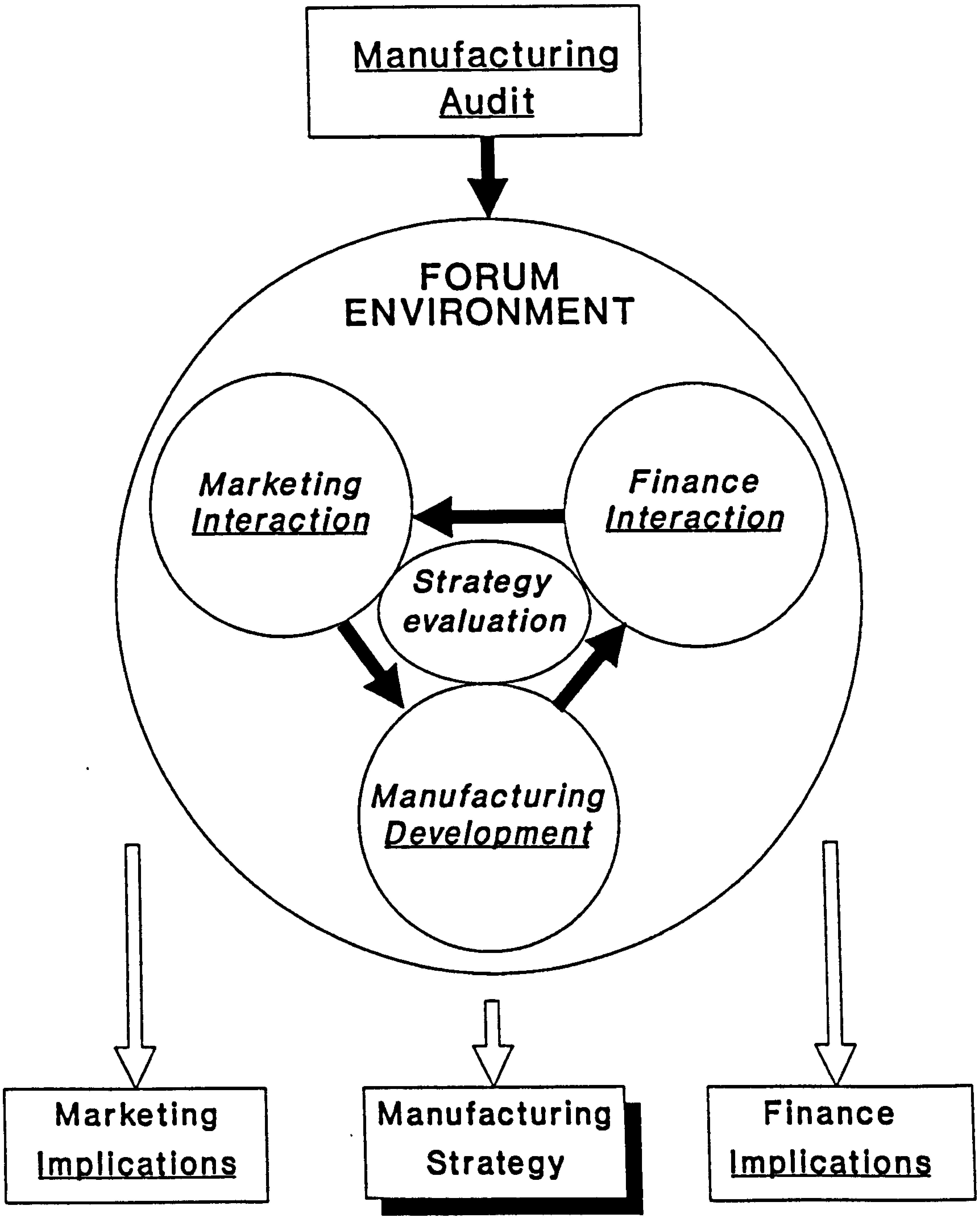

Figure 2.7: An externally supportive manufacturing strategy formulation process (Source: Baines et al, 1993a)

7. Strategic choice: Selection of the options for implementation.

Each of these stages may be addressed differently, dependent on whether an internally or externally supportive process is being applied.

Hofer and Schendel (1978) see that stages 1 - 4 (inclusive) are concerned with establishing the value of competitive factors external to an organisation and contrasting these against internal manufacturing performance. The scope of this analysis is extended to explore opportunities and threats that may drastically alter the environment within which a company is competing. The anticipated gap between external factors and internal manufacturing performance, forms a platform on which strategy formulation can commence. The objective of the ensuing formulation activity is to create a strategy that achieves congruence between internal and external factors.

Hofer and Schendel associate stage 5 with the identification of strategic alternatives. This activity is where formal planning and synthesis processes converge. The literature generally agrees that strategy formulation will take into account factors other than those presented in formal planning. However, information from earlier stages, through a mechanism such as a manufacturing audit, can stimulate and guide this activity by providing an analytical base from which new strategies can be synthesised. The outcome of this stage is a number of alternative manufacturing strategies.

The motive at stage 6 is seen by Hofer and Schendel as establishing a ranking in the suitability of strategies, such that stage 7, strategy choice, can take place. Stage 6 is concerned with assessing the impact, in terms of manufacturing objectives, of proposed strategic alternatives. It is important to note that this activity seeks to establish how a strategy will effect a systems performance, and is distinct from evaluating the success of a strategy that has been applied.

Hofer and Schendel consider that stage 7 is concerned with strategy choice and is intertwined with the previous stage of strategy evaluation. If strategy evaluation is comprehensive and complete, such that all appropriate factors are considered, then the preferred strategy should be obvious. Mintzberg et al (1976) argue that the evaluation-choice routine may be considered in three modes, namely:

- Judgement; one individual makes a choice in his own mind with procedures that he does not, perhaps cannot, explain.
- Bargaining; selection is made by a group of decision makers with conflicting goal systems, each exercising judgement.

- Analysis; factual evaluation is carried out, generally by technocrats, followed by management choice by judgement or bargaining.

It is possible to extend the evaluation-choice routine to feedback into the activity of generating strategic alternatives. This could occur when the new knowledge gained from strategy evaluation is used to stimulate idea generation or refinement of strategic options. Such a view is taken by Schwenk and Thomas (1983) who see analysis supporting a debate and discussion between decision makers through providing assessment of various alternatives, and providing a starting point for the generation of new alternatives. This approach is formally advocated in the conceptual strategy formulation process given by Baines et al (1993a).

In conclusion, an explicit strategy could be produced by mental synthesis alone, but it appears that formal planning processes offer significant support in this role. Such processes have seven common steps. These steps span from the assessment of the current strategy of an organisation, to choosing the most appropriate strategy for implementation.

2.4 A REVIEW OF CURRENT RESEARCH ISSUES

Previous sections have introduced the concept of manufacturing strategy, justified its importance, and explored how it can be formed. Against this background this section reviews the opinions of authors as to the issues that need to be addressed by future research. From this information a case is observed for work that focuses in the area of manufacturing strategy evaluation. Finally, to appreciate the form that future research in such an area should take, guidelines on research process are explored.

2.4.1 Overview of general research issues.

In a broad review of strategic operations management literature, Adam and Swamidass (1989) concluded that:

> "In reading this review, the reader may rightly come away with the feeling that the strategy research in the area is spotty and lacks dedicated research effort."

The embryonic nature of this subject is stressed by Hill (1987) who states that until as recently as 1987 there were only four books, in the English speaking world, on the subject of manufacturing strategy which have substance. However, a call to develop a strong research base in this area has existed for some time, for example Voss (1984).

To investigate the contributions that do exist in the literature a distinction can be made between descriptive and prescriptive work. Descriptive work considers how strategies do form in organisations, whilst prescriptive work is concerned with how organisations should go about developing strategies (Mintzberg and Quinn, 1991). Considerable descriptive research about general strategy formation has been conducted by Mintzberg (1973, 1978, 1987, 1990, 1994), Miller and Friesen (1978), Quinn (1978), and Mintzberg and Quinn (1991). Whilst rigorous observations have been made about manufacturing strategy formulation processes in practice by Marucheck et al (1990), Voss (1990, 1992) and Anderson et al (1991).

Apparent in the literature, is a particularly urgent need for work that prescribes how to improve the manufacturing performance of a company. This need is typified by Samson (1990) who states that:

> "A great deficiency of this literature is that it is not enough merely frequently to remind manufacturing industry of what to do and of the need for improvement. The literature should also provide the means, the mechanism and the decision support for 'how to improve'."

The extent of such prescriptive research efforts can be viewed from whether manufacturing strategy content or process has been investigated. Matthews and Foo (1990) in a review of almost ninety published articles, considering issues in the chain from starting strategy formulation to measuring its impact, conclude that process has been studied infrequently. Authors who support this view that manufacturing strategy content has received considerable attention while processes for strategy formulation have been largely overlooked include Adam and Swamidass (1989), Anderson et al (1989), Leong et al (1990), Marucheck et al (1990) and Voss (1990). This situation is succinctly summarised by Anderson et al (1991) who state that:

> "...the process for formulating, analysing and implementing operations strategy is begging for both conceptual and empirical research."

It is therefore appropriate to identify what the outstanding research issues are when prescribing how strategy formulation should be carried out.

2.4.2 Research issues on manufacturing strategy formulation

There are significant opportunities to contribute to the research base in the manufacturing strategy discipline by addressing issues of formulation. Section (2.3.2) has introduced formal planning processes and stressed their high value in orchestrating strategy formulation. Therefore, it is appropriate to focus the attention here at such prescriptive processes. Typically there are seven steps of strategy formulation in such processes (Section 2.3.3) and these provide a suitable structure for a review of research progress in this area.

Conceptual frameworks of manufacturing strategy formulation have been developed by authors such as Skinner (1969), Wheelwright (1978), Hill (1980, 1985), and Fine and Hax (1984, 1985). Likewise, the initial stages of strategy formulation have received detailed attention from Platts (1990), and Platts and Gregory (1990a, 1990b). Platts (1990), for example, has created an audit approach that provides a procedural step in a process of manufacturing strategy formulation. This audit analytically tackles tasks such as identification and recording of current data, practices, capabilities and perceptions. The process culminates in identifying manufacturing objectives and manufacturing practices that require revision within a company. On completion of this research Platts (1990) observes that:

> "There appears to be a need for a similar prescriptive methodology to be developed for the synthesis of revised strategy. This should cover the generation of alternative practices, the initial assessment of the expected effects and the selection of the most suitable set."

Platts is effectively calling for work on the latter of the seven strategy formulation steps. These are the steps of strategic alternatives, strategic evaluation and strategic choice. As previously highlighted, the generation of strategic alternatives is generally accepted to be a creative process of synthesis by strategic formulators based around information presented in formal planning processes. The work of such authors as De Bono (1971, 1992) generally provides assistance in this task. Strategy evaluation and choice have however received less attention in the literature. Indeed, authors such as Schroeder (in Skinner et al, 1985) call for work on how to evaluate manufacturing strategy. This view is consistent with a research requirement seen earlier by Voss (1984):

> "Research is needed into how best for a given task or set of tasks, the operating policy choices can be reduced to a manageable set, and possibly optimised."

Manufacturing strategy evaluation therefore appears to be an important area for a research thrust.

2.4.3 Research issues on manufacturing strategy evaluation

First, it is important to stress that the concern here is with evaluating the impact of a proposed manufacturing strategy on a company. This is not to be mistaken with work that considers assessing what the impact has been of implementing a strategy. Work in this latter area has been carried out by such authors as Swamidass (1986), Swamidass and Newell (1987), and Marucheck et al (1990).

At a general level, Mintzberg et al (1976) have investigated the evaluation-choice routine in strategy formulation and identified three components of decision making, namely, judgement, bargaining and analysis (Section 2.3.3). This provides a convenient structure for viewing the contributions in the literature.

To support judgements from an individual or group of individuals, and as a general creativity stimulus, Schwenk and Thomas (1983) propose techniques such as brain-storming, synectics, morphological analysis, Delphi procedures and scenario construction. Instances when judgemental evaluation performs better than quantitative approaches has been researched by Sanders and Ritzman (1991). In this empirically based work they conclude that the best form of forecasting is one that takes advantage of both quantitative methods and judgement. Furthermore, Sanders and Ritzman found that quantitative methods outperform judgement during periods of stability, but reliance should be placed on judgement during periods of change. Intriguingly, they found in extremely changing time series, that judgement from true experts is so valuable that it alone should be used.

The call for research on how to construct analytical models has existed for some time. From a general perspective Ansoff and Brandenburg (1971) call for a mechanism that will allow alternative organisation designs to be modelled, the outcome of each design predicted against objectives, allowing the most suitable design to be selected. Cohen and Cyert (1973) maintain a call for work but focus on quantitative models in particular. Later, Adam and Swamidass (1989) specifically identify a need for decision aids. More recently Samson (1990) sees that a major opportunity in the decision science field is providing aids that can help manufacturing executives gain insight about the relationship between decisions and decision variables.

There is therefore a strong support from the literature for an analytical mechanism that will enable the evaluation of a manufacturing strategy. Intriguingly, authors such as Ansoff and Brandenburg (1971) favour a predictive mechanism, whilst Samson mainly seeks insight into the behaviour of a manufacturing system. Work in this area should reflect these requirements. However, the extent of previous work in manufacturing strategy evaluation must first be known.

2.4.4 Research issues on the analytical evaluation of a manufacturing strategy

There is a wide variety of work of an apparently analytical nature. Some work is concerned with pseudo-analysis tools that focus on providing structured enquiry, judgement and problem solving about a real world object or system under study. These tools are occasionally referred to as models, though this thesis will use the term 'methodology'. This somewhat pedantic step is necessary to enforce a distinction from 'models' that are an abstract representation and emulation of a real system. Such models will be discussed later in this section.

Many tools that can be termed methodologies appear to have originated from corporate and business planning literature, for example the 'Boston Consulting Group, growth share matrix' (Porter, 1980); the 'General Electric McKinsey, industry attractiveness - business strength matrix' (Hax and Majluf, 1984); and the 'product/market evolution portfolio matrix' (Thompson and Strickland, 1980). An appropriate term for these particular methods is considered to be 'traditional strategy tools'. Table 2.9 gives an overview and description of some common traditional strategy tools currently available.

Traditional strategy tools can provide assistance in overall formulation as well as specific strategy evaluation. For example 'product life cycle' diagrams can aid in the identification of product families and in focusing discussions about evolution of product sales. Other tools can directly assist in evaluating the effect of a manufacturing strategy, for example 'price of non-competitiveness matrix', 'learning curve' and 'product-process matrix' (Table 2.9).

The traditional strategy tools have a role in strategy evaluation that is relatively well described in the literature. There do appear however to be opportunities to improve the definition of this role, and to tailor the characteristics of these tools specifically to manufacturing strategy formulation. For example, Probert et al (1993) have adapted a number of traditional strategy tools to address issues of vertical integration in the development of a manufacturing strategy.

There are other analytical tools that can also be categorised as methodologies, for example, 'decision tree analysis' (Cooke and Slack, 1991; Samson, 1991)

Tool	Source	Description
Product life cycle diagrams	Porter, 1980; Hill, 1985; Anderson et al, 1989; Hayes and Wheelwright, 1984.	The hypothesis that industries and products pass through a number of phases which are induction, growth, maturity and decline.
Price of non-competitiveness (PONC11)	Maull and Hughes, 1990	Mechanism for estimating the gain to be made from improvements in order winning criteria.
Process for structuring make-or-buy decisions	Probert et al, 1993	Methodology features identification of core manufacturing capabilities, assessment of the role of technology in manufacturing, the development of a cost model to support make or buy decisions, and review of strategic implications of varying degrees of vertical integration.
Learning curve	Anderson et al, 1989	Empirically derived method of analysing how costs vary as cumulative production volume increases.
Product-process matrix	Hill, 1985; Hayes and Wheelwright, 1984; Anderson et al, 1989	Determining how manufacturing system design relates to product volume.
Product differentiation / buying process matrix	Hofer and Schendel, 1978	Investigating the relationship between preference and loyalty among buyers that reduces sensitivity to price differentials amongst existing products.
Interpretational structural modelling	Porter et al, 1982	Mechanism for ranking suitability of alternatives.

Table 2.9: Overview of traditional strategy tools

'Ishikawa cause and effect diagrams' (Evans, 1993); 'decision process modelling' (Bennett et al, 1990); 'cognitive maps' (Eden, 1990); and 'qualitative system dynamics' (Wolstenholme, 1990).

Unlike traditional strategy tools the contribution that these tools can make to manufacturing strategy formulation, is poorly documented in the literature. There are some important exceptions to this criticism, for example, the work of Samson (1991) on decision tree analysis. A plausible research topic could be to investigate how such tools can assist in strategy evaluation through structuring enquiry and judgement between strategy formulators.

Models are a second mechanism for analytical evaluation of a manufacturing strategy. These models are defined as an abstract representation and emulation of a real world object or system under study. Authors that recognise models to be of this form include Cooke and Slack (1991), Schmidt (1985), Feltner and Weiner (1985), and Morgan (1990). A variety of model forms exist, for example, financial planning (Naylor and Mansfield, 1977); Discrete Event Simulation (DES) (Love and Barton, 1993); and Systems Dynamics (SD) (Kumar and Vrat, 1989).

The potential value of modelling appears to be high, for example, Copacino and Rosenfield (1985) see that decision support models are useful both for measuring the impact of proposed plans, as well as for determining the most efficient way to support the corporate plan. Likewise, as previously introduced, Ansoff and Brandenburg (1971) advocate a modelling approach. The preference for models appears to have occurred as they provide both prediction about, and insight into, the behaviour of a manufacturing system, as observed by Suri and Diehl (1985). However, there is no apparent literature that claims to have explicitly and thoroughly addressed the application of modelling to the analytical evaluation of a manufacturing strategy.

The literature that has specifically addressed modelling in general strategy formulation is contentious. For example, whilst discussing corporate planning Kumar and Vrat (1989) advocate a SD approach. Likewise, Reagan-Cirincione et al (1991) see this type of model as particularly useful when a problem is very complex, the outcomes of action are likely to be realised far into the future, and the effects of possible solutions are unclear. However, Love and Barton (1993) are cautious about high level modelling techniques, such as SD, as they see that inherent approximations undermine the accuracy and utility of the results generated.

A reason for this contention could be the lack of a consistent knowledge base about the relative performance of models. Such knowledge relies to some extent on a foundation of experimental results. However, a considerable amount of literature on modelling is not empirically based. Nelson (1986), Horrocks (1987), Christy and Kleindorfer (1990), Danzyger (1990), Vercellis (1991), and Foong and Hoang (1993), all provide concepts for aspects of strategy evaluation but their approaches do not appear to have been assessed in practice. This situation may have arisen because of the difficulty of conducting empirical manufacturing strategy research, as previously highlighted in Section 2.2.1. For example, Wainwright (1993) attempts such work but, due to difficulties with his collaborating company, experiences a wide disparity of results from which no firm conclusions could be gauged.

Some work does give an empirical assessment but often this is in isolation to the performance of other modelling techniques. For example, Nymon (1987), Berman and Kautz (1990), and McClelland (1992) give indications of performance but this is not related to other possibly suitable techniques. This situation may well aggravate the contention highlighted above.

The potential value of models to strategy formulation does not appear to have been comprehensively addressed, but is thought to be high because of its ability to provide both insight and prediction about a manufacturing system. However, existing work in the literature on modelling in strategy formulation contains both contradictions and empirical weaknesses. Therefore, the role of modelling in the evaluation of a manufacturing strategy is felt to be a worthy topic for a concentrated research effort and the chosen area for the research described in this thesis.

2.4.5 Guidelines on the process of strategy research

Accepting that a research thrust in the area of strategy evaluation is justified, it is appropriate to explore the issues that surround research methodologies in this field. Platts (1993) draws from several sources of manufacturing strategy literature to identify three major shortcomings of current research approaches, namely:

1. Poor conceptual base.
2. Low level of empirical work and theory testing.
3. Lack of relevance to the 'real world'.

The concerns surrounding the conceptual base are succinctly summarised by Hill (1987) who says:

> "...research must aim at developing a proper conceptual base for this area; we do not need publications which generalise from inadequate research evidence, or are sets of statements based on our own views."

Insufficient empirical work is observed and criticised by authors such as Schroeder (in Skinner et al 1985), Leong et al (1990). This situation is summed up by Anderson et al (1989) as:

> "The literature is largely expository in nature - it contains very few empirical studies."

Platts (1993) criticises the traditional academic approach of interviews, one day visits and questionnaires, as being unrewarding to industrial collaborators and consultants. He sees such approaches as lacking relevance to organisations that ought to profit from research. Platts then addresses the shortcomings of current research by proposing three guidelines for research that seek to develop processes and frameworks in the strategy field, these are:

1. The process must link to existing frameworks.
2. There must be adequate empirical testing and verification of any proposed process.
3. The results of the research must be relevant to the practising manager.

These guidelines have been developed, observed, and seen to be appropriate in the earlier work of Platts (1990). Furthermore, there is a general absence in the literature of verified, distinctly different, alternatives to the guidelines of Platts. Therefore, it is appropriate to adhere to such guidelines when programming and executing a study on manufacturing strategy.

2.5 CONCLUSION

This chapter has introduced the concept of manufacturing strategy, determining that this concept has value in achieving the competitive advantage being sought by the business strategy of a company, and establishing that effective strategy formulation can be achieved through the application of a formal planning process. However, this chapter has also shown that a strong body of research has yet to evolve in this area and as a consequence a number of research opportunities exist. A particularly worthy topic is seen as the application of modelling to the analytical evaluation of a manufacturing strategy. Furthermore, a number of guidelines on research process exist in the literature about how research in this area should be conducted.

The manufacturing strategy literature reviewed in this chapter has enabled some consideration of modelling approaches to be made. However, many more forms of models exist than appear to have been explicitly considered for manufacturing strategy evaluation. Therefore, to allow a precise aim and programme to be developed for this research, it is important that the extent of previous work in the general area of modelling must first be explored.

CHAPTER 3

MODELLING LITERATURE REVIEW

To determine a precise aim and programme for this research, the full extent of the knowledge in the literature on modelling must be known. The objective of this chapter is to establish such a foundation of knowledge. This objective is realised, and the chapter structured, to first develop from the literature a taxonomy of models. This taxonomy is then used to expose the variety of models available, and a number of representative modelling approaches are chosen for each sub-class of the taxonomy. Through these representative modelling approaches, the extent and nature of previous work on modelling is explored, and in particular contributions are sought that make good the modelling weaknesses identified in the manufacturing strategy literature. Finally, conclusions are drawn on the contributions in the modelling literature.

3.1 FOUNDATION TO MODEL TAXONOMY

A taxonomy is a framework of classification. Provision of an unambiguous framework requires a clear definition of scope and consistent terminology. This section provides a suitable foundation for a taxonomy of models by addressing both of these issues.

This thesis is concerned with models that are an abstract representation and emulation of a real world object or system (Section 2.4.4). Such models exhibit at least one distinctive quality that pertains to the real object or system, for example, visual impact, geometric dimensions, or behaviour. These are distinctly different from, and this taxonomy does not include 'methodologies' that are approaches for structured enquiry, judgement and problem solving about a real world object or system.

Unfortunately, this categorisation is not definitive as some techniques can be applied as a model and a methodology. For example, the operation of a machine tool could be illustrated by an Ishikawa cause and effect diagram (Section 2.4.4) even though this technique is more usually applied to establishing relationships between specific factors and their respective causes. A more usual application of this technique would be, for example, as used by Joseph et al (1990) in an investigation into causes of poor product quality.

Furthermore, some modelling techniques, such as Soft Systems Methodology (SSM) (Checkland, 1988; Checkland and Scholes, 1990), incorporate both a methodology and modelling approach, in this case a Rich Picture (RP) as a model around which an enquiry is conducted. Indeed, within the field of decision support literature generally, authors often support their description of modelling with an application methodology. Examples of this are Carrie (1988) and Law and Kelton (1991). Therefore, it is important to recognise that a distinction between methodologies and models is not definitive and needs to be cautiously applied.

Used in construction of the model taxonomy are the terms, 'model instance', 'model type', 'modelling technique' and 'modelling tool'. Each of these terms requires a fuller explanation.

Banerjee and Basu (1993) provide a suitable definition of model instance and model type. They see a model instance as a specific formal representation used in addressing a particular problem, whereas a model type is a possibly infinite collection of model instances characterised by a set of rules and/or properties that distinguish instances of that model type from those of other model types. Hence, when the term 'model' is used in isolation in the literature, and also within this thesis, this is usually an implicit reference to a model instance.

The properties and rules associated with defining a model type need not be constrained to a particular grouping of modelling instances, and can be applied to group together models at various levels within a hierarchical taxonomy. For example, physical models may be considered as one model type, within which a subset of analogue model type may be found (Section 3.2.1).

When discussing a model type that is directly involved in model construction this thesis applies the term modelling technique. This terminology enforces a distinction between varying definitions of model type in a hierarchical taxonomy, and the principal mechanism that provides a basis for actual model construction. In this sense a modelling tool is the means through which a modelling technique can be applied, and the modelling technique can be associated with a set of distinguishing properties and rules.

Some modelling techniques may be applied in practice using computer based modelling tools, and a number of tools are seen to exist for various modelling techniques. The actual modelling tools are not as important to this research, as it is the underlying technique that is seen to characterise the capabilities of a modelling tool.

Having established the scope and terminology associated with the model taxonomy, design of an appropriate taxonomy for this research may proceed.

3.2 REVIEW OF EXISTING MODEL TYPE TAXONOMIES

In this thesis a taxonomy is required to thoroughly establish the range of modelling techniques that support manufacturing strategy evaluation. Unfortunately, the literature does not provide a consensus on a form of model type taxonomy. For example, Ackoff and Sasieni (1968) refer to three categories of models, namely, iconic, analogue, and symbolic models, whereas Mihram (1972) refers to replication, quasi-replica, analogue, descriptive, simular[1] and formalization[2] models. Schmidt (1985) has attempted to address this situation by identifying that models can be classified according to the dimensions of:

1. The manner in which the model describes the system.
2. The purpose of the model.
3. The description of the time dependent behaviour of the system.
4. Description of the random behaviour of elements of the system.
5. The description of system change as a discrete or continuous phenomena.

Each of these dimensions offers a potential taxonomy framework. This section explores the meaning, popularity and consensus in the literature of each dimension.

3.2.1 Model type taxonomy based on modelling medium

Schmidt (1985) considers that this classification should be termed modelling manner. However, to ensure a distinction from model purpose, the term model medium is adopted within this thesis. Modelling medium therefore, refers to the material substance from which a model is created (Schmidt, 1985). The literature

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[1] Mihram introduced the word simular as a substitute for simulation, this is discussed further in Section 3.3.

[2] This term has been subsequently changed in this thesis to formalisation to reflect popular English spelling.

contains a number of taxonomies based on modelling medium, more recent contributions include Shannon (1975), Carrie (1988), Pidd (1988), Watson (1989), Law and Kelton (1991), while a particularly comprehensive framework is provided by Mihram (1972).

Mihram plots an evolution of model taxonomies commencing with Rosenblueth and Wiener (1945) who draw a distinction between material and formal models. Material models are referred to as physical objects, while formal models are considered to be based on symbolic representations and logic. Mihram points out that Churchman et al (1957), were first to draw a distinction between iconic, analogue and symbolic models. Interestingly this categorisation is still supported by Ackoff (Ackoff and Sasieni, 1968), having worked with Churchman in 1956, and referred to during his work with Sasieni in 1968. Ackoff and Sasieni (1968) defined iconic models as generally looking like what they represent, that is images, whereas analogues[3] use one set of properties to represent another set of properties, and symbolic models are based on variables and relationships between them. Mihram considers the iconic and analogue models of Churchman et al (1957), to be synonymous with the material models of Rosenblueth and Wiener, with a similar association existing between symbolic and formal models.

According to Mihram (1972) the first recorded attempt to subdivide symbolic models was made by Sayre and Crosson (1963). They saw a subdivision into formalisations and simulations based on whether or not the symbols were manipulated by a well formed discipline, such as mathematics or mathematical logic, in order to arrive at a particular numerical value. Mihram supports the views of Sayre and Crosson, but is concerned that the term simulation was open to misinterpretation, and so modifies this term to simular models.

In completion Mihram compiled a model classification framework, predominantly based on modelling medium, that brought together the views of a wide variety of researchers (Table 3.1). In this framework all models are thought to be either material or symbolic. Material models are suggested to be either, replication, quasi-replicas, or analogues. Symbolic models are subdivided into descriptive, simular, and formalisations. In pursuit of greater precision Mihram also considered the characteristics of static, dynamic, stochastic or deterministic.

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[3] Some authors use the term analog models. To avoid confusion with the machine named analog computer this thesis has adopted throughout the term analogue when referring to a category of physical models.

		Physical			Symbolic			
		Replication	Quasi-replica	Analogue	Descriptive	Simular	Formalization	
Static	Deterministic	Earthen relief map	Road map	Statue of B. Franklin	Ten commandments	Decision logic tables	Ohm's law	*(From top to bottom)* Increasing generality.
	Stochastic	Critical dosage test	Weather map	Die toss for Russian roulette	Weather report	Non-adaptive, random chess playing program	Equilibrium queue length	
Dynamic	Deterministic	Model train set	Planetarium show	Analog computer circuitry	Constitution of the USA	Critical path algorithms	Lanchester's laws	
	Stochastic	Drosophila genetic experiment	CRT display of endurance test	White noise generator	Test on Darwinian evolution	Vehicle-by-vehicle transportation model	Stochastic differential equation	

(From left to right) Increasing abstraction,
Increasing inferential facility,
Decreasing reality.

Table 3.1: Classification of model types (Source: Mihram, 1972)

Unfortunately, Mihrams taxonomy has not been universally adopted in the literature as illustrated by the following examples.

Shannon (1975) presents a view that models are either iconic, analogue or symbolic. However, he does note that iconic models are sometimes referred to as physical models, and that physical models may be full size or scaled down. Likewise, Shannon points out that symbolic models may also be referred to as mathematical models.

Pidd (1988) views models as being either scale, mathematical or logical. He considers computer simulation to be one form of logical model, along with computer flow charts. Pidd sees mathematical models as a series of equations that may sometimes be solved to produce an optimum solution.

Carrie (1988) refers to three categories of models, namely, iconic, logical and simulation. In complete contradiction to Pidd, Carrie sees a logical model as an often optimising analytical relationship, whereas he defines simulation modelling as studying the behaviour of a system as a whole by defining in detail how various components interact with each other.

Finally, Law and Kelton (1991) consider models to be either physical or mathematical, where physical models can also be referred to as iconic models. They suggest that mathematical models are either analytical solutions or simulations.

3.2.2 Model type taxonomy based on model purpose

Schmidt (1985) considers that models can be classed as either descriptive or normative depending on their purpose. A descriptive model is seen as describing the behaviour of a system, whilst a normative prescribes a course of actions.

A number of similar distinctions exist in the literature such as, evaluative versus generative models (Suri, 1985); descriptive versus optimisation models (Watson, 1989); and descriptive versus prescriptive models (Shannon, 1975). However, there are also a number of alternatives. Schmidt, and Shannon both cite a classification given by ElMaghraby (1968) that recognises five important uses of models, these are, understanding, communication, instruction and training, prediction, and control. Also, Feltner and Weiner (1985) see model purpose as an aid for planning, implementation, and control. Cooke and Slack (1991) consider model purpose as improving understanding, stimulating creativity, and providing assistance in evaluating alternative courses of action.

3.2.3 Model type taxonomy based on static and dynamic characteristics

Common to authors such as Mihram (1972), Schmidt (1985), Kumar and Vrat (1989) is a taxonomy that considers static and dynamic characteristics of a model. A dynamic model is one which has attributes which alter with time whereas a static model does not consider time dependent behaviour (Mihram, 1972).

As manufacturing strategy can be associated with the implementation of changes with respect to time (Section 2.1.2), it appears appropriate that supportive models should be dynamic, and hence that a static or dynamic distinction is useful. However, as pointed out by Mihram (1972), this approach is limited in that some dynamic models are actually a generalisation of the static model variety. It is apparent therefore, that a static model could be used to investigate a system's performance over time by repeating a static calculation, with values of variables updated as appropriate, at specific time intervals. Alternatively, time could be considered by introducing time averaged values within a model and considering the resultant information to be an indication of steady state system performance.

3.2.4 Model type taxonomy based on stochastic and deterministic characteristics

Mihram (1972) and Schmidt (1985), along with Kumar and Vrat (1989) consider a taxonomy based on, or incorporating, stochastic and deterministic characteristics of a model. Pidd (1988) states that a deterministic system is one whose behaviour is entirely predictable. Likewise, a stochastic system is one whose behaviour cannot be entirely predicted, though some statement may be made about how likely certain events are. Although, Tocher (1963) likened industrial situations to a set of stochastic gear wheels clicking around irregularly, Pidd (1988) points out that in some senses, the distinction between stochastic and deterministic systems is artificial. He argues that it is more a statement of the knowledge about a system or the amount of control over that system exercised by an observer. Nevertheless, in environments of uncertainty a model may need to be capable of receiving a range of values for the exogenous[4] variables, whereas such variance may not be necessary when modelling stable environments. It is apparent therefore that a model taxonomy based on stochastic and deterministic characteristics is actually established on the capability of a model to deal with

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[4] Exogenous variables are factors that form independent inputs into a model which may be taken as acting upon the decision. Endogenous variables are generated from the interaction of a models input factors and the structure of the decision itself (Cooke and Slack, 1991).

exogenous variables. Some modelling techniques may accommodate a range of values for exogenous variables, whilst others could perform quite clumsily in such a situation.

3.2.5 Model type taxonomy based on discrete or continuous phenomena

Schmidt (1985), and Law and Kelton (1991) consider a taxonomy, or branch of a larger taxonomy, to be the manner by which a model represents the advance of time within a real system. This distinction is apparent between, for example, a Discrete Event Simulation (DES) model (Section 3.4.5), and a model based on a hydraulic representation of a real system. The hydraulic model can provide a replication of the time dependent behaviour of the real system whilst the DES model approximates the behaviour of real activities to step function changes.

3.3 DEVELOPMENT OF A MODEL TYPE TAXONOMY

The literature offers a number of model type taxonomies. Unfortunately, no one taxonomy is free of limitations. Taxonomies based on both modelling medium or model purpose are popular, but lack a consensus on form and terminology, whilst distinctions based on static, dynamic, stochastic, deterministic, discrete, or continuous characteristics can be imprecise. This section uses knowledge of existing model type taxonomies to define a framework that will provide a contemporary categorisation of modelling techniques.

A taxonomy based on modelling medium is most popular in the literature and provides a particularly comprehensive framework (Section 3.2.1). Mihram (1972) in particular gives a detailed and comprehensive taxonomy, but incorporates some distinctions based on static, dynamic, stochastic, and deterministic characteristics that are considered to be imprecise (Sections 3.2.3, 3.2.4). Moreover, the work of Mihram is not universally adopted in the literature by later researchers, and is relatively early and in danger of being out of step with current semantics. Therefore, to develop an acceptable taxonomy at this point, the material based classification of Mihram is taken as a coarse foundation, and then refined using common views and terminology in the literature.

Consider first, the category of models that Mihram termed 'physical'. This terminology is strongly supported in the literature, for example Shannon (1975), Carrie (1988), Law and Kelton (1991). However, there are some varying opinions in the literature on the appropriate sub-classes of physical models. Shannon (1975) and Schmidt (1985) consider iconic and analogue models, whereas Carrie (1988), and Law and Kelton (1991) see iconic and physical models to be synonymous. Mihram is effectively subdividing models that are often termed iconic, into two distinct classes, of replication and quasi-replica, and in doing so enhancing the precision of the terminology. However, an amendment can be made to the definition of quasi-replica models given by Mihram, in that a dimension need only be modified in a model rather than be missing altogether. Therefore, these two sub-classes have been adopted with definitions based on Mihram (1972):

> Replication model: A spatial transform of an original physical object in which the dimentionality of the modelling is retained in the replica.
>
> Quasi-replica model: A physical model in which one or more of the dimensions of the physical object are missing or modified.

Some authors recognise the existence of analogue models (Section 3.2.1). Whilst this is not universal, no case is apparent to formally dismiss such models. Hence, this sub-class of model types has also been adopted here, with a suitable definition again taken from Mihram:

> Analogue model: A model which bears no direct resemblance to the modelled phenomena.

Consider now, the category of models that Mihram termed 'symbolic'. Whilst the term symbolic is popular in the literature (Ackoff and Sasieni, 1968; Shannon, 1975; Watson, 1989), a few authors, such as Law and Kelton (1991), do see mathematical models as the appropriate name for this category. Furthermore, opinions also vary considerably on the appropriate sub-class of symbolic model types. As a foundation, Mihram considers these sub-classes to be, formalisations, simular and descriptive.

Consider first formalisations, which Mihram felt to be a class of symbolic models in which the symbols are manipulated by a well formed discipline. There is strong support that one subset of symbolic model types is some form of mathematical representation of a system (Shannon, 1975; Pidd, 1988; Watson, 1989; Breugnot et al, 1990; Law and Kelton, 1991). Likewise, authors such as ElMaghraby and Ravi (1992) recognise model forms that use mathematical variables and explicit expressions to represent the physical qualities and behaviour of an actual system. Carrie (1988) stresses that often these equations can be solved to give the optimum solution for the problem encountered, and that these models are optimising in the sense that they yield the one best value for the function concerned. There are however instances where, due to the complexity of the system involved, no optimum solutions can be found directly, and suitable conditions need to be established through a number of iterations (Law and Kelton, 1991). Law and Kelton (1991) point out that in this case a mathematical model can be studied by numerically exercising the input question to see how the output is effected.

The association of explicit expressions with mathematical models, is also consistent with the definition of formalisations given by Mihram. However, the term mathematical model is very popular in the literature whereas formalisation is not. Therefore, this sub-class will adopt the term mathematical model along with an associated definition provided by Carrie (1988):

> Mathematical model: Explicit analytical formulae describing known relationships.

Consider simular models that Mihram defined as a sub-class of symbolic models whose component symbols are not entirely manipulated by the operations of well formed mathematical disciplines. Mihram introduced the term simular models as he recognised that the word simulation was being loosely used. Even so, it can still be argued that physical models are all examples of simulations in as much as they imitate reality (Cooke and Slack, 1991). Therefore, it may be thought to be imprecise of authors such as Mihram to incorporate an explicit model type distinction on simulation, at one specific level in a hierarchical taxonomy, when simulation can be used implicitly to relate to other categories in the taxonomy.

Whilst the term simulation is weak because it can be generally applied, it is also vague for the sub-class that it is intended to represent. As Schmidt (1985) points out, the distinction between mathematical and simulation models is not one that can be easily drawn. Some of this difficulty appears to have occurred because both model forms rely on mathematics, inherent to which, are numerical and logical expressions. A demonstration of this contention is provided by Pidd (1988), who describes System Dynamics (SD) (Section 3.4.5) as a form of simulation that is expressed in a mathematical form. However, some distinction between these model forms becomes apparent when the process of model construction is investigated.

Carrie (1988) considers simulation modelling as describing the behaviour of a system as a whole, by defining in detail how various components interact with each other. For example, simulation modelling with SD consists of tracing through, step-by-step, the actual flow of orders, goods, and information, and observing the series of new decisions required (Forrester, 1958). Hence, a more precise term for the simulation model sub-class would be 'implicit mathematical models'. Unfortunately, adoption of such new phraseology risks misinterpretation of the research contribution in this thesis. Therefore, to reflect popular usage in the literature, this thesis will cautiously adopt the term simulation for the category of models that Mihram (1972) termed simular models. A suitable definition of simulation is derived from Carrie (1988) as:

> Simulation model: A model of the behaviour of a system as a whole by defining in detail how various components interact with each other.

Finally, consider the category of models that Mihram termed descriptive. The term descriptive models can be confused with a model's purpose, as shown by Shannon (1975) and Schmidt (1985). Riggs (1970) and Heizer and Render (1988) use the term schematic model for a drawing or chart of reality. Therefore, to overcome the contention associated with the word descriptive this thesis will use the term schematic for a symbolic model that does not contain any manipulation of variables, rather it is a structured statement of a system's content, structure and interactions. A schematic model will be defined in this thesis as:

> Schematic model: A graphical representation of a system using symbols.

In conclusion, the work of Mihram (1972) has provided a foundation against which the views of more recent authors, and evaluations in terminology semantics, can be contrast. The resulting taxonomy and model type definitions are presented in Table 3.2.

3.4 CATEGORISATION OF MODELLING TECHNIQUES

The previous section has established a taxonomy of models, thus providing a basic framework through which a comprehensive range of modelling techniques for manufacturing strategy evaluation can be investigated. The term modelling technique has been defined in Section 3.1 as the principal mechanism that provides the basis for model construction in an operational sense. The range of models, and associated modelling techniques, can be illustrated by identifying one or more representative modelling techniques for each sub-class in the model taxonomy. These representative techniques, termed generic techniques, should capture the flavour of each model type whilst respecting that the task in hand is to support the evaluation of a manufacturing strategy.

Main class	Sub-class	Definition
Physical	Replication	A spatial transform of an original physical object in which the dimentionality of the modelling is retained in the replica.
	Quasi-replica	A physical model in which one or more of the dimensions of the physical object are missing or modified.
	Analogue	A model which bears no direct resemblance to the modelled phenomena.
Symbolic	Schematic	A graphical representation of a system using symbols.
	Simulation	A model of the behaviour of a system as a whole by defining in detail how various components interact with each other.
	Mathematical	Explicit analytical formulae describing known relationships.

Table 3.2: Taxonomy of model types

A pedantic appraisal of modelling techniques would find that some approaches do not neatly fall into the taxonomy developed here, rather they span a number of categories. For example, 'Petri-nets' (Section 3.4.5) is a simulation technique that provides a graphical representation as a schematic model. Likewise, there are a number of instances where modelling techniques from a number of categories have been combined to provide a cohesive modelling tool for a particular application. For example, a combination of $IDEF_0$ (Section 3.4.4), Discrete Event Simulation (DES)(Section 3.4.5), and financial modelling (Section 3.4.6) (Williams and Pontin, 1989), and financial modelling with SD (Thompson, 1986). These concerns have been addressed by identifying the principal modelling techniques involved in each case and then cataloguing these independently.

Finally, this section is structured to individually consider the sub-classes in the model taxonomy shown in Table 3.2. A summary of the modelling techniques chosen in each case is given in Table 3.3.

3.4.1 Physical replication models

Models in this category have been defined as spatial transforms of a real world object or system. As these models are materially not far removed from the actual real system under study, they can be said to exhibit a low level of abstraction from reality. This close association means that there is limited opportunity for various forms of model to exist. A range of models is provided because a model may, or may not, contain the complete functionality that exists in the real system.

One such model occurs when a spatial replica of the physical features, and visual aesthetics, of a system is constructed that lacks functionality. Such is the case with body work styling in the automotive industry. Alternatively, aesthetics and functionality may be combined to provide a model that is a complete replica. Indeed, this second case can be considered to exist when, for example, a machine tool is installed within a factory but is awaiting commissioning prior to being entered into production. The commissioning activity can be thought of as a form of modelling, used to perform adjustments that ensure full operational functionality, and which ceases when the machine is entered into production.

In each of these examples given above, the model form varies to suit the purpose of the model, likewise the modelling technique varies to suit the model form. In the case of automotive body work styling, the modelling technique may be sculpture. Whereas, with a pre-commissioned machine tool the modelling

Main class	Sub-class	Generic modelling technique	Abbreviated term used
Physical	Replication	Model construction using an identical mechanism to that used in the real system under study.	Replica
		Model construction using any mechanism that provides a spatially identical model to the real system under study.	Non-functional replica
	Quasi-replica	Model construction using any mechanism that provides a fully functional scaled model.	Scale
		Model construction using any mechanism that provides a scaled model that lacks functionality.	Non-functional scale
		Model construction using any mechanism that provides a two dimensional scaled model that lacks functionality.	2D non-functional scale
	Analogue	Modelling using an analog computer.	Analog
Symbolic	Schematic	Rich Picture	RP
		Integrated Enterprise Modelling	IEM
		$IDEF_0$	$IDEF_0$
	Simulation	Discrete Event Simulation	DES
		System Dynamics	SD
	Mathematical	Queuing Theory	QT
		Activity Based Costing	ABC
		Business Planning	BP

Table 3.3: Generic modelling techniques

technique can be considered to be the machining, casting, and fabrication processes, that have been used to manufacture the machine tool. In the former case the modelling technique may be generalised as model construction using any mechanism that provides a spatially identical model to the real system under study. Likewise, the latter case can be generalised as model construction using an identical mechanism to that used in the real system under study.

These two approaches are believed to adequately represent this sub-class and are therefore chosen as generic modelling techniques.

3.4.2 Physical quasi-replica models

These models have been defined as physical models with one dimension modified or missing. Similar to physical replication models, a distinction exists based on whether functionality is combined with a quasi replica model.

One form of quasi-replica model is where two dimensions are scaled up or down in size, the third dimension is missing, and there is a lack of functionality. An example of such a model is a photograph. An alternative model form occurs where a model is still scaled up or down in size and functionality is absent, but the third dimension is now present. An example of this second case is a static scale model. Such models are often used for factory layout planning (Carrie, 1988). Finally, functionality may be retained in a physically scaled model of the real system. An actual application of such a model is provided by O'Reilly et al (1984) who describes a 1/35 scale model of an automotive painting process that consists of 62 position sensors, 39 stops activated by solenoids, 31 pneumatically operated lift tables and 46 motors.

The roles of scale and functionality provide three generic modelling techniques for this category, as summarised in Table 3.3.

3.4.3 Physical analogue models

Physical analogue models have been defined as bearing no direct visual resemblance to the system being modelled. There is an absence in the previous sub-classes of physical models that exhibit functional, but not physical, similarity to the real system being studied. This niche is filled by analogue models.

Ackoff and Sasieni (1968) cite an example of an analogue model being a hydraulic system representing electrical, traffic, and economic systems. An example of an analogue model of a manufacturing system can be provided by an electrical circuit model. In this case electrical elements such as transistors, resistors and capacitors are connected in such a way as to represent a manufacturing process. To model discrete product manufacture a digital electrical signal generator could be used as an input to such a model. This form of modelling technique appears to have been popular when analog computers are applied (Mihram, 1972).

Of the modelling techniques in this category, an approach to modelling using analog electrical circuiting appears to be suited to manufacturing system modelling and is therefore chosen as the generic technique to represent the analogue category.

3.4.4 Symbolic schematic models

Such models have been defined as a symbolic graphical representation. A common example of a schematic model is an engineering drawing. Such a drawing makes use of an abstract graphical representation of a component. In this example a change in symbolic representation, say from third to first angle projection, would effectively invoke the use of a second modelling technique. Therefore, as this example illustrates, there is considerable opportunity for modelling technique diversity.

This diversity has been harnessed through a process of considering the range of formality, in other words complexity of graphical syntax, associated with modelling techniques. This has been coupled with a search for techniques that are advocated within the literature as particularly capable, or providing a bias towards, manufacturing system modelling.

The most involved modelling syntax appears to exist within systems analysis techniques. Within this category are such techniques as, Data Flow Diagrams (DFD) (Downs et al, 1992; Johansson et al, 1993); Input/Output Analysis (Olsmats et al, 1988; LUCAS, 1989); CORE (Kehoe et al, 1987; LUCAS, 1989); $IDEF_0$ (Brovoco and Yadav, 1985; LUCAS, 1989; Williams and Pontin, 1989; Johansson et al, 1993); Structured Analysis and Design Technique (SADT) (Marca and McGowan, 1986; Ziya Aktas, 1987); and Structured Systems Analysis and Design Methodology (SSADM) (Kehoe et al, 1987).

A common approach is $IDEF_0$ (Baines and Hughes, 1985; Brovoco and Yadav, 1985; Brovoco et al, 1988; Baines and Colquhoun, 1990, 1991). The $IDEF_0$ technique produces a model which is essentially a flow diagram that illustrates the activities within a manufacturing system, this technique is described in greater detail in Appendix A.1. This technique is characterised by both a specific syntax and decomposition of a system content to various levels of detail.

The origins of $IDEF_0$ lie in the development of SADT by, amongst others, D. T. Ross (Marca and McGowan, 1986; LUCAS, 1989). Marca and McGowan describe $IDEF_0$ as a standardised subset of SADT which has been promoted by the United States Department of Defence under their ICAM (Integrated Computer Aided Manufacturing) programme. The IDEF acronym is formed by taking the 'I' from ICAM and 'DEF' from definition (Brovoco and Yadav, 1985). Where SADT has been developed to address all phases of a systems development (Ziya Aktas, 1987), $IDEF_0$ is intended purely for representing the functional relationships in a manufacturing system (Baines and Colquhoun, 1991). However, $IDEF_0$ is the name given to one standard and there are at least three IDEF variants discussed in the literature[5]. $IDEF_0$ views a system as the set of functions it performs. $IDEF_1$ views a system by studying information it contains. $IDEF_2$ views the time dependent behaviour of a system (Brovoco and Yadav, 1985). Due to the support given to $IDEF_0$ in the literature, it has been chosen as a generic modelling technique for this study.

As presented above, $IDEF_0$ is believed to be typical of a classical approach to structured system analysis and design. Such techniques are characterised by strict rules and considerable abstraction from the system being modelled. As an alternative to this classical approach, a modeller may use techniques such as 'material flow charts' (Currie, 1959; Johansson et al, 1993). These are common operational research data capture techniques that provide a graphically similar symbolic representation to a system being modelled by $IDEF_0$.

Business Process Re-engineering (BPR) (Johansson et al, 1993) appears to have been a recent catalyst for a number of modelling innovations. A variety of techniques have been constructed to bridge the features of such techniques as $IDEF_0$ and material flow charts to give a comprehensive model of a business. The term Integrated Enterprise Modelling (IEM) (Mertins et al, 1991) can be given to these approaches. IEM is an emerging topic in the literature and there are inconsistencies in the use of terminology. However, because IEM is closely associated with BPR, and features a more relaxed syntax than $IDEF_0$, it is also chosen as a generic modelling technique. This technique is described in Appendix A.2.

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[5] Though not supported in the literature, discussions with other researchers and software companies have established the existence of fourteen IDEF standards each addressing a particular application.

Finally, Rich Pictures (RP) are an integral part of Soft Systems Methodology (SSM) and have no strict syntax. These have been established, through the contribution of authors such as Checkland (1988), to illustrate the content and behaviour of a system as a means to promote communication between individuals. Such pictures are a cartoon like illustration of the system under study, as shown in Figure 3.1. These pictures are intended to break down the communication barriers that are associated with written statements and technical diagrams. Therefore, because of this extremely relaxed graphical syntax RP is also chosen as a generic modelling technique in this study.

In summary, although a wide range of modelling techniques exist in this category, by examining the formality of model construction three pertinent generic approaches have been identified, namely $IDEF_0$, IEM and RP. These techniques are summaries on Table 3.3.

3.4.5 Symbolic simulation models

Simulation has been defined as modelling the behaviour of a system as a whole by defining in detail how various components interact with each other. A review of the literature has established that there are three principal forms of simulation modelling techniques, namely continuous, discrete event and combined. There are however some recent additions, or evolution's on a theme, that need to be considered before generic modelling techniques can be chosen.

Consider foremost Discrete Event Simulation (DES). This modelling technique is defined by Roth (1987) as measurements made on variables which are affected by instantaneous changes of system state. However, a number of approaches to DES modelling are apparent.

The time varying behaviour of a system can be modelled using $IDEF_2$ (Brovoco and Yadav, 1985). This technique is intended to complement $IDEF_0$ and $IDEF_1$ to provide a comprehensive modelling approach. As $IDEF_2$ is based on an instantaneous system change (Brovoco and Yadav, 1985) it is a form of DES. Unfortunately, the $IDEF_2$ technique could not be pursued as it is not in the public domain (Williams and Pontin, 1989). However, research by Popplewell and Bell (1990) is at an advanced stage to provide an $IDEF_0$ based DES package.

Schmidt et al (1991) discuss Object Oriented Simulation (OOS), Artificial Neural Network Simulation (ANNS), as well as DES. However, the distinction between OOS and DES in this work is actually based on the principles of the computer language used. DES is considered to be applied using procedural computer

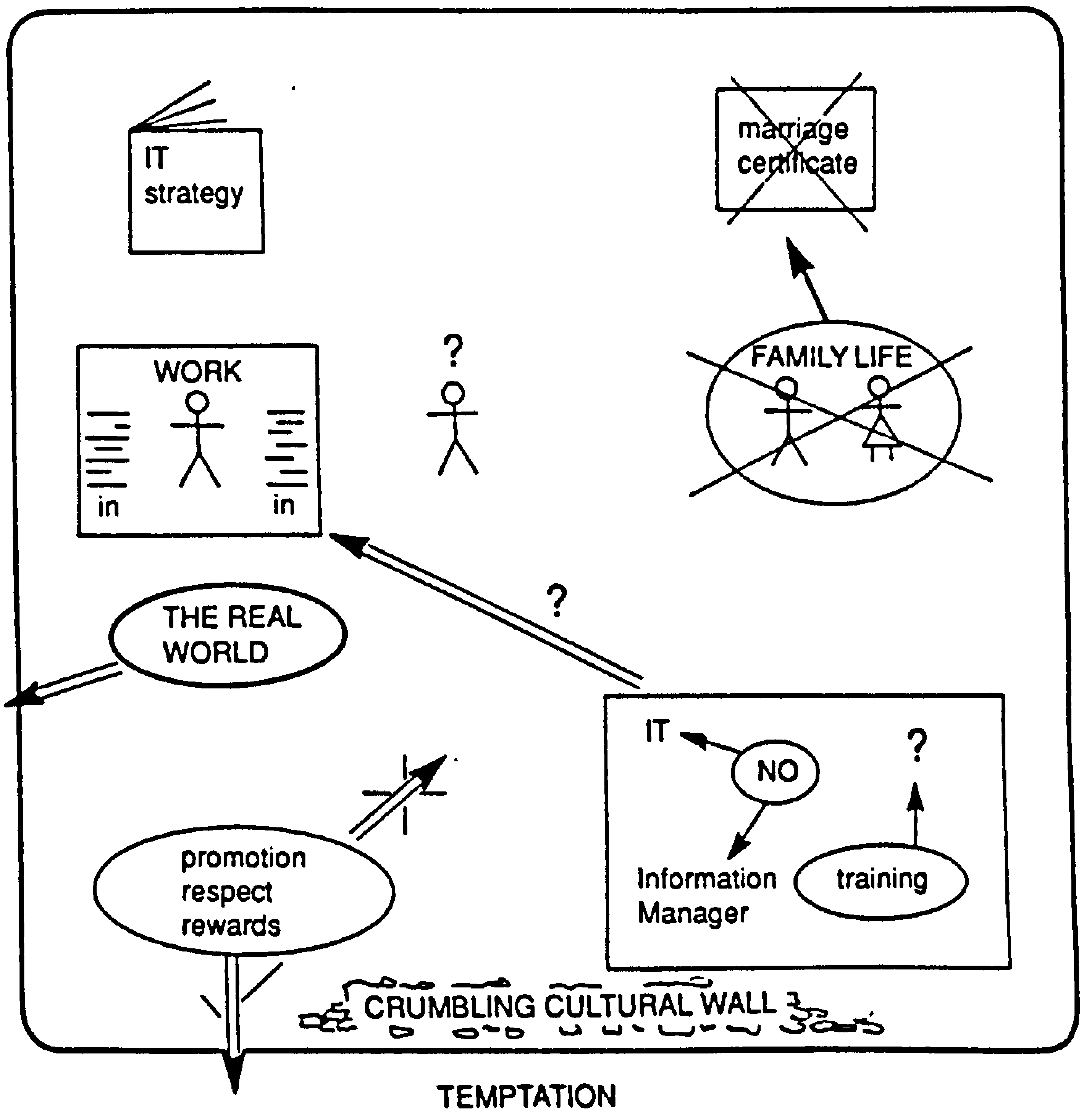

Figure 3.1: Rich Picture of a problem situation (Source: Davis and Ledington, 1991)

programing languages, whilst OOS is applied using object-oriented languages which are generally seen by authors such as Graham (1991) as providing improved programming efficiency through the use of polymorphism, abstraction, and inheritance. The principles of DES are however independent of the computer language used, indeed DES can be performed without a computer using 'activity cycle diagrams' as illustrated by Carrie (1988) and Williams and Pontin (1989).

Schmidt et al (1991) describe an ANNS model as basically a black box with a set of inputs that yield a set of outputs. They state that ANNS models are programed by training, but the route to acquiring the output is difficult to relate to the system being modelled. Furthermore, they see that ANNS models are weakest in the same areas as the human brain; exact mathematical answers, computational logic and speed. Likewise, Fishwick (1989) concludes that ANNS models provide a less powerful tool than traditional simulation approaches. Other artificial intelligence applications to simulation, focus on reducing expertise required for model building and interpreting simulation results with expert judgement (Garzia et al, 1986).

DES can be provided through the application of 'Petri-nets' and 'coloured Petri-nets'. Cecil et al (1992) cite several examples of the use of Petri-nets in the modelling, analysis and control of systems that can be considered to perform discrete component manufacture. They see one of the main advantages of this approach to DES being a graphical system representation. Unfortunately, Petri-nets are at a relatively embryonic stage and extensive research and development is needed to increase the scope of this technique to modelling, analysis, and control of manufacturing systems (Cecil et al, 1992).

In summary, although a number of evolution's are apparent, DES is an appropriate generic modelling technique for this study. This approach differs significantly from continuous simulation. A more detailed description of DES is given in Appendix A.3.

Continuous simulation is a modelling technique that is concerned with constructing a model in which the state variables change continuously with respect to time (Law and Kelton, 1991). Such models involve differential equations that give relationships for the rate of change of the system variables with time. Law and Kelton point out that if the differential equations are particularly simple, they can be solved analytically to give the values of the state variables, for all values of time, as a function of the values of the state variables at time zero. However, such a direct solution is rarely feasible where real systems are involved and a numerical approach needs to be adopted (Pidd, 1988). Pidd points out that such an approach is incorporated into System Dynamics (SD) where the differential equations that describe the behaviour of a real system are represented by difference equations.

The origin of SD, as given by Wolstenholme (1990), commenced with Forrester (1961, 1968) who created a subject area originally known as 'industrial dynamics'. As pointed out by Towill (1993a), the subject received this name because it was focused at work in terms of strategies for improving industrial systems performance. He goes on to say that for a brief while the methodology became known in the UK as 'managerial dynamics', and more recently the field has been named SD due to the expanding range of applications considered by Forrester, often involving the social sciences.

Wolstenholme (1990) points out that SD can be considered in terms of 'qualitative' or 'quantitative' approaches. He states that qualitative SD is concerned with creating cause and effect diagrams that are known as casual loop, or influence diagrams. Whereas quantitative SD is defined by Wolstenholme as quantitative computer simulation modelling, as described in Appendix A.4. Qualitative SD pertains to a methodology as described in Section 2.4.4 and will consequently not be considered further. Any future reference to SD in this thesis will imply a quantitative approach.

Continuous simulation modelling in a SD guise has been applied to a variety of business and manufacturing applications; Forrester (1958) examines modelling of production and distribution systems; Dangerfield and Roberts (1993) apply SD to investigate scenarios of the consequences of capacity requirements in the UK steel industry; Edghill et al (1987) and Olsmats et al (1988) have applied this technique to the modelling of production, inventory and distribution systems. The literature also describes a number of SD applications in financial modelling, see for example Thompson (1986). In this second case, explicit financial equations are imbedded in a SD modelling tool, and exercised with a range of input variables. The popularity of SD justifies its choice as a second generic modelling technique for this category of model types.

Combined simulation is a combination of discrete and continuous approaches. The capability of combined simulation can be established through a consideration of discrete and continuous approaches. Hence, this approach has not been considered independently and the chosen generic techniques for this category are SD and DES.

3.4.6 Symbolic mathematical models

Mathematical modelling has been defined as the use of explicit analytical formulae to describe known relationships. From a general perspective, a wide variety of mathematical models have been developed to describe the effect of particular relationships. In this sense equations that relate mass, acceleration and force, or price, cost and profit, are all examples of mathematical models. Modelling techniques in this instance are developed for a specific set of applications. This association is often so close, that the modelling technique is inevitably a structured expression that only requires populating with numerical values about the system being modelled. Therefore, the process chosen to review mathematical modelling techniques is to identify sets of applications of interest in manufacturing strategy evaluation, and to subsequently relate these back to identify modelling techniques.

Cited earlier, Ansoff and Brandenburg (1971) summarise the task of analytical models as allowing alternative organisation designs to be modelled, the outcome of each design predicted against objectives, allowing the most suitable design to be selected. In manufacturing strategy formulation such objectives are market and financially oriented (Section 2.1.2). Therefore, modelling techniques of interest are those which provide market and financial information of the effect of developments to a manufacturing system.

Market criteria consist of product based information such as lead time, volume, etc. Modelling techniques that provide such information include, 'control theory concepts' (Axsater, 1985; Popplewell and Bonney, 1987; Towill, 1992); 'metamodels' (Jothishankar and Wang, 1993), and Queuing Theory (QT) (Suri, 1985; Suri and Diehl, 1985, 1987; Haider and Suri, 1990; ElMaghraby and Ravi, 1992).

Axsater (1985) gives three forms of standard control theory methods, namely 'linear deterministic', 'linear stochastic', and 'non-linear deterministic'. However, he observes in the literature a slight decline in interest in this subject. Considerable achievements though, have been made in the recent past by Edghill et al (1987), Popplewell and Bonney (1987), and Cheema et al (1989). Edghill et al (1987) note that analytical control theory is labour intensive, and requires a degree of specialisation not to be expected from potential industrial users with no previous experience.

A metamodel is often constructed to approximate the behaviour of elements within a simulation model. In situations where frequent model execution is necessary, a metamodel is simpler and less costly than conducting many simulation experiments (Jothishankar and Wang, 1993). Hence, there are a number of applications within the literature of metamodelling being applied to production control situations, for example, Lin et al (1992). However, to construct a metamodel it is invariably necessary to carry out some simulations of input-parameter combinations to obtain data from which the parameters of the metamodel are established (Law and Kelton, 1991). Therefore, if a system can be adequately modelled with a simulation technique, then the arguments for applying metamodelling are significantly compromised.

QT predicts the average behaviour of a manufacturing system over a medium to long time horizon (Suri and Diehl, 1985). Suri and Diehl see that the overall insight that QT provides is appropriate for the design and planning stage of a manufacturing system. Likewise, Haider et al (1986) state that from their experience QT models are effective at the initial analysis level of a manufacturing system. Therefore, as control theory concepts and metamodels exhibit some significant limitations, it is appropriate that QT is chosen as one form of generic model for this category. A more detailed description of QT is given in Appendix A.5.

Financial criteria are addressed by Cooke and Slack (1991) using two forms of financial models. The first is mainly concerned with conventional accounting measures and relationships, whereas the second focuses on long time scales.

A number of financial modelling techniques exist for accounting measures and relationships, these include 'marginal costing', 'absorption costing' (Harper, 1967); Activity Based Costing (ABC) (Innes and Mitchell, 1989; Steeple and Winters, 1993); 'throughput accounting' (Steeple and Winters, 1993). Likewise, some models have been developed for a special purposes such as IVAN (InVestment ANalysis)(Williams and Pontin, 1989).

ABC has been developed to overcome limitations associated with traditional accounting procedures, and as pointed out by Steeple and Winters (1993), the main research work on ABC has been carried out at the Harvard Business School by Cooper, Kaplan and Johnson. Kaplan (1984) observed that reliance on traditional costing systems in the current competitive environment would provide an inadequate picture of manufacturing efficiency and competitiveness. However, Steeple and Winters (1993), credit Newton (1991) with research that has established that few companies have successfully implemented ABC. Likewise, Cooper (1990) states that implementation of an appropriate ABC can require prohibitive effort and time scales.

ABC need not however directly replace traditional accounting procedures, rather it can be used as a diagnostic tool to lay bare all overhead costs and to establish inaccuracies within an established accounting system (Barbee, 1993). This argument is further supported by Drury and Pettifer (1993) who argue that ABC should not be used to produce monthly profit statements, traditional systems can be used for that, rather ABC should be used for strategic decisions and profitability analysis. Furthermore, ABC has a close association with absorption costing (Piper and Whalley, 1990, 1991) suggesting that a company can be flexible to the extent that ABC is adopted. On the basis of suitability as a diagnostic tool, ABC is adopted as a generic modelling technique. A description of this approach is given in Appendix A.6.

Throughput accounting does not allocate costs to products with respect to their use and therefore is not as competent as ABC (Steeple and Winters, 1993).

Mathematical modelling techniques that consider the long term performance of a business are termed Business Planning (BP) models or 'financial planning systems' (Gray, 1984). Motteram and Sizer (1992) argue that major investments as part of a world class manufacturing strategy, will significantly effect business performance when implemented. They say that if an incorrect judgement is made it is unlikely that the decision could be reversed and that therefore, financial evaluation should be prepared as a detailed business case. The structure of such models is based on financial conventions, some of which are legally enforced, such as tax laws, therefore few variations of models exist. Variety is only possible where a choice in convention exists, such is the case in depreciating the value of a capital investment. Therefore, BP has been chosen as a suitable generic technique, and is described in Appendix A.7.

3.4.7 Summary of generic modelling techniques

The previous section has established fourteen modelling techniques to comprehensively represent the forms of modelling available for manufacturing strategy evaluation. These generic techniques are summarised in Table 3.3.

3.5 MODELLING LITERATURE ON MANUFACTURING STRATEGY EVALUATION.

Chapter 3 has provided a broad and structured enquiry into modelling and identified fourteen representative modelling techniques. Therefore, to complement the strategy literature and, to conclude this chapter, this knowledge can be applied to gain a second perspective on the extent to which existing research has addressed modelling in the evaluation of a manufacturing strategy. As modelling work that has explicitly considered manufacturing strategy evaluation is exposed in the previous chapter, it is necessary to focus here on contributions in the literature that are implicitly concerned with manufacturing strategy evaluation. Such contributions are expected to be typified as work that supports high level decision making within manufacturing system design, but not explicitly claiming to be associated with manufacturing strategy formulation. Further focus is possible by searching for research that redresses the weaknesses in the literature that were identified from a manufacturing strategy perspective, hence seeking contributions in the modelling literature that address the contradictions and empirical weaknesses observed in Section 2.4.4.

The modelling literature holds an expanse of assertive statements on which modelling technique to apply in a particular situation. These statements are sometimes contradictory and usually unsupported empirically. Especially common are comments that advocate DES. For example ElMaghraby and Ravi (1992), whilst referring to DES, see that:

> "Nowadays, simulation has become an indispensable tool to study the behaviour of complex systems..."

Similar assertive statements exist about the unsuitability of modelling techniques. For example, Buchanan and Scott (1992), are cited though not endorsed by, Suri and de Treville (1992) for claiming that the:

> "...often abstract nature of many articles on queuing suggests that queuing theory is just that: only theory and difficult to apply in practice."

Also, Pidd (1988) states:

> "....queuing theory models..........cannot cope with many types of problem."

There are however similarly assertive views, held by a number of authors, that completely contradict those given above. Suri (1985), for example, states in reference to QT:

"In the early stages of manufacturing planning it offers an efficient alternative to simulation."

Likewise, Suri and Diehl (1985) state that:

'Typically, such models (queuing theory) come within 5% to 15% of the values obtained for detailed simulation."

Other authors are less assertive and give more reasoned arguments for their beliefs. Carrie (1988), for example, generally dismisses logical[6] models because they depend on explicit analytical formulae describing known relationships which on the whole do not occur within manufacturing systems. Carrie says:

"Since most manufacturing systems are indeed complex, simulation is a most suitable tool."

and Son (1991) agrees and states that:

".... manufacturing systems can be too dynamic and complex in nature to describe completely in mathematical terms. Hence, a computer simulation approach has prevailed in comparing conventional manufacturing with advanced manufacturing systems..."

Whilst reasoned arguments are of greater worth to research than unsupported assertive statements, there is a natural preference to seek out empirical research. Such work is typified by Franks (1993) who provides a questionnaire based appraisal of eleven methods of 'enterprise modelling'. Snowdon and Ammons (1988) give a similar comprehensive survey of 'queuing network software tools'. Whilst Steeple and Winters (1993) provide a questionnaire based evaluation of accountancy costing procedures, and Innes and Mitchell (1989) give a comprehensive review of ABC studies.

In general however, empirical evidence is sparse, furthermore the studies that do exist tend to contrast models of a similar type rather than investigating performance across categories of model types. Within the modelling literature there is a relatively strong conceptual base, in as much as, a wide variety of modelling approaches are described. However, there is very little conceptual work bridging both manufacturing strategy and modelling research disciplines.

In summary, literature that has been reviewed from a modelling technique perspective is sometimes contradictory in nature, and empirical work is sparse and generally limited to contrasting comparable techniques. Therefore, rather

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[6] Logical models given by Carrie (1988) are interpreted to be equivalent to mathematical models in this thesis.

than redressing the deficits in the strategy literature, a large deficiency in existing knowledge is also apparent in the modelling literature.

3.6 CONCLUSION

This chapter has formed a taxonomy through which models for manufacturing strategy evaluation have been rigorously investigated. This taxonomy has identified fourteen modelling techniques to comprehensively represent approaches to modelling in manufacturing strategy evaluation. A subsequent appraisal of literature associated with these techniques has established findings that concur with Chapter 2 of this thesis, namely, that modelling in the evaluation of a manufacturing strategy is a subject requiring research attention.

CHAPTER 4
RESEARCH AIM AND PROGRAMME

The intention of this research is to assist practitioners in the process of manufacturing strategy formulation. A review of literature in Chapters 2 and 3 has comprehensively explored the progress of previous research and intimated the direction and form that future work should take. This chapter summarises the knowledge supplied from these earlier chapters to generate a precise aim that will fulfil the intention of this research. A research programme is then developed to realise this aim.

4.1 DEVELOPMENT OF RESEARCH AIM

The importance of the concept of manufacturing strategy is widely accepted in the literature (Section 2.2). However a qualifying strong research base has yet to evolve (Section 2.4.1). As discussed in Section 2.4.1 there is a paucity of both descriptive and prescriptive research work. Prescriptive work is concerned with how strategies should be formed whilst descriptive work considers how strategies form in practice. Within each of these categories research efforts can be viewed from whether manufacturing strategy content or process has been investigated. There is a greater contribution in the literature as to 'what' a strategy has or should contain as opposed to 'how' the content of a strategy has or should be chosen. However, if an overall view is taken as to whether future work should be either descriptive or prescriptive, content or process focused, it is clearly apparent that there are opportunities in each area with the literature supporting a particularly urgent need to provide prescriptive processes for manufacturing strategy formulation.

Hofer and Schendel (1978) identify seven stages that are included implicitly or explicitly in major strategy formulation processes. Section 2.4.2 highlights how authors such as Platts (1990), and Platts and Gregory (1990a, 1990b) have focused their contributions to address the earlier stages of such processes whilst the later stages, in particular strategy evaluation and choice, have not received similar explicit attention. At a general level, Mintzberg et al (1976) have investigated the evaluation-choice routine in strategy formulation and identified three components of decision making, namely, judgement, bargaining and analysis. From a manufacturing perspective however, the literature has for some time called for analysis based strategy evaluation methods to support judgement and bargaining in manufacturing strategy formulation (Section 2.4.3).

Apparent in the manufacturing strategy literature are a group of pseudo-analysis methods that include traditional strategy tools (Section 2.4.4). Such methods provide structured enquiry, judgement and problem solving about a real world object or system under study, and generally have a role in manufacturing strategy formulation that is relatively well defined in the strategy literature.

Modelling is a second analytical method, and such models provide an abstract representation and emulation of a real world object or system under study. It is apparent in Section 2.4.4 that there is an absence of work that has explicitly addressed modelling in manufacturing strategy evaluation, yet such work is considered to hold significant potential. The contributions that do exist in the manufacturing strategy literature are fraught with contradictions and empirical weaknesses. Furthermore, a similar situation is also apparent within the modelling literature, when a general review of manufacturing system modelling is made (Section 3.5). It has also been noted in Section 3.5 that existing studies tend to be limited to contrasting models of a similar type, rather than investigating performance across categories of model types. On this basis, previous work in this area is seen to exhibit significant weaknesses.

A potentially valuable research topic is therefore to investigate the application of models in the analytical evaluation of a manufacturing strategy. A model, or to be precise, a model instance, can be thought of as a specific formal representation used in addressing a particular problem (Section 3.1). Clearly, the contribution of this research will be greater if modelling can be supported across a range of industrial applications. Models are often constructed in an operational sense using a modelling tool, the principles of which are dependent on the encapsulated modelling technique (Section 3.1). Therefore, to maximise the contribution of the research in this thesis, a justified focus is to establish the appropriate principles of a modelling tool that distinctly supports manufacturing strategy evaluation. Such a focus should give a backbone of knowledge that may enable the development of a number of modelling tool variants, and subsequently the use of models in manufacturing strategy evaluation, across a wide range of industrial situations.

The manner in which research into manufacturing strategy should be conducted is addressed in the literature. In particular the literature is critical of impractical or unsupported conceptual solutions (Section 2.4.5). Furthermore, there is strong advice that research work should link existing contributions, provide adequate empirical testing and verification, and ensure relevance to the practising manager. Such advice should be observed when developing a research aim and programme.

Taking into account the reasoning given above a research aim is submitted for this thesis that will, if satisfied, make a worthy contribution to knowledge about manufacturing strategy formulation. This aim is:

> 'To form and verify the principles of a modelling tool that will enable a practical analytical evaluation of a manufacturing system performance, as a strategy is applied, and in doing so directly support judgement and bargaining in strategy evaluation, as a procedure in formal planning processes.'

To conclude, the deliverables of this research will need to be the principles of a modelling tool that is tailored to manufacturing strategy evaluation, as illustrated schematically in Figure 4.1. This modelling tool should enable a manufacturing system to be represented by a model, which is then capable of accepting a series of modifications to represent the implementation of a manufacturing strategy. The resulting model behaviour should be in a form that will allow assessment of the performance of a manufacturing system, in terms of measures that are appropriate to manufacturing strategy formulation. As highlighted in Section 2.4.4, the purpose of modelling in this situation should be both prediction and insight into the behaviour of a manufacturing system. For example, a strategy formulator may use such a model to evaluate the effect of the introduction of a new manufacturing process, an alternative process organisation, or manufacturing control system, on such measures as product lead time and cost.

The remainder of this chapter addresses development of a research programme to realise this aim.

4.2 DEVELOPMENT OF RESEARCH PROGRAMME

The research programme is a sequence of activities that are to be carried out to realise the aim of this research. Explicit in the research aim is an intention to form and verify the principles of a modelling tool. As verification cannot commence until the principles are formed, the research programme can be considered in two phases. Within each of these phases a number of stages exist

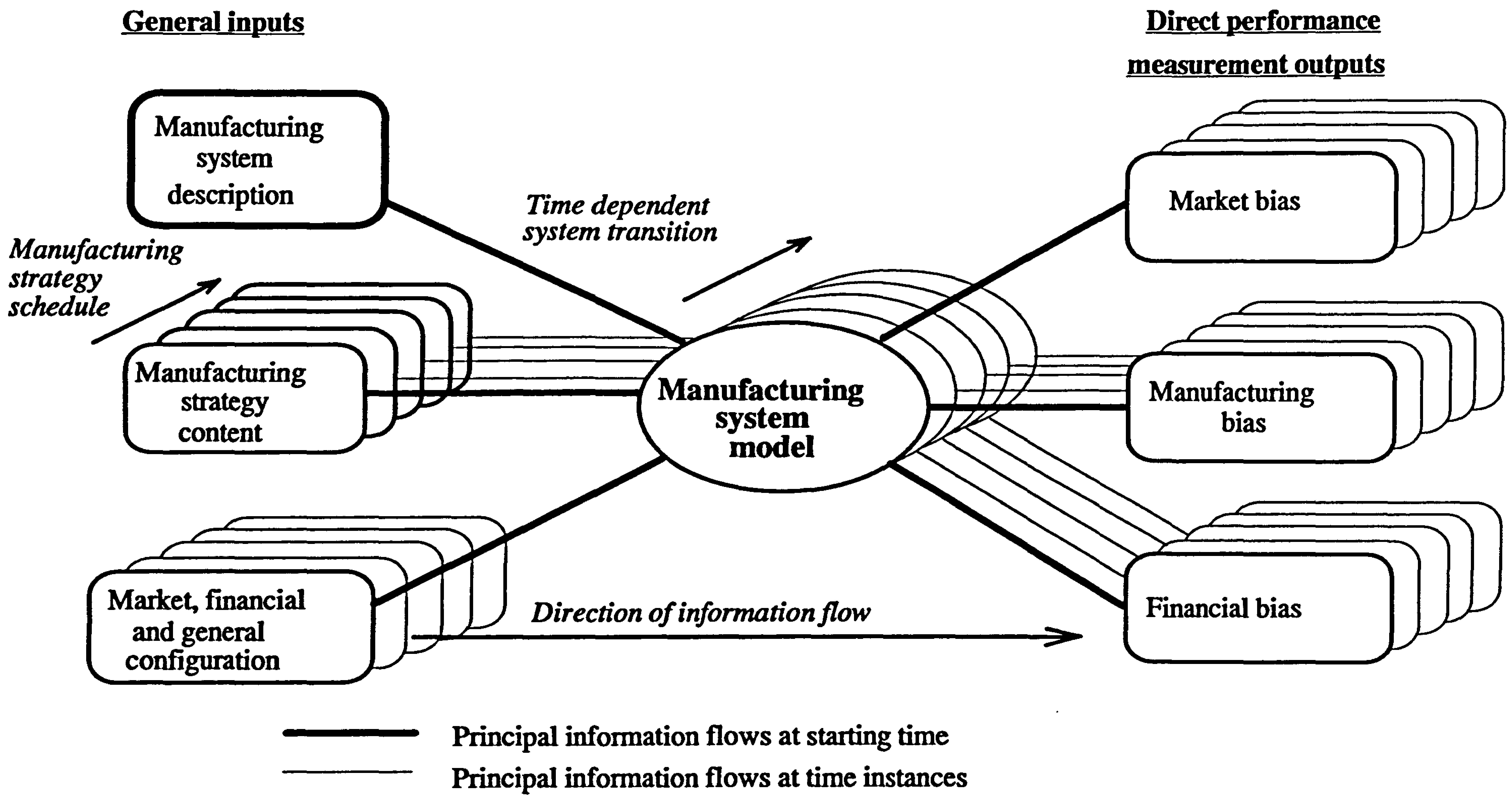

Figure 4.1: General structure of manufacturing strategy evaluation tool

and form an overall framework of activities for this study. This section will determine the required stages, the associated objectives and guiding methods and policies, necessary to realise each objective. Further detail about the activities at each stage will subsequently be added, prior to execution of the associated stage, so as to take advantage of knowledge gained from the execution of preceding stages. Hence, the remainder of this thesis presents each research stage as a separate chapter, within which, the detailed research activity at that stage is discussed.

4.2.1 Phase 1 : Formation of the principles of the modelling tool

The task in the first phase of the research programme is to form the principles of a modelling tool that is tailored for manufacturing strategy evaluation. These principles are determined by the modelling technique that is encapsulated within a modelling tool (Section 3.1). Therefore, formation of the principles of a modelling tool is achieved by establishing the appropriate modelling technique, or combination of techniques, on which to base the development of a modelling tool. Hence, a focus on the requirements and capabilities of modelling techniques will be predominant throughout this section.

The previously described weaknesses in the literature are twofold and affect the manner in which this work should proceed. Firstly, a verified modelling solution that is tailored to the manufacturing strategy evaluation role is not apparent. Secondly, and more significant here, knowledge about the capabilities of existing modelling techniques is limited, contentious and empirically weak.

Three methods exist of addressing the development of a modelling solution for the strategy evaluation task. One approach is to completely ignore existing knowledge, allowing an uninfluenced development of a modelling tool to proceed, and in this way it may be possible to deliver a fundamentally new modelling approach. The concern here is that considerable effort may be expended only to arrive at a modelling technique that already exists. A second method is to develop a modelling tool on the basis of the existing knowledge about modelling techniques in the literature. However, the weaknesses in the existing literature may mislead research efforts and deliver a sub-optimum solution. Furthermore, both the first and second method will eventually require testing to be carried out over a range of modelling approaches, so as to gain confidence that the developed modelling tool is suited to the task of manufacturing strategy evaluation, and to avoid being criticised as an unsupported conceptual solution. A third method is to first critically assess the capabilities of existing modelling techniques, and on the basis of this foundation of knowledge, develop a modelling tool. Unfortunately, the originality of the ensuing modelling solution may be compromised. As De Bono (1992) points out:

> "It is normal when entering a new field to read up all that there is to read about the new field. If you do not do so then you cannot make use of what is known and you risk wasting your time reinventing the wheel. But if you do all this reading you wreck your chances of being original."

Such a risk is however necessary if work in this field is to proceed in a logical manner; foundations are required on which future work can build, and against which future contributions can be compared. Leedy (1980) refers to this situation as the 'circle or helix of research'. He states that:

> "Research always gives rise to further unexplored questions. In the helix conception, the solution of the research problem begets still other problems, and thus research becomes a spiral continuing progressively onward."

The method preferred in this study is therefore to first establish a foundation of knowledge, and from this develop a bespoke modelling solution. The knowledge required is an objective, comprehensive, and in-depth understanding of the capabilities of existing modelling techniques in the analytical evaluation of a manufacturing strategy.

To establish an objective body of knowledge about existing modelling approaches, some form of measurement system is first required against which the performance of comparable modelling techniques can be plotted. However, two significant issues are apparent and need to be addressed for such a measurement system to be formed, namely, how to identify the appropriate measures of performance for a model and modelling tool, and how to associate the requirements of a model and modelling tool to the requirements of a modelling technique. These two issues are addressed as follows.

As previously highlighted, a model can be thought of as a specific formal representation, and a modelling tool as the mechanism through which construction of a model is carried out. As models and modelling tools can be directly associated with the application of modelling, it appears logical that personnel and literature associated with manufacturing strategy formulation are more likely to hold perceptions and expectations of models and modelling tools, rather than modelling techniques. Therefore, it is appropriate to initially investigate a measuring system from the perspective of a model and modelling tool.

The general form of a measurement system can be gained by considering that a model and modelling tool is sought that upholds the general strategy concept described in Section 2.1, and satisfies the research aim of supporting formal planning processes (Section 4.1).

Formal planning processes can be viewed as either internally or externally supportive (Section 2.3.3). From the literature regarding these processes, and the general concept of manufacturing strategy, an attempt can be made to determine a set of criteria that describe the expectations of a model and modelling tool. Unfortunately, the embryonic nature of manufacturing strategy (Section 2.4.1), threatens confidence that all these criteria can be established from the literature. For example, by the nature of the information source, unpublished work cannot be considered in this manner. Therefore, in an attempt to overcome this deficiency, the knowledge gained from the literature can be reinforced with the opinions of practitioners who are knowledgeable about the practical formulation of manufacturing strategy, as to their expectations of a model and modelling tool. Identification of such practitioners is considered in Section 5.1.

To maximise the usefulness of the contributions of practitioners to this research, the method through which their opinions are surveyed requires careful consideration. A survey can be based on either interviews or questionnaires. Moore (1986) argues that questionnaires can only give a superficial impression of a situation. This view can be tempered to a degree by considering more advanced questionnaire based survey methods (Fowler, 1988). However, Moore does suggest that an increasingly popular approach is the 'in-depth interview', where a few people are subjected to a detailed, and inevitably less structured, encounter. He cites advantages of such an approach as being that answers are qualified and the results gained are of greater depth. A disadvantage appears to be that greater resources will be required to execute this approach compared to questionnaires for the same sample size.

A choice between whether to solicit opinion through interviews or questionnaires can be made by postulating the nature of the questions to be asked and the potential respondents. As the concept of manufacturing strategy is a relatively recent development, and model based evaluation particularly embryonic, the questions are likely to be complex and require considerable explanation in order to gain a valuable response. Likewise, for the same reasons the number of people involved with explicit strategy evaluation is felt to be small and populated across a range of disciplines from academia to consultancy. For these reasons an in-depth interview is preferred in this situation. This approach is developed and structured in Section 5.1. Hence, through the literature and in-depth interviews with practitioners, the appropriate measures of performance for a model and modelling tool should be established.

The second issue is how to relate the expectations of a model and modelling tool, to the requirements of a modelling technique. As stated earlier in this section, to develop the principles of a modelling tool, knowledge is required about the capabilities of a modelling technique. However, if the personnel described above are directly questioned about modelling techniques, there is a danger that requests will be made for a computer based modelling tool that has file handling facilities, a specific menu structure, or a hardware platform. While it is important that such desires are taken into account in a modelling tool, these are generally less significant when considering the requirements of a modelling technique. Therefore, some method is required of distinguishing between the features of a model and modelling tool, and the specific characteristics of the associated modelling technique, so that such features can be removed from a debate about the requirements of a modelling technique. A method of divorcing these issues is to question whether the desired capability could be provided solely from the modelling tool medium. For example, file handling capabilities can be incorporated into a computer software package, without the package being associated with manufacturing system modelling. To facilitate the distinction in this case, the opinion can be sought of practitioners who are knowledgeable about the design of modelling tools. The identification and collaboration with such personnel is discussed in Section 5.1. Hence, through the further assistance of practitioners, the requirements of a modelling technique should be transposed from the expectations of a model and modelling tool.

To summarise, on the basis of the arguments highlighted above, the first research activity is:

Objective of stage 1 : To establish the requirements of a modelling technique in manufacturing strategy evaluation.

As illustrated in Figure 4.2, the method of realising this objective is to first carry out an activity to establish the perceived expectations of a model and modelling tool. This is performed by considering the concept of manufacturing strategy and formal planning processes, initially from the literature, but to reinforce this with

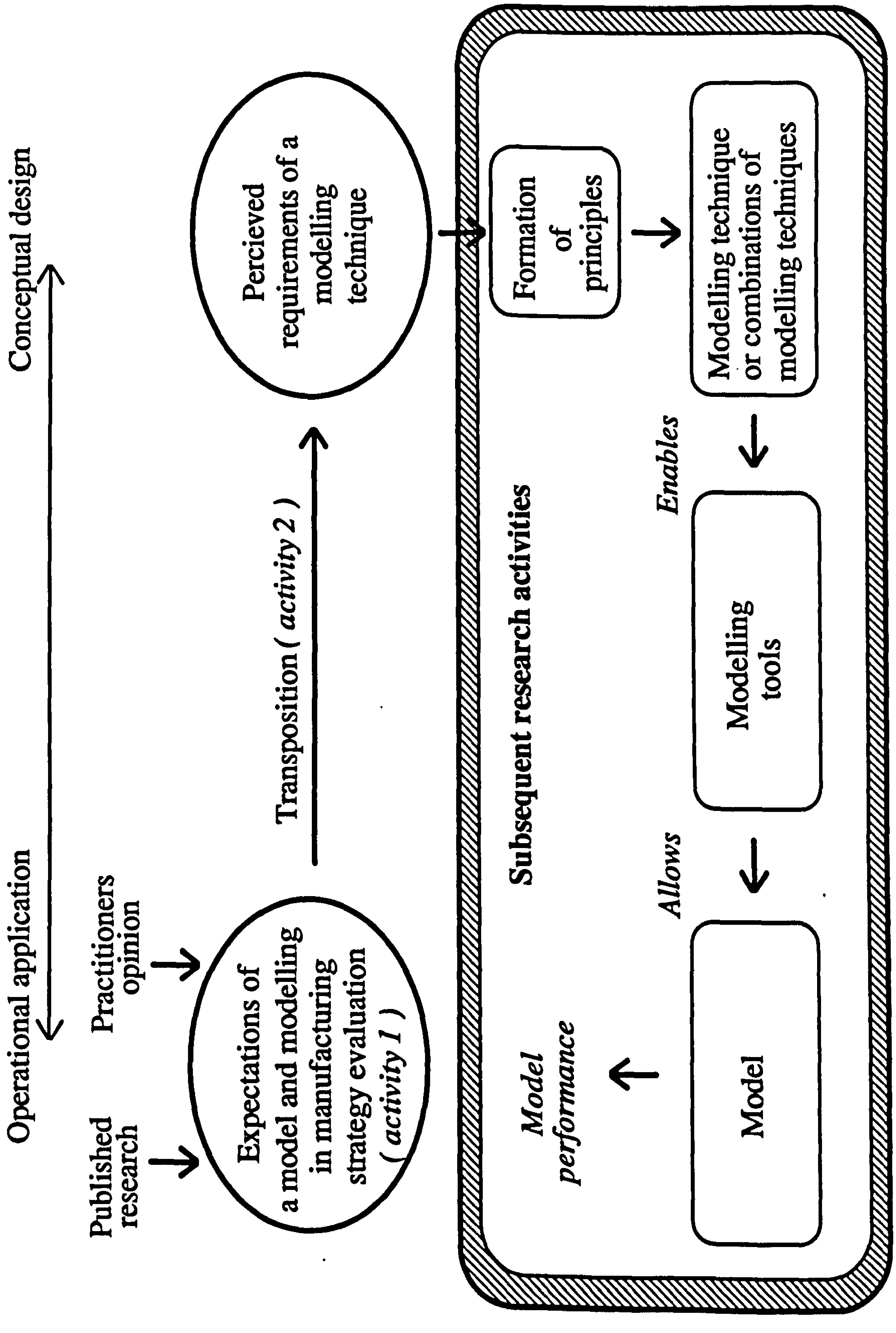

Figure 4.2: Establishing the requirement set

knowledge developed through in-depth interviews with practitioners. Further assistance will then be sought from practitioners to relate these expectations to the requirements of a modelling technique. The outcome of this stage will be a set of criteria, termed the 'requirement set', against which modelling techniques can be evaluated. The choice of practitioners, and structure of the in-depth interviews, is considered in greater detail in Section 5.1.

Once a measuring system has been defined, then assessment of modelling techniques can commence. In order to adhere to the advice in the literature this assessment should be empirically based, with the results being relevant to practising managers (Section 4.1). An appropriate test is therefore to directly experiment with modelling techniques in the same context as they could be applied in manufacturing strategy evaluation. Fourteen generic modelling techniques have been identified in Chapter 3 for the strategy evaluation role, each of these are candidates for such experimentation.

Unfortunately, an initial examination of the generic modelling techniques reveals that the experimentation approach described above would be difficult to resource in this study. For example, such experimentation could mean the construction of a physical replica of a factory. A method is therefore sought to gain empirical evidence, but to minimise the resources required to do so. In such a situation Beveridge (1950) advises screening a large number of samples so as to rationalise the experimentation programme. Such rationalisation is possible with modelling techniques if the empirical information in the literature can be used as the mechanism for such screening. However, the limitations of this literature are such, that it is only adequate if it can be used to identify unequivocally unsuitable modelling techniques. Furthermore, a method is required to improve the extent to which this literature can be validly applied.

A mechanism for extending the application of the existing literature is deductive reasoning. Deduction is concerned with the derivation of statements from another given statement (Chalmers, 1978). As Chalmers points out, deduction deals with logic and predictions, unlike induction that is concerned with establishing truth from experience. A suitable deductive argument is, for example, if evidence exists that a modelling technique requires excessive resources to apply when modelling a manufacturing system, then because manufacturing strategy is concerned with manufacturing systems, such a technique will also require excessive resources to apply to manufacturing strategy evaluation.

Each modelling technique can therefore be considered in this way. The process can proceed by searching for clear evidence from the literature on the performance of models, tools and techniques. If this evidence is associated with manufacturing strategy evaluation it can be used directly. However, if only general evidence is found, then if possible the performance of the modelling approach can be measured against the requirement set using deduction. If a modelling technique performs particularly poorly compared to other modelling approaches, then it will be discounted from further consideration in this work.

It is however important to note that because of the weaknesses of the literature it will be necessary to err on the side of caution and not to penalise a modelling technique because of an absence of credible literature. Hence, initially it will be assumed that each of the 14 modelling techniques are suitable for the task of manufacturing strategy evaluation, and only to be dismissed where unequivocal evidence exists of unsuitability against the requirement set. Therefore, if a technique survives this research stage it does not necessarily mean that the technique fulfils all the requirements of strategy evaluation, rather that a failing situation has yet to be found. The technique should then be carried forward for further consideration.

Finally, in some instances it may be necessary to interpret the capabilities of a modelling technique from the performance of a modelling tool and model. This interpretation is concerned with identifying the capabilities of a modelling technique in terms of the requirement set, from the performance of a model and modelling tool. Fortunately, the requirement set criteria imply the aspects of model and modelling tool performance of interest. Therefore, this interpretation is simply a task of identifying from the performance of the model and modelling tool, only criteria that are explicit in the requirement set.

To summarise, on the basis of the arguments highlighted above, the second research activity is:

Objective of stage 2 : To rationalise the number of generic modelling techniques carried forward for intensive experimentation.

The method of realising this objective will be by using existing knowledge in the literature, either directly or indirectly, to determine which modelling techniques are clearly unsuitable for the task of manufacturing strategy evaluation. This method is developed further in Section 6.1.

Assuming that screening reduces the number of generic modelling techniques so that experimentation becomes feasible, an associated experimentation programme can be applied to critically appraise the capabilities of the remaining modelling techniques. As highlighted above, a most appropriate test is to assess modelling techniques in the same context as they could be applied in practice, namely, with the experiments synthesising the evaluation of a manufacturing strategy in an industrial situation. Many factors however need to be considered, in order to convert such an intention into a rigorous but efficient experimentation programme.

First, adopting the view of Popper, as presented by Chalmers (1978), a general approach to experimentation is to form a hypothesis and then design experiments that present facts about the hypothesis. On the basis of these facts, interpretation is then performed in an attempt to falsify the hypothesis. There is no apparent reason why experimentation with modelling techniques should not follow this approach.

From a falsificationists view, experimentation seeks to disprove rather than prove the hypothesis. There is no method that enables scientific theory to be proven true or probably true (Chalmers, 1978). Chalmers states that a hypothesis slowly transforms into a theory as it withstands an ever greater number of experiments. Indeed, it can be argued that a theory is merely a hypothesis waiting to be falsified. Hence, experimentation can only prove limitations in the capabilities of modelling techniques. If such a limitation is experienced in one, out of many experiments, then a weakness has been exposed. However, failure to expose any limitations may occur because sufficient searching and verified experimentation has not been conducted.

The starting point for such experimentation is the modelling techniques provided from the preceding stage of research. A hypothesis can be formed for each generic modelling technique, in that, the technique satisfies all the requirements of modelling in strategy evaluation. The process can proceed by searching for clear contradictory empirical evidence that falsifies each hypothesis. In situations where such evidence is found, this means that the modelling technique capabilities are limited in the strategy evaluation role. Hence, the focus for experimentation becomes one of searching for limitations and not attempting to prove capabilities of a modelling technique.

Adopting this focus, detailed experiment design cannot take place until the measurement system has been fully formed by stage 2 of this research programme. This is the case because experimentation will need to be designed to reflect these requirements, hence experiment design will be addressed in Chapter 7. However, it is probable that a number of experiments will be necessary to assess each modelling technique. To refer to these the term 'experiment set' will be used in this thesis. To facilitate the design of the experiment set a number of policies need to be established here, namely, a method of efficiently gaining generalised results; a method of establishing the capabilities of a modelling technique from the performance of a modelling tool; and a method of efficiently establishing the performance of combinations of modelling techniques. Guiding policies are established for each of these issues as follows.

For the desired knowledge base of modelling techniques to be valuable, it is necessary that the results gained are not only true for a few industrial situations, but rather the results gained should be generalisations of the modelling technique capabilities. As Chalmers (1978) points out, for generalisations to be considered legitimate a number of conditions must be satisfied, namely:

- The number of observation statements forming the basis of a generalisation must be large.
- The observation must be repeated under a wide variety of conditions.
- No accepted observation statement should conflict with the derived universal theory.

Unfortunately, significant resources may be necessary to conduct each experiment set. For example, techniques such as Discrete Event Simulation (DES) are generally supported in the literature, and direct experimentation may well be necessary. In a previous consultancy project the author recorded that approximately 450 hours were required to construct a DES model of a machine shop that roughly consisted of 40 personnel, 24 machines, and nine similar manufacturing development scenarios. In this instance, the construction time included data collection and a small amount of personnel education. Hence, if an experiment set contained similar practical work, it could require considerable time to execute.

A dilemma exists in that, applying a small number of experiment sets for each modelling technique may attract the criticism that results are case specific. Whereas, experimentation with a large number of experiment sets may be difficult to resource. A method of gaining representative results of the capabilities of modelling techniques is required, while reducing the extent of experimentation to a minimum.

A solution to this dilemma is to adopt a similar approach as in stage 1 of this research programme, namely, to make use of the opinions of practitioners. In this case practitioners could first be used to assist in the verification of experiments. Practitioners could subsequently assist in the interpretation of results and the forming of conclusions from experimentation at one manufacturing company. Such an approach would require the participation of suitably knowledgeable personnel who are prepared to attempt objective criticism of the experimental work, and identify abnormalities in the results on the basis of their experiences. However, there are two issues that need to be addressed before such an approach can be adopted, namely, identification of appropriate personnel, and how to gain useful inputs from such personnel.

A set of appropriate personnel become apparent when reasoning that often modelling techniques are applied in practice using modelling tools, and that particularly capable tools are likely to be commercial products that are serviced by sales and support staff. Such staff should be knowledgeable about the modelling tool that they support, and hence provide a good source of expertise. Unfortunately, they are also likely to be bias towards the modelling tool they service, and naturally prejudiced against other modelling tools and techniques. Hence, a rigorous method will be necessary to gain verification of experimentation and generalisation of results from this source. This issue will be addressed further in Section 7.1.

Once the results of experimentation with models and modelling tools have been attained, it will be necessary to interpret from these the capabilities of modelling techniques. Again, this interpretation is concerned with identifying the capabilities of a modelling technique in terms of the requirement set, from the performance of a model and modelling tool. The same approach can be applied here as discussed earlier in this section.

Finally, to provide a broad base of knowledge about modelling, it is necessary to establish the capabilities of combinations of modelling techniques. An immediately obvious method of testing combinations is to use the same experimental approach as for individual techniques. Unfortunately, the number of experiments necessary to test all possible combinations could be large, as indicated by the following equation:

$$Cn = 2^n - 1 - n$$

Where : Cn = The number of possible experiments.

n = The number of modelling techniques under consideration.

Such an amount of detailed and rigorous experimentation again presents a resource issue. However, one resolution is to deduce the capabilities of combinations of modelling techniques from the experimental results of individual modelling techniques. For example, if two modelling techniques are considered as one, strengths may cancel weaknesses, and the resulting capabilities be greater than for the constituent techniques. Using this approach, once the capabilities of individual techniques are known, the combined limitations can be deduced through comparing the strengths and weaknesses associated with each constituent technique. However, as such a large number of combinations may need to be analysed in this manner, a systematic methodology will be needed. This methodology will be established in Chapter 7.

To summarise, on the basis of the arguments highlighted above, the third research activity is:

Objective of stage 3 : to establish empirical evidence as to the suitability of generic modelling techniques to the task of analytical evaluation of a manufacturing strategy.

The method of realising this objective is illustrated in Figure 4.3. This diagram shows that the experimental approach will be to assess modelling techniques at a manufacturing company using contemporary modelling tools, and that practitioners will be used to assist in inferring the capabilities of modelling techniques and generalisation of results. However, a number of issues need to be addressed to form a practical experimentation programme, namely, design of the experiment set; choice of industrial test-bed and modelling tools; a method of gaining opinion from modelling practitioners; and design of a systematic method of deduction to establish the performance of combining modelling techniques. Each of these issues is addressed in Chapter 7. On completion of this critical appraisal a comprehensive and in-depth knowledge base should have been formed about the relative capabilities of generic modelling techniques in the analytical evaluation of a manufacturing strategy.

Once the capabilities of both individual and combined techniques are known, the principles of a modelling tool can be designed. As justified earlier in this section, an attempt should be made to establish the principles of a modelling tool from existing modelling techniques because this will capitalise on existing knowledge whilst also presenting a foundation for future work. This policy should be

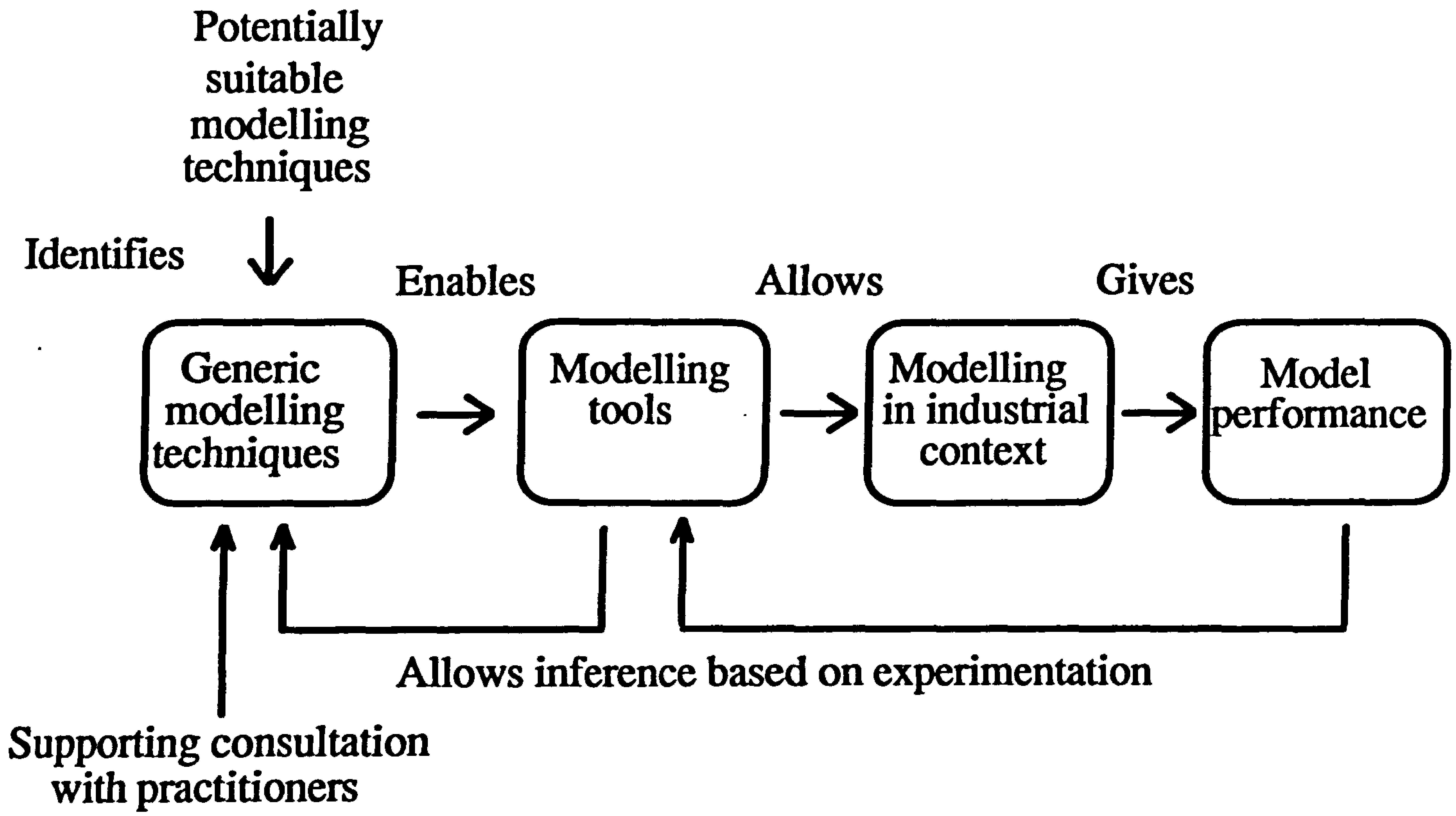

Figure 4.3: Experimental assessment of generic modelling techniques

followed if possible, but the precise approach that needs to be taken at this stage will be dependent on the results of the preceding research stage.

If the results of the preceding experimental stage show that a number of individual, or combinations of, modelling techniques, satisfy the requirements of manufacturing strategy evaluation, then the activity here should consist of choosing one modelling technique to develop further. Such a choice should be possible through some form of ranking of techniques on the basis of their capabilities. This ranking will be feasible as it is unlikely that all techniques will share identical capabilities.

Alternatively, if no individual, or combinations of, modelling techniques, exhibit the required capabilities, then the research activity at this stage becomes more complex. In such a situation it will be necessary to examine the shortfall between the requirements of modelling, and the capabilities of the most favourable modelling approach. Depending on the extent of this shortfall, a decision will be needed as to whether to proceed with this modelling solution, or attempt to create a new modelling technique.

To summarise, on the basis of the arguments highlighted above, the fourth research activity is:

Objective of stage 4 : is to form the principles of a modelling tool for the analytical evaluation of a manufacturing strategy.

The method of realising this objective is by establishing the most suitable modelling solution to manufacturing strategy evaluation, or by attempting to create a new modelling technique on the basis of the results gained in Chapter 7.

On completion of this fourth stage in the research programme, the principles of a modelling tool that will support the analytical evaluation of a manufacturing strategy, should have been established.

4.2.2 Phase 2 : Verification of the principles of the modelling tool

Once the principles of a modelling tool have been formed, in order to realise the aim of this thesis, it is necessary for verification to be carried out. To design a method for achieving this, the objective of such verification first needs to be specified. To set the context for developing such an objective and following the advice in the literature, verification should be attempted through an industrially based experimentation programme.

From the aim statement in Section 4.1, verification is required to demonstrate that the modelling tool principles will enable an evaluation of the effect of a manufacturing strategy on the performance of a manufacturing system, and in doing so directly support judgement and bargaining in strategy evaluation, as a procedure in formal planning processes. However, a contentious issue here is the extent to which the principles of the modelling tool should be verified.

The extent to which verification should be carried out depends on the claim that is to be made about the competence of the modelling solution. If a claim was made that the modelling tool principles will always be the most appropriate to strategy evaluation, then testing may need to be carried out across a very large distribution of companies. Such a claim is appealing, but effectively impractical within the resources of this study.

Guidance on the practical extent of testing is offered by Noltingk (1965), who states that unproved equipment should never be left to the tender mercies of a user who is not in the laboratory's team, and that field tests should always be conducted by understanding and sympathetic personnel. He points out that a robust prototype is necessary to avoid criticisms associated with the nature of a flimsy prototype affecting the objectivity of results. However, the focus in this research on the requirements and capabilities of modelling techniques, will have at best stimulated the development of an embryonic form of a modelling tool. Therefore, before extensive testing can commence, the formerly established modelling solution will need to be developed into a robust modelling tool. Such development may also be expensive and time consuming, and the results influenced by the features provided by the modelling medium.

There is however an intermediate stage of development that has to be considered, namely, gaining sufficient confidence in the modelling solution to justify an investment of resources into the construction of a robust modelling tool. This will be particularly true if the modelling solution is based on a combination of modelling techniques, as the capability of such an approach would have been established through deductive analysis rather than direct experimentation. By the nature of the objective at such an intermediate stage, an extensive investment in resources is not required, and testing at one industrial test-bed should be sufficient. However, such testing would need to be objective and in-depth so as to closely examine the capabilities of the modelling tool principles. Therefore, the objective of verification here will be to demonstrate that the principles of the modelling tool are correct, to an extent that justifies a subsequent investment of resources to produce a robust prototype that can be used for more extensive testing.

To realise the objective given above, a method of performing verification is required. The requirement set developed at stage 1, will be a specification of the capabilities that are required of a modelling technique for the evaluation of a manufacturing strategy. Hence, a method of verification is to demonstrate that the modelling tool principles satisfy the requirement set.

The industrial test-bed will need to be changed to demonstrate that the modelling solution is not limited to one set of circumstances. Furthermore, the experimental programme will need to be modified to verify the complete modelling solution, rather than a critical appraisal of individual modelling techniques. It will however be generally acceptable, to use as a foundation, the approach to experimentation developed at stage 3.

An aspect of the approach to experimentation that will however need to be altered is the role taken by the researcher. It will be necessary to demonstrate that the researcher will not have influenced the results gained about the capabilities of existing modelling techniques. As Platts (1993) states when looking to test his manufacturing strategy audit:

> "...there is always a worry that the testing of the strategy process might be too person-dependent. One way around this is to carry out some case studies using different facilitators. Ideally the facilitators should have little previous experience so that they would rely on, and work within, the process and not make intuitive leaps to solutions."

When considering the design of the experimentation programme, an opportunity exists to directly assess whether the modelling solution is indeed beneficial to practising managers in a strategy formulation role, supporting both judgement and bargaining between such personnel. The requirement set has been developed by taking into account the needs of practising managers. Therefore, if the requirements set is valid, and the modelling solution fulfils all the requirements, then such modelling, by implication, should be beneficial to practising managers. However, by involving practising managers in experimentation, an opportunity exists to directly assess usefulness of modelling, and hence to comment on the validity of the requirement set.

Expanding the experimentation programme to directly consider the usefulness of modelling, means that a method is required of assessing how well the modelling solution does indeed aid practising managers concerned with strategy formulation. An immediate apparent test is to invite such personnel to comment on the modelling solution, in practice however maintaining objectivity of such an assessment may be difficult. Experimentation may be sensitive, for example, to the opinion of strategy formulators being unjustly dependent on the features of a computer software package. Alternatively, such users could be prejudiced by a coarse prototype assembled from separate modelling tools, or the level of skill or familiarity necessary for application of a modelling tool. Detailed design of the experiment programme should address these factors so that the views of these personnel remain objective.

To summarise, on the basis of the arguments highlighted above, the fifth research activity is:

Objective of stage 5 : to attempt primary verification of the principles formed for the modelling tool, so that development into a robust prototype is justified.

The method at this stage is to test the previously formed modelling tool principles in an experimentation programme at a second industrial test-bed. This testing should attempt to demonstrate that the modelling solution satisfies the requirement set, but also that judgement and bargaining between practising managers is supported. Such an approach to testing will allow the modelling solution, and the validity of the requirement set, to be assessed. To enable this verification, Chapter 9 will need to consider the detailed design of the experimentation programme, choice of industrial test-bed, and choice of model builder.

4.2.3 Overview of research programme

The previous section has established five stages, and associated objectives and methods, to realise the aim of this research. These stages will be given the following titles in the remainder of this thesis:

Stage 1 : Requirements of modelling in manufacturing strategy evaluation.

Stage 2 : Establishing potentially suitable generic modelling techniques.

Stage 3 : Experimental assessment of generic modelling techniques.

Stage 4 : Forming the principles of a modelling tool.

Stage 5 : Testing the principles of a modelling tool.

These stages collectively form the overall research programme that is illustrated graphically in Figure 4.4.

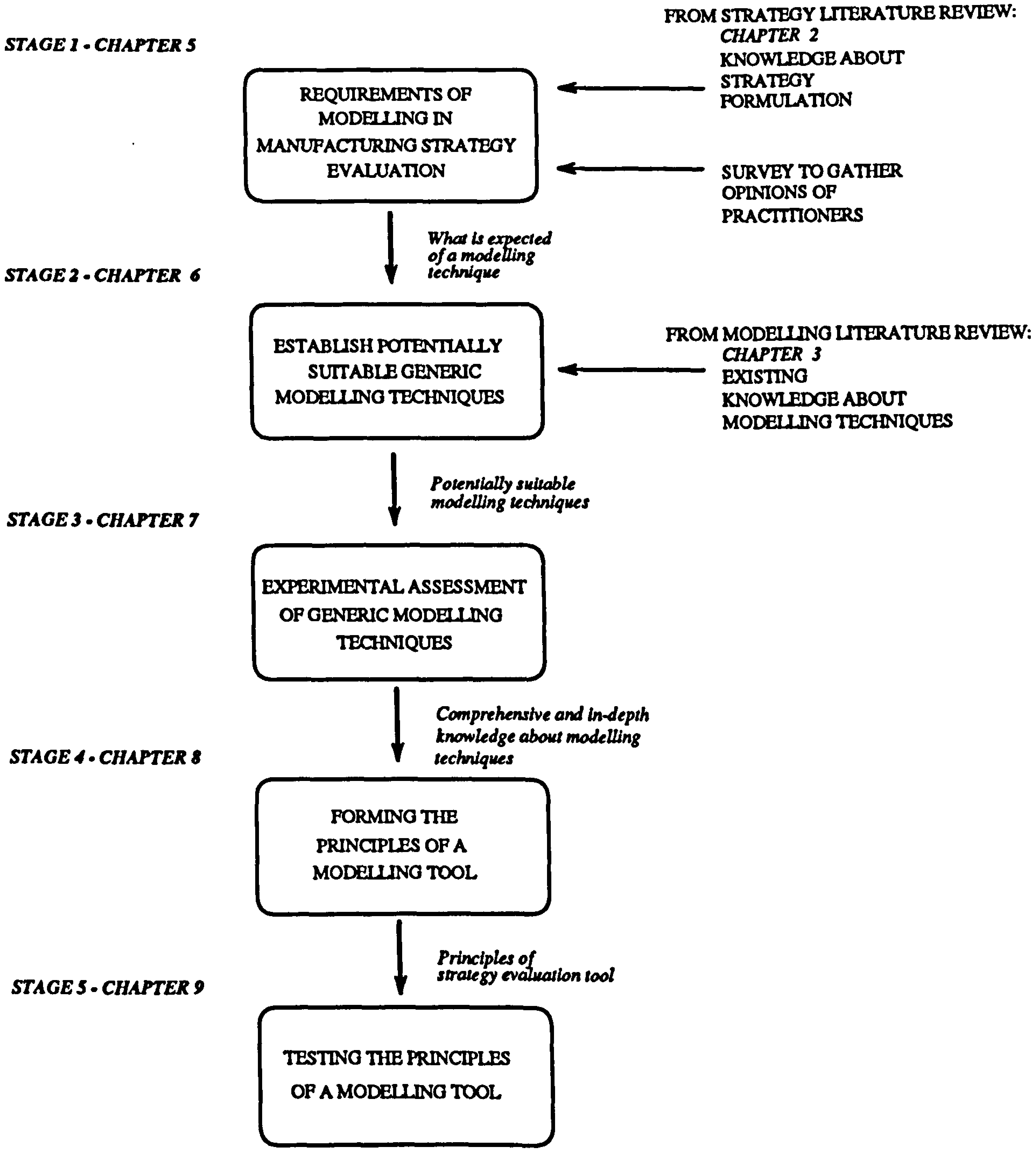

Figure 4.4: Overview of research programme

CHAPTER 5

REQUIREMENTS OF MODELLING IN MANUFACTURING STRATEGY EVALUATION

The preceding chapter has established that the first objective in the research programme should be to define what is required of a modelling technique in manufacturing strategy evaluation. This chapter describes work that has established these requirements through the literature and the participation of practitioners.

This chapter commences by briefly stating in the first section the research programme at this stage. In line with this research programme, the second section focuses on the role of a model and modelling tool in manufacturing strategy evaluation, and from this analysis, four categories of requirements of modelling are identified. The following sections then explore each of these categories to establish a detailed set of requirements, termed the 'requirement set', that reflects the desired capabilities of a modelling technique. The final section of this chapter presents a complete summary of the resulting requirement set.

5.1 STAGE 1 RESEARCH PROGRAMME

Chapter 4 has determined that the outcome of this stage of the research programme should be a measuring system, termed the requirement set, against which the performance of modelling techniques can be plotted. Furthermore, the research activity should commence by considering the concept of manufacturing strategy and formal planning processes, initially from the literature, and then developed by seeking the opinions of practitioners through a number of in-depth interviews. Once the expectations of modelling are known, the assistance of practitioners should be used further to relate these expectations to the requirements of a modelling technique. To enable this activity to proceed the choice of practitioners, and the method of conducting the in-depth interviews, must be addressed.

Personnel are required who can advise on the perceived requirements of a model and modelling tool in manufacturing strategy evaluation, and who can also assist in relating this information into the requirements of a modelling technique. To provide this information practitioners are needed who are knowledgeable of either manufacturing strategy formulation, or modelling approaches, or both. A range of practitioners can be identified through exploring the sources of contributions in the literature. Such an initial review has established that the main contributors are either academics, industrialists, consultants or vendors of modelling tools. Therefore, the method will be to identify a small number of practitioners who are representative of each of these four areas, and then carry out in-depth interviews with such personnel.

The objective of an in-depth interview is to collect complex information, containing a high proportion of opinion, attitude and personal experience (Moore, 1986). Moore advises to set up an interview in which the respondent is prepared to discuss at length, a subject which is of equal interest to them and to the interviewer. He also stresses the importance of building up trust, rapport, and a confident relationship between the respondent and the interviewer. Moore points out that a difficulty with this interviewing approach is in keeping discussions moving in the right direction, and a need for the subject to be well known by the interviewer so that matters can be discussed confidently and responses appropriately assessed. He believes that such interviews should be preceded by information gathering exercises, and they can be used to form a background of semi-structure to the interview.

The information in the literature on the concept of manufacturing strategy and formal planning processes, can be used to provide an appropriate background to in-depth interviews if presented succinctly. To deliver this information, a concise and diagrammatic description of the origin, aim, and content of the work addressed in this thesis, can be presented in a document. Then, when interviewing practitioners, this document can be used to set the context of the research, and then used to form a structure against which discussions can proceed. On the basis of such input, the content of this document can subsequently be refined, and hence the derived knowledge developed.

In summary, the research activity at this stage consists of establishing the perceived requirements of a model and modelling tool from the literature. Then this knowledge is reinforced by presenting this information in a discussion document that is then used to structure in-depth discussions with practitioners who are either academics, industrialists, consultants or vendors of modelling tools. The following sections of this chapter are the result of applying this research programme.

5.2 ESTABLISHING THE GENERAL REQUIREMENTS OF MODELLING

An appropriate starting point, in defining the requirement set, is to consider how a model and modelling tool could operate in practice within the general concept of manufacturing strategy. Section 4.1 has postulated that a suitable modelling approach for manufacturing strategy evaluation would commence with a modelling tool that will allow a manufacturing system to be represented by a model. Such a model should be capable of modification to reflect the implementation of a manufacturing strategy. The resulting model behaviour could then be assessed against the performance measures that are appropriate to manufacturing strategy formulation.

From this description of model operation, a number of requirements of a model become apparent. Firstly, some model flexibility is necessary in order to accommodate the range of manufacturing system developments that are associated with the concept of manufacturing strategy. As identified in Section 2.1.2, these developments can be viewed in terms of changes to the structure and infrastructure of a manufacturing system. Secondly, a model should provide performance measures that are consistent with the manufacturing objectives associated with manufacturing strategy formulation. Thirdly, the time taken to realise a strategy is an important aspect of the strategy concept, as time will be necessary to execute changes to a manufacturing system and for the associated effect to be experienced (Section 2.1.2). Therefore, a model should enable an assessment of the transition of the capabilities of a manufacturing system as a strategy is implemented. Hence, three categories of requirements of modelling are immediately apparent.

Absent above is a measure of the practical viability of modelling. Even if modelling fulfils the three sets of requirements so far established, other issues may still inhibit application, such as the ability of a model to accurately predict the effect of a change, along with the costs and benefits of using a model. Therefore, a fourth category of requirements exist, termed here the serviceability of modelling.

On the basis of this brief analysis four initial categories of requirements of modelling are established. These categories are:

- Assessment of structural and infrastructural changes to a manufacturing system.

- Indication of performance in terms of manufacturing objectives.
- Assessment of system transition.
- Serviceability.

The following section will examine the content of each of these categories in more detail. This will be achieved by considering, for each category, the requirements of a model, modelling tool, and ultimately a modelling technique.

5.3 ASSESSMENT OF STRUCTURAL AND INFRASTRUCTURAL CHANGES TO A MANUFACTURING SYSTEM

There are a number of views in the literature as to what constitutes the structural and infrastructural changes to a manufacturing system that a strategy has the jurisdiction to affect. This is illustrated in Table 2.6. Section 2.1.2 has explored this issue in some detail and observed, for example, that both terminology and the associated span of changes are not consistent. Platts (1990) however, has been credited for reviewing the intentions of various authors and subsequently providing a platform of terminology and categorisation in this situation. This platform has been adopted by this thesis, along with the term 'policy areas' (Section 2.1.2), and the categories given in Table 2.5.

The categories in Table 2.5 represent the span of changes to a manufacturing system, across which a strategy formulator is likely to require evaluation to be performed. However, externally supportive strategy formulation processes (Section 2.3.3) are a relatively recent evolution on the theme of internally supportive processes, for which there is a subsequent paucity of associated literature, and hence a concern here that the categories offered by Platts may be incomplete. Therefore, the approach taken is to first consider the span of changes for an internally supportive process, and then question whether any modifications to this set are necessary to support an externally supportive process.

A correlation has been observed to exist in Section 2.1.2, that as the policy area categories proposed in the literature reduce in breadth, then the number of functional strategies suggested increase. The externally supportive process offered by New (1989), along with an evolution to this approach given by Baines et al (1993a), are both based on a smaller rather than larger number of functional strategies. This implies that a broad range of structural and infrastructural changes should be considered during strategy formulation. Fortunately, the work of Platts (1990) is an amalgam of views and as a consequence is a particularly broad set of policy areas. Therefore, no modification is necessary to the policy areas given in Table 2.5.

In summary, a modelling tool is required that will enable a model to be constructed that allows changes to a manufacturing system to be evaluated, across the structure and infrastructure represented by the policy areas in Table 2.5. These requirements can be directly related to the characteristics required of a modelling technique.

5.4 INDICATION OF PERFORMANCE IN TERMS OF MANUFACTURING OBJECTIVES

There are a number of issues that need to be explored within this category, namely, gaining an external and internal view of model performance, along with providing measures of product features, design flexibility and quality. This section addresses each of these issues in turn.

5.4.1 An external view of model performance

The manufacturing objectives that are generally associated with the manufacturing strategy concept have been explored in Section 2.1.2. From this investigation a set of manufacturing objectives have been adopted from Platts (1990), and these are also termed the competitive criteria (Table 2.3). However, it has also been noted in Section 2.1.2 that this set of criteria may be incomplete, as an explicit link to the financial performance of a business is vague. The current set of criteria focus on the contribution that the manufacturing activity makes to the saleability of a product or product family. Therefore, further consideration is necessary as to the range of manufacturing objectives that should be provided by a modelling tool.

In a review of the literature, Adam and Swamidass (1989) credit only Hill (1985) and Wheelwright (1984), with advocating variables that expose the consistency between manufacturing strategy and business strategy at an early stage in formulation. In this case the terms business and financial strategy are being treated as synonymous, as it is a link with the financial component of business strategy that is in question. Platts and others, only view the financial implications of a manufacturing strategy in a financial justification activity, late in their strategy formulation process. Such justification would usually be constructed using Discounted Cash Flow (DCF) or Internal Rate of Return (IRR)

(Greenhalgh, 1990). The issue here is whether the set of manufacturing objectives ought to be expanded to ensure consistency between manufacturing and the financial strategy at an earlier stage in strategy formulation.

To address this issue it is first appropriate to investigate whether there is any potential benefit in such early linking between manufacturing and financial strategies. The conceptual externally supportive formulation process, presented by Baines et al (1993a) in Section 2.3.3, does advocate such linking. Baines argues that such a link is beneficial as it allows for the application of externally supportive manufacturing strategies, which themselves can be strongly associated with world class manufacturing companies (Baines et al, 1993b).

Accepting that such an approach is potentially beneficial, the appropriate measures for such linking need to be investigated. Hax and Majluf (1984) cite the work of Stonich (1981) for proposing four measures of business performance, namely, strategic funds programmes, market share increase, return on assets, and cash flows, the latter two being concerned with a financial perspective. Likewise, Adam and Swamidass (1989) argue that the financial performance measures commonly found in the business strategy literature are growth in sales, growth in return on assets, and growth in return on sales.

These financial measures can be redefined into a more basic set of performance indicators. Growth in sales, if measured from a financial perspective, is a view of how the financial turnover of a company is changing over time. Growth in return on assets can similarly be viewed as a change in Return On Investment (ROI) against time. Likewise, growth in return on sales is a statement of profit relative to turnover. Therefore, a group of measures that relate the contribution of manufacturing to the financial performance of a business consists of turnover, ROI, profit and cash flow. There are however many other measures and financial ratios that can complement this set. However, this set is considered here to be the basic variables to assess consistency between financial and manufacturing strategy, and will hence be added to the manufacturing objectives. A model, modelling tool and modelling technique, are expected to support generation of these manufacturing objectives.

5.4.2 An internal view of model performance

The manufacturing objectives highlighted above ensure links between manufacturing, financial and marketing functional strategies at an early stage in strategy formulation. These variables can be considered to give an external view of manufacturing system performance. Much of the literature emphasises a need to maintain such an external view and not to consider internal measures such as resource utilisation, for example:

> "Manufacturing should be judged by external criteria, not internal criteria."
> Schroeder and Lahr (1990).

The motive of this argument is laudable, in that, it opposes a piecemeal development of a manufacturing system. However, the argument fails to consider that a practitioner, faced with formulating a manufacturing strategy, needs clues as to the manufacturing processes or resources within a manufacturing system that are inhibiting overall performance. This may be the case particularly where a large, complex system, is being studied.

The strategy formulator can be appeased to some extent, and without compromising the argument above, if a user is allowed to explore the performance of the principal elements and sub-systems that make up a model. For example, a model should allow a strategy formulator to investigate the effect that a particular manufacturing process, or department within a factory, has on product lead time or other manufacturing objectives. This capability is considered here to be a desirable characteristic of a model, and hence will be adopted as a requirement of a modelling technique. This thesis will use the term 'contribution' when referring to the provision of manufacturing objectives at a sub-system level within a model. However, this measure will not illustrate the intensity of activity that is occurring at a resource or sub-system level.

The measure of 'utilisation' of a manufacturing process or resource is frequently dismissed within the literature as a stimulus of piecemeal development. For example, Adam and Swamidass (1989) point out, that the real test of manufacturing strategy is its effect on operating and overall performance. A measure of utilisation can however reveal important information about why a manufacturing system is performing in a certain manner. For example, a delay in product lead time may be caused by a manufacturing resource being heavily utilised. In this sense utilisation is not used as an operational management measure, rather, it can be one of a set of measures to assist in the analysis of a manufacturing system. Therefore, to complement the contribution measure given above, utilisation of a manufacturing processes or resources is also considered to be necessary.

To summarise, the arguments given in this section have reasoned that in strategy evaluation, a model is required to provide internal measures of manufacturing system performance. These internal measures, support strategy formulation through providing analysis of the manufacturing processes or resources within a manufacturing system.

Finally, to emphasise that the internal measures of utilisation and contribution are used to support analysis, and are not intended to be strict manufacturing objectives in the operation of a facility, the term given to this category of requirements will be changed from manufacturing objectives to 'performance measures'. This terminology change is applied throughout the remainder of this thesis.

5.4.3 Providing measures of product features, design flexibility and quality

The use of a model to provide the required performance measures, defined in Section 5.4.1 and 5.4.2, requires careful consideration. A valuable intimation of how a model can provide these performance measures is given by postulating the application of a 'physical replica' model (Section 3.4.1) of a small manufacturing facility. When executing such a model, some values of model performance can be gained directly, such as the volume of products produced each hour. If this concept of direct measurement is contrast against the performance measures established above, then all but three measures appear to be of this form. The three conflicting performance measures are product features, quality and design flexibility.

A question is posed as to how a model can provide values for each of these three measures? An initial retort from some practitioners was to provide an 'index' value for each measure. In this manner a model could generate a value for a product family, such as, '1' being equivalent to poor, '2' being equivalent to fair, and '3' being equivalent to good quality or flexibility. Such an approach is often applied in the strategy literature, for example see DTI (1988). However, the researcher considered that this approach could in practice cause contention between strategy formulators when attempting to designate such values, and a preference existed for a more factual method.

Investigating first the performance measures of product features and design flexibility further, DTI (1988) gives the following definitions:

Product Features :	Adding capability to the product, or choice for the customer.

Design Flexibility : Having the ability to produce products to a customer's specification (customisation).

It is apparent that under some conditions there is duplication in these definitions, as by providing a large variety of choice in product features, a product can be matched to customers specifications. The distinction that is believed to be intended above, is that there is a difference between an intended and planned variation in a products specification, and the capability of a manufacturing system to react to an unexpected and unforeseen requirement to modify the design of a product. This reflects the argument given by Quinn (1978) who stresses that strategy deals with unknowable factors. Clearly, if a strategy formulator has little or no conception as to the products that a company will need to provide in the future, then a high value of design flexibility is necessary. Such is the case in a 'jobbing' environment (Hill, 1985).

Product modifications concerned with product features may be considered to reflect a proactive intention of a company to offer a variety of product characteristics, whereas design flexibility can be thought of as a reactive method of offering such variety. Clearly, there are trade-offs associated with choosing a manufacturing strategy that provides high design flexibility rather than product features, and vice versa. For example, Hayes and Wheelwright (1984) see that an inflexible assembly line generally promises lower costs, whereas a company that chases demand generally has higher production costs. On this basis, while a direct measure for product features and design flexibility may not be possible, the effect of a company choosing to pursue each of these objectives could be assessed indirectly. Product features and design flexibility could be treated as an input into a model, and as conditions under which a model should operate, with the effects being measured in terms of product cost, lead time, etc.

Dealing with product features and design flexibility in this manner means that a model may be configured to offer a range of planned and intended product variants, commensurate with the intended product features, or tested against an ability to deal with requests made for unplanned product variants as is commensurate with design flexibility. The effect of the model configuration can be measured indirectly in terms of measures such as product cost, lead time, etc. Dealing with design flexibility in this way contravenes to an extent the argument put forward by Quinn (1978) that strategy deals with unknowable factors. In this case product modifications will be treated as 'knowable' and hence deterministic by the strategy formulators using a model. Such an approach to manufacturing system modelling is endorsed by Edgehill (1991) who argues that:

> "Clearly, the inputs to live manufacturing systems are not deterministic; sales patterns are influenced by many factors......as unpredictable as the weather. However, in studying how a system reacts to a variety of deterministic inputs it is possible to determine how the system would meet unpredictable eventualities."

Quality can be considered in a number of ways, but in particular here, capability, reliability and conformance. Quality capability is a statement about the features of a product, whereas quality reliability is concerned with the reliability of a product in service. Quality capability is synonymous with product features, and reliability is a function of quality capability and conformance. Quality conformance is a measure of how well an actual product specification, as determined by manufacture, compares to the specification promised to a customer. Therefore, it is the measure of quality conformance that is of interest here.

To assess quality conformance, some measure is needed of the number of products that do not attain the required specification during manufacture. In practice a number of quality conformance indicators are available internally and externally to a manufacturing system. Internally, quality conformance can be measured in terms of defective components and scrapped products. This however demands some form of inspection activity to compare manufactured products to their required specification, and all products will need to be assessed in some manner for an absolute measure of quality conformance. If complete quality conformance does not occur and defective products are produced and released into a market, then external effects of quality conformance may be apparent such as returned products and reduced customer demand. However, this external effect appears to be more difficult to assess than internal measures, as customer response to poor quality conformance may vary considerably and be difficult to measure accurately. Some form of internal quality conformance indicator is therefore favoured within a model.

To negate any need for external performance measures, only products that fulfil the desired specification, as determined by the product features and design flexibility discussed above, should be treated as valid production within a model. Quality conformance can be treated as a nominal specification that products must match or exceed in order to be registered as production. Any substandard products are not recorded as viable manufacturing production, though the associated manufacturing costs must still be accounted for. This approach will allow, for example, the assessment of alternative quality assurance strategies. Furthermore, it supports a strategy formulator who will probably make an assessment of market potential on the basis of products being supplied to the customer at the specification promised.

To summarise, this section has considered at some length how performance measures can be assessed by a model, and has established that product features and design flexibility can be dealt with as a specification input into a model. The effect of producing this specification can then be evaluated in terms of lead time, cost, volume, etc. Quality conformance can be managed by recording as output from a model, only the production of those products that attain an acceptable specification. In this way all three criteria can be established, as illustrated in Figure 5.1.

Finally, the consequence of this reasoning is that none of the three criteria are treated as direct measures of manufacturing system performance. A modelling tool must be capable of configuring a model to manage these criteria, and these can be directly related to the requirements of a modelling technique.

5.5 ASSESSMENT OF SYSTEM TRANSITION

Chapter 2 has credited the work of Hayes and Wheelwright (1984) for explicitly recognising that a period of time is inevitably necessary for manufacturing capabilities to be changed, and for the impact of such changes to be observed. Likewise, it is an intention that this research should allow both insight and prediction about the future performance of a manufacturing system (Section 4.1).

When considering such prediction, a question that arises is whether a model ought to be based on a company's existing manufacturing system and then modified to reflect a strategy, or should the model be concerned with some futuristic manufacturing system and then a strategy sought that connects the future and current state. A benefit of the latter approach is that a 'green field' model may help to stimulate creativity amongst strategy formulation. However, there is a risk that such an approach may threaten the credibility of a model because an association with a green field site may be perceived as being idealistic amongst practising managers. Furthermore, it does not take into account that a link between current and future states may not be possible within the resources available to a company. Although the former approach potentially inhibits

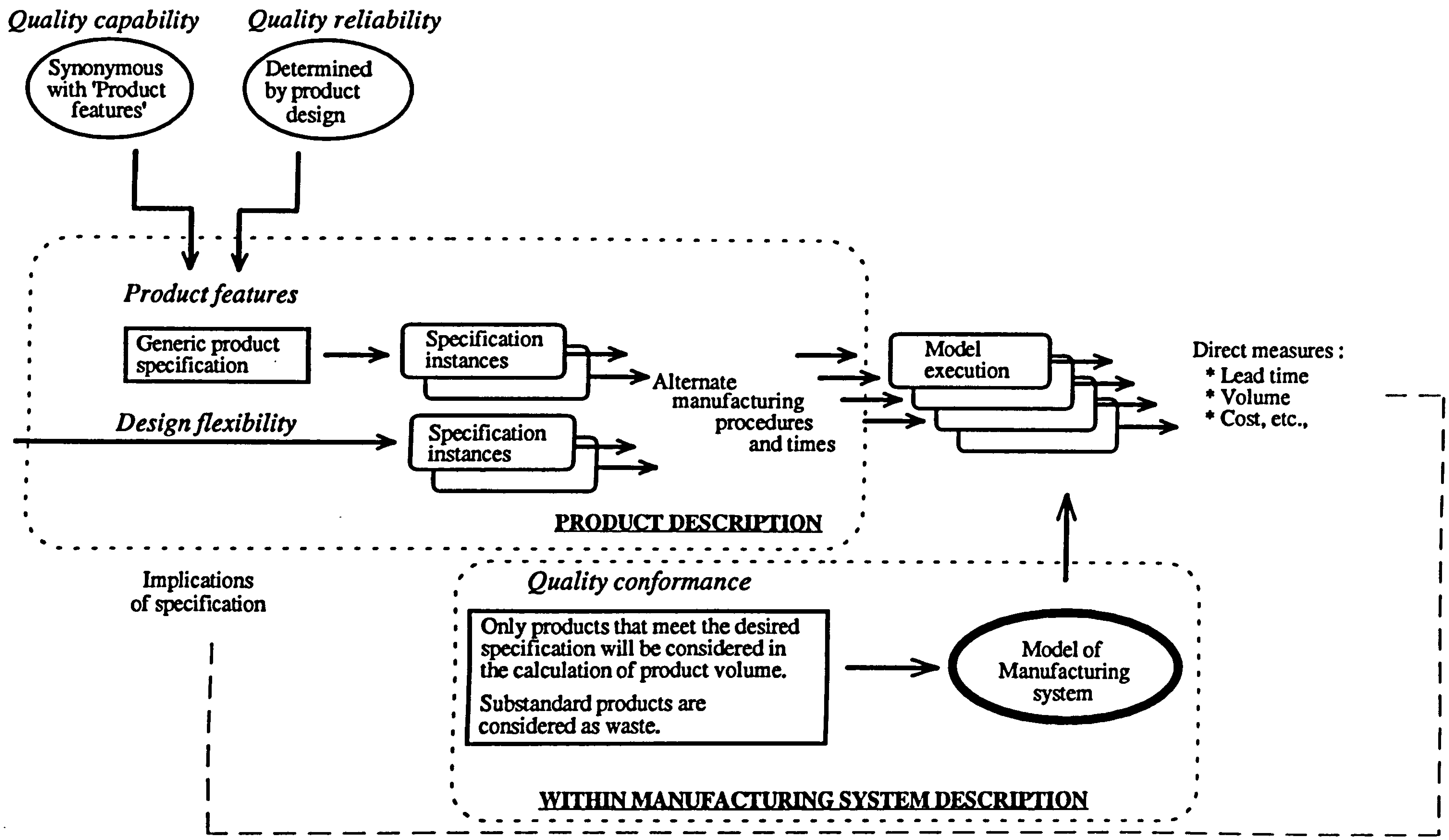

Figure 5.1: Dealing with product features, design flexibility and quality conformance

creativity, it is favoured here because of the pragmatic association. Therefore, a model should be based on the existing state of a manufacturing system, and then provide a prediction of manufacturing performance during the transition to a future state.

To place in context what can be expected of the predictive capabilities of a model it is interesting to examine an ancient, but highly appropriate, view of 'the future'. Pirsig (1974) gives an ancient Greek perspective of the future as:

> "They saw the future as something that came upon them from behind their backs with the past receding away before their eyes."

As Pirsig points out, knowledge of the future can only be established from a projection of the past. Hence, some authors, such as Thomas and Schwenk (1984), recognise the implications of future predictions and emphasise that evaluation processes should focus on a comparison of alternatives and checks on the sensitivity of these alternatives to error, miss-estimation and future surprises. In this thesis the emphasis has been moved from attempting to establish what 'will' happen to what 'could' happen, because this second approach is more realistic when discussing the predictive capability of a model.

Authors such as Danzyger (1990) build on the transitional changes to the behaviour of a manufacturing system and strongly associate manufacturing strategy with a detailed implementation schedule. This schedule is intended to orchestrate the transition of a manufacturing system from a current state to one that attains some desired manufacturing objectives. Danzyger (1990) and Greenhalgh (1990) suggest the use of Program Evaluation and Review Technique (PERT), a time phased network diagram, as an aid in this situation. Such tools provide a time based continuum against which the implementation of a strategy's content can be viewed, along with the users predicted effects of a strategy on the performance of a manufacturing system. It is important to note however, that such tools contain no analytical evaluation capabilities, and are totally reliant on the users estimates of the impact of a change on the performance of a manufacturing system. In contrast, a valid requirement of a model is felt to be the prediction of the transitional performance of a manufacturing system under such transitional situations.

To summarise, a modelling tool is required that will enable a model to be constructed of the existing state of a manufacturing system, and will then predict the effect on manufacturing system performance as the transitional changes associated with manufacturing strategy content are brought about. These requirements can be directly related to the desired capabilities of a modelling technique.

5.6 SERVICEABILITY

A strategy formulator will be concerned with the viability of applying a modelling tool in practice. As pointed out by Banerjee and Basu (1993), selection of a modelling approach depends on the resources available, such as funds and human skill. This point is taken further by Balci (1990) who argues about modelling, that:

> "A technique whose solution is estimated to be too costly or is judged to be not sufficiently beneficial with respect to the study objectives should be disregarded. Among the qualified ones, the technique with the highest expected benefits/cost ratio should be selected."

These statements emphasise an issue of serviceability that is related to resources, and the consumption of resources may be summarised as a cost for model construction. Baines et al (1991) argue that the primary cost of applying a modelling tool, is the purchase price of the modelling tool, and the cost associated with the time taken to apply the tool by the user. They argue that, as the number of applications increase within a company then, assuming no further purchases are necessary, the user's application time and associated cost become dominant. Hence, the initial concern is with purchase price, application time and associated cost.

Purchase price is dependent on the expertise and resources that have been invested to produce a modelling tool, and the characteristics of the market within which the modelling tool is sold. A high market demand may allow the vendor to set a purchase price that is significantly higher than the cost of producing the modelling tool. Likewise, the relationship between purchase price and production cost may vary dependent on market conditions. Therefore, to remove market factors from consideration, this thesis will focus on the resources invested and the cost associated with producing a modelling tool, rather than the price at which vendors choose to sell a modelling tool.

The cost associated with the time taken to apply a modelling tool is a function of the expertise and resources required during this time. If a user requires a high level of expertise to apply a modelling tool, then typically such a user is likely to command a higher value on their working time, than a user who requires no particular skill or training. Hence, the expertise and resources associated with applying a modelling tool, may influence its adoption and application in practice, and should be accounted for in the requirement set.

The expertise required in applying a modelling tool is a function of the complexity inherent to the modelling technique. To some extent this complexity also affects the cost associated with producing a modelling tool. Therefore, a variable of application cost will be used here to represent the expertise and resources required in both construction and application of a modelling tool. This amalgam is based on an assumption that if a modelling approach exhibits a low complexity it will require less expertise and resources to construct and apply a modelling tool, than a more complex modelling technique.

In summary, the criteria of application cost and time will be added to the requirement set to reflect the expertise, resources and duration required to apply a modelling approach.

The work of Sargent (1987) however suggests that cost is only one element of the wider issue of model serviceability. He highlights that users are also concerned with whether models and the information derived from them can be used with confidence. The activities of 'model verification' and 'model validation' are then presented as mechanisms for developing confidence. He states that verification is concerned with ensuring that a model performs as intended, whilst validation ensures that the intended model is an accurate representation of the real system being modelled. In this case Sargent is offering accuracy as an insurance of confidence, and the relevance of model accuracy is stressed by many authors. For example, Morgan (1990) considers accuracy to be of prime importance. However, Sargent qualifies the use of accuracy by also considering credibility. Credibility is concerned with how believable the results of a model are. Accuracy and credibility are both independent statements about model validity. Intriguingly, a model may be accurate and not credible, or more dangerously, not accurate but credible.

On the basis of the arguments presented above it is apparent that a strategy formulator will require a modelling tool to provide an accurate and credible model quickly and inexpensively. A modelling technique should enable the construction of such a modelling tool.

5.7 CONCLUSION

The research described in this chapter has established what is required of a modelling technique in the analytical evaluation of a manufacturing strategy. The requirement set given in Table 5.1 can now act as a measuring system against which the capability of existing modelling techniques can be assessed.

The opinions of practitioners were sought extensively during the evolution of the arguments and reasoning contained within this chapter. Whilst not dwelling on individual contributions, some comments about the success of this method are appropriate. In all, the process was successful with particularly useful contributions being received from academics and vendors of modelling tools. There were numerous conflicting opinions, especially from the latter party. However, both groups appeared to understand the issues being addressed and offered useful contributions.

Category of requirements	Requirements of evaluation
Structural and infrastructural changes to a manufacturing system	1. Facilities 2. Capacity 3. Span of process 4. Processes 5. Human resources 6. Quality 7. Control policy 8. Suppliers 9. New products
Performance measures[1]	1. Delivery lead time 2. Delivery reliability 3. Volume flexibility 4. Cost 5. Activity utilisation 6. Activity contribution 7. Cash flow 8. Turnover 9. Profit 10. Return on investment
System transition	1. Time dependency 2. Content change
Serviceability	1. Application cost 2. Application time 3. Accuracy 4. Credibility

Table 5.1: Requirement set of a modelling technique for analytical evaluation of a manufacturing strategy

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[1] The manufacturing objectives of product features, design flexibility and quality conformance are not included in this table because they are to be treated as inputs and conditions under which a modelling tool will operate (Section 5.4.3).

CHAPTER 6

ESTABLISHING POTENTIALLY SUITABLE GENERIC MODELLING TECHNIQUES

The objective of this second stage of the research programme is to rationalise the number of generic modelling techniques carried forward for intensive experimentation. This objective is realised by screening the generic modelling techniques, so as to establish which ones have distinct limitations when contrast against the requirement set from the preceding chapter. This screening is achieved either directly or indirectly from information in the literature.

This chapter is structured to first present a brief review of the research programme at this stage. On the basis of this programme the following sections present an appraisal of the generic modelling techniques against each category of the requirement set, and dismiss modelling techniques from further consideration where distinct limitations are apparent. Finally, this chapter concludes by presenting the modelling techniques that are carried forward for detailed experimentation.

6.1 STAGE 2 RESEARCH PROGRAMME

Fourteen generic modelling techniques have been chosen to represent the variety of modelling approaches (Table 3.3). As established in Chapter 4, screening is necessary to rationalise the number of generic modelling techniques carried forward for experimentation. This screening is to be carried out through the existing evidence in the literature. However, so as not to penalise a modelling technique because of an absence of credible literature, it will be necessary to commence this activity by assuming that each modelling technique is suitable to the task of manufacturing strategy evaluation.

Chapter 5 has generated a set of criteria, termed the requirement set, that a generic modelling technique will need to exhibit (Table 5.1). These requirements can be summarised into four categories:

1. Assessment of structural and infrastructural changes to a manufacturing system.

2. Performance measurement.
3. Assessment of system transition.
4. Serviceability.

Assessment of a modelling technique against the requirements in categories 1, 2 and 3 can be achieved through direct comparisons. However, the fourth category of serviceability calls for a different approach because no absolute values of acceptable performance are available for these requirement criteria.

In the category of serviceability are the criteria of, application cost, application time, accuracy, and credibility. In this case, stating whether a modelling technique has strong or weak performance, depends on the relative capabilities of other techniques. Accepting that serviceability is relative, an attempt will be made to identify any polarisation across the capabilities of generic modelling techniques. This means that a statement of high or low suitability will be made for a modelling technique, relative to the other generic techniques under consideration.

Where a generic modelling technique exhibits any limitations it will be a candidate for being discounted from further involvement in this research. However, prior to such an action, consideration will be given as to whether the modelling approach can form a viable combination with other techniques. Care however will need to be taken as it is permissible that, if a weak generic modelling technique is combined with a strong approach, the weak approach my offer little to the combination but still be reinstated. Therefore, the action of reinstating a generic modelling technique will only be considered where some distinct capability is offered through the combination.

In summary, this section has stated the objective and programme of this stage of research. The following sections of this chapter are the product of applying this research programme. The conclusion of this chapter comments on the success of this approach.

6.2 ASSESSMENT OF STRUCTURAL AND INFRASTRUCTURAL CHANGES TO A MANUFACTURING SYSTEM

The issue here is whether concerns exist with any generic modelling technique that supports modelling across policy areas associated with a manufacturing strategy, as illustrated in Table 5.1. Physical models offer some concerns, this being particularly the case with scale and analog models, as the following discussion reveals.

Using a scale model it is possible to build a dimensionally smaller or larger model of a modelling facility, and for the model to provide some form of functionality. For example, O'Reilly et al (1984) has formerly been cited for describing a 1/35 scale model of an automotive painting process that consists of 62 position sensors, 39 stops activated by solenoids, 31 pneumatically operated lift tables and 46 motors. Saunders et al (1991) present a scale model of a production system, incorporating materials handling, based on an electric model train, to test alternative production and repair schedules. Law and Kelton (1991) cite an example of a table-top model of a materials handling system.

Scale models appear to be principally restricted where human resource issues are concerned. Unlike machinery, a human cannot be physically scaled down, a human icon could be included in a model but will lack functionality. This can be overcome to some extent by a person interacting with a model as if working with the real system. If however such an approach is adopted then strictly an amalgam is being formed with a replica model. Therefore, scale models will only be retained for further consideration if replica models are also retained.

It is important to mention that both non-functional scale models, and 2D non-functional scale models are not affected by the human resource issue. This is the case because there is no functionality offered by each of these approaches, and representation of a human resource by an inert icon is acceptable.

Recent literature on analog computer models, or analogue[1] models in general, is extremely scarce. Authors such as Mihram (1972) explain that analog computer models are constructed by connecting electrical elements such as transistors, resistors and capacitors, in such a way as to represent continuous process systems. Pritsker (1990) points out that during the 1950s and 1960s analog computers were the primary means for performing continuous simulations. He also states that analog computers lack the logical control functions and data storage capabilities of the digital computer.

As well as limitations of the analog computer hardware, there is also a concern that the user will need to be conversant in control theory to program such a machine. Edgehill et al (1987) have been previously cited for arguing that

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[1] The term 'analogue' refers to a category of physical models in the model taxonomy (Section 3.3), whilst an 'analog' computer model is the modelling technique that has been chosen to represent the analogue category of models (Section 3.4.3).

analytical control theory is labour intensive, and requires a degree of specialisation not to be expected from potential industrial users with no previous experience.

On this basis it is felt that modelling using an analog computer approach would have limited flexibility because of hardware limitations, and may be difficult to apply by personnel who lack control theory expertise. An analog computer modelling approach will not therefore be considered further in this research.

Considering symbolic models, there are a number of assertions in the literature as to the flexibility of mathematical models in particular. A previously referenced example is Pidd (1988) who states:

> "....queuing theory models..........cannot cope with many types of problem."

However, such an assertion is countered by Suri and Diehl (1985) who see such approaches as the right tool for the planning and preliminary evaluation of a manufacturing system design. Likewise, there are similar debates in the literature contrasting System Dynamics (SD) and Discrete Event Simulation (DES) modelling techniques. An example of this case is Love and Barton (1993) who argue that the SD approach introduces approximations that undermine the accuracy or even the utility of the results generated. In a similar manner, Towill (1993b) counters this with an argument that:

> "We feel that many critics of System Dynamics as a methodology have failed to distinguish between the general concepts and one particular approach to modelling and system performance."

The contentions associated with the existence of a debate, and the particular nature of the flexibility required in manufacturing strategy evaluation, undermines confidence in discounting such techniques on the basis of this form of evidence.

In summary, although a number of concerns exist, only scale and analog computer models can be confidently dismissed when considering the span of changes to a manufacturing system associated with a manufacturing strategy.

6.3 PERFORMANCE MEASUREMENT

Chapter 5 has argued that internal and external measures of manufacturing system performance are necessary. The external measures allow consistency to be maintained with marketing and financial strategies, whereas the internal measures support strategy formulation through providing analysis of the activities within a manufacturing system. These measures are shown in Table 5.1.

Unfortunately, a comparison of the required performance measures, against the capabilities of a generic modelling technique, is difficult to conduct through the literature. This is because in most articles the performance measurement capabilities of modelling techniques are presented implicitly, and as a consequence, there is little confidence that absent performance measures are true limitations rather than simply omissions.

Accepting this concern, a coarse review of performance measures is still possible. Each of the required performance measures have in common the fact that some form of numerical capability is necessary. This is to reflect a need of modelling to provide both insight and prediction about the effect of a manufacturing strategy (Section 4.1). On this basis the literature is adequate to support a review on whether or not a modelling technique supports performance measurement, and hence, an investigation can proceed by establishing whether or not a modelling approach can provide numerical information. If a generic modelling technique satisfies this requirement then, assuming all other requirements are satisfied, a more critical enquiry into the performance measures supported by a modelling technique will be conducted during the experimentation in the following chapter.

On this basis a number of both physical and symbolic models have distinct limitations. The physical modelling techniques of non-functional replica, non-functional scale and 2D non-functional scale, by definition, do not contain the necessary functionality to provide numerical capabilities. The symbolic modelling techniques, of Rich Pictures (RP), Integrated Enterprise Modelling (IEM) and $IDEF_0$, are also limited in this instance for a similar reason. The focus of RP for example, is on gaining consensus amongst personnel involved in the problem solving process. This view is directly supported by Checkland (1988) who states that no matter how the models are used for comparison with the real world, the aim is not to 'improve the models' but to find accommodation between different interests in a situation. Therefore, RP can be discounted from further consideration. However, with both IEM and $IDEF_0$ an opportunity exists to form a combination with other modelling approaches.

Although IEM and $IDEF_0$ are characterised by a lack of numerical capability, recent innovations in modelling tools are making provisions to overcome these limitations. For example, DESIGN/IDEF (Section 7.2.4) allows numerical attributes to be assigned to an activity. To be strict, such functionality is actually provided by enveloping a mathematical modelling facility within the IDEF$_0$ modelling tool. However, such a combination is distinct in the manner in which an IDEF$_0$ model will allow, through the decomposition facility, a mathematical model to be constructed. To acknowledge the numerical capabilities, both IDEF$_0$ and IEM will be retained for further study.

Finally, a potential exists to combine a non-functional replica, a 2D non-functional scale or a non-functional scale model, with symbolic models to provide the required numerical capabilities. These approaches could be combined with either a simulation or mathematical modelling technique. The potential benefit in each case is an improvement in model credibility through the realism associated with physical models. However, combining physical and symbolic models is likely to be difficult. Furthermore, the nature of symbolic models is such that they can be computer based and provide 2D graphical animation, and this negates some of the perceived credibility benefits of physical models. Finally, there is a high probability that model construction costs will be higher with a combined modelling approach. On this basis, a combination of physical and symbolic models will only be warranted, and investigated further in this thesis, if the credibility of symbolic models is an issue that causes concern.

6.4 ASSESSMENT OF SYSTEM TRANSITION

It has formerly been established that modelling should allow both the behaviour of a manufacturing system, along with changes to the content of the system, to be evaluated as time advances (Table 5.1). The issue here is whether there are any generic modelling techniques unable to support the construction of such models.

There is a concern that RP, IEM and IDEF$_0$ forms of symbolic models are static illustrations of the content, interactions and structure, of a manufacturing system. Such static illustrations can be thought of as 'snap-shots' of a manufacturing system at an instant in time. Section 6.3 has identified that a combination of IEM and IDEF$_0$, with some form of mathematical model, may provide a numerical capability. Furthermore, adopting such numerical capabilities may also coarsely overcome some concerns of only providing a snap-shot of a manufacturing systems performance. This may be accomplished, to some extent, by using time averaged values or linking a number of models to represent phases in the evaluation of a manufacturing system. Indeed, if an approach of linking together models to assess system transition is accepted, then no modelling techniques can be categorically dismissed at this stage.

6.5 SERVICEABILITY

Chapter 5 has established that modelling should provide credible and accurate models at low application cost and time. As highlighted in Section 6.1, the method here is to establish models of high or low serviceability.

A review of the literature has revealed that both application cost and time are prominent concerns with some forms of physical models. For example, Hogg et al (1991) consider the construction of a flight simulator, the dynamic behaviour of which, is well matched to an aircraft. They state that such a model can be classed as a replica of the aircraft system under consideration, and in this case the cost advantage of the simulator compared with experimentation with the real system is given as being in the order of 10 to 1. However, the cost associated with experimentation with an aircraft is very high and thus the cost of the model is also high. This concern is reinforced by ElMaghraby and Ravi (1992) who argue that the major disadvantage of physical simulators is their cost. They point out that the construction of these simulators is tedious and time consuming, along with them being relatively inflexible after construction. Therefore, it can be deduced that a physical replica of a manufacturing system will also exhibit these limitations of high cost and inflexibility once constructed.

There are however various generic modelling techniques within the physical category. Whilst the concerns highlighted above are undoubtedly true of a replica model, this is not the case for 2D non-functional scale models. An example of this later type of model being a photograph. Likewise, there is little confidence that non-functional replica, non-functional scale, and analog computer models, can be discounted on the basis of application cost and build time.

A scale model however does include functionality and may be expensive to provide. Consider the form that such a model of a typical factory would take, containing products, materials handling, etc. Furthermore, human resources could be included by forming an amalgam with a replica model (Section 6.2). On this basis, such a model is more closely associated with a replica than the non-functional forms of model given above. Therefore, scale models are considered here to have low serviceability. Hence, such models will be discounted on this basis.

6.6 SUMMARY OF DISTINCT LIMITATIONS WITH GENERIC MODELLING TECHNIQUES

This section has sought to discount generic modelling techniques from further analysis on the basis of distinct limitations in capabilities apparent in the literature. These limitations are summarised in Tables 6.1 and 6.2.

All physical models have been discounted because they are restricted by either flexibility, numerical capabilities or serviceability. A physical replica requires excessive resources to apply, and can also be expensive to modify once constructed. Non-functional replica, non-functional scale, and 2D non-functional scale models are limited because, by definition, no numerical capabilities are available. Scale models are restricted because although they contain functionality, it is not possible to directly model human resources, also embedding functionality into such a model is likely to be expensive. Finally, analog computer models have a limited flexibility.

The symbolic models that appear to have distinct limitations are RP, IEM and $IDEF_0$. Each of these techniques were initially discounted because they lack numerical capabilities and only provide a snap-shot of the content and structure at an instant in time. However, recent innovations in modelling tools have combined $IDEF_0$ and IEM modelling approaches with mathematical models that appear to counteract these limitations. Therefore, both of these techniques will be carried forward for further appraisal.

As a result of this analysis seven techniques are potentially suitable for the task of manufacturing strategy evaluation, these techniques are presented in Table 6.3.

6.7 CONCLUSION

This chapter has successfully screened out seven generic modelling techniques from further consideration. This rationalisation has been achieved through applying evidence from the literature that clearly exposes the distinct limitations of seven of the modelling techniques. The remaining generic modelling techniques are listed in Table 6.3.

Requirement set	Generic physical modelling techniques					
	Replica	Non-functional replica	Scale	Non-functional scale	2D Non-functional scale	Analog
Structure and infrastructure	*	*	Modelling human resources	*	*	General flexibility
Performance measurement	*	numerical capabilities	*	numerical capabilities	numerical capabilities	*
System transition	*	*	*	*	*	*
Serviceability	Low	*	Low	*	*	*

* = No decisive evidence apparent about limitations in this category.

Table 6.1: Distinct limitations with physical modelling techniques

Requirement set	Generic symbolic modelling techniques							
	RP	IEM	$IDEF_0$	DES	SD	QT	ABC	BP
Structure and infrastructure	*	*	*	*	*	*	*	*
Performance measurement	numerical capabilities	numerical capabilities	numerical capabilities	*	*	*	*	*
System transition	System Snap shot	System Snap shot	System Snap shot	*	*	*	*	*
Serviceability	*	*	*	*	*	*	*	*

* = No decisive evidence apparent about limitations in this category.

Table 6.2: Distinct limitations with symbolic modelling techniques

Main class	Sub-class	Generic modelling technique	Abbreviated term used
Symbolic	Schematic	Integrated Enterprise Modelling	IEM
		$IDEF_0$	$IDEF_0$
	Simulation	Discrete Event Simulation	DES
		System Dynamics	SD
	Mathematical	Queuing Theory	QT
		Activity Based Costing	ABC
		Business Planning	BP

Table 6.3: Potentially suitable generic modelling techniques

The models that have been discounted are mostly physical types. This conclusion may appear to be logical when a reflection is made on the lack of literature supporting the application of such models. Generally, the articles in the literature only superficially consider physical models for completeness in studies on modelling. Much work is descriptive, applying particular modelling tools to a specific application, with little work truly considering the strengths and weaknesses of the underlying modelling techniques. Literature concerning recent work on analog computer models is almost non-existent. This is unsatisfactory because, although discounted in this case, physical models may still have a role in general manufacturing systems engineering and management.

CHAPTER 7

EXPERIMENTAL ASSESSMENT OF GENERIC MODELLING TECHNIQUES

The objective of the research at this stage is to critically appraise the suitability of generic modelling techniques to the task of analytical evaluation of a manufacturing strategy. This objective is realised through the design and application of a set of industrially based experiments, through which contemporary tools are used to construct models, and establish the capabilities of generic modelling techniques against the requirements of manufacturing strategy evaluation. Practitioners with modelling expertise are used extensively to verify experimentation and ensure generalisation of results.

The structure of this chapter is as illustrated in Figure 7.1. The first section presents the research programme at this stage. This programme briefly summarises the intended research activity, as established in Chapter 4, and develops guidelines for the experimentation programme with which this chapter is concerned. The second section applies these guidelines to detail the experimentation programme, and hence addresses experimental design and control, the selection of an industrial test-bed and modelling tools, and design of an analysis methodology. The third section presents the execution of this experimentation programme and provides both results of experimentation and analysis. Finally, these results are discussed and conclusions drawn as to the suitability of individual and combined modelling techniques to the task of analytical evaluation of a manufacturing strategy.

7.1 STAGE 3 RESEARCH PROGRAMME

The intended research programme at this stage has been established in principle in Chapter 4. This section augments this prior proposal with knowledge gained from the execution of research stages 1 and 2, so as to provide guidelines for the design of the experimentation programme.

Chapter 5 has established a 'requirement set' that defines the task of a modelling technique in the role of analytical evaluation of a manufacturing strategy. Chapter 6 has established that seven generic modelling techniques require critical

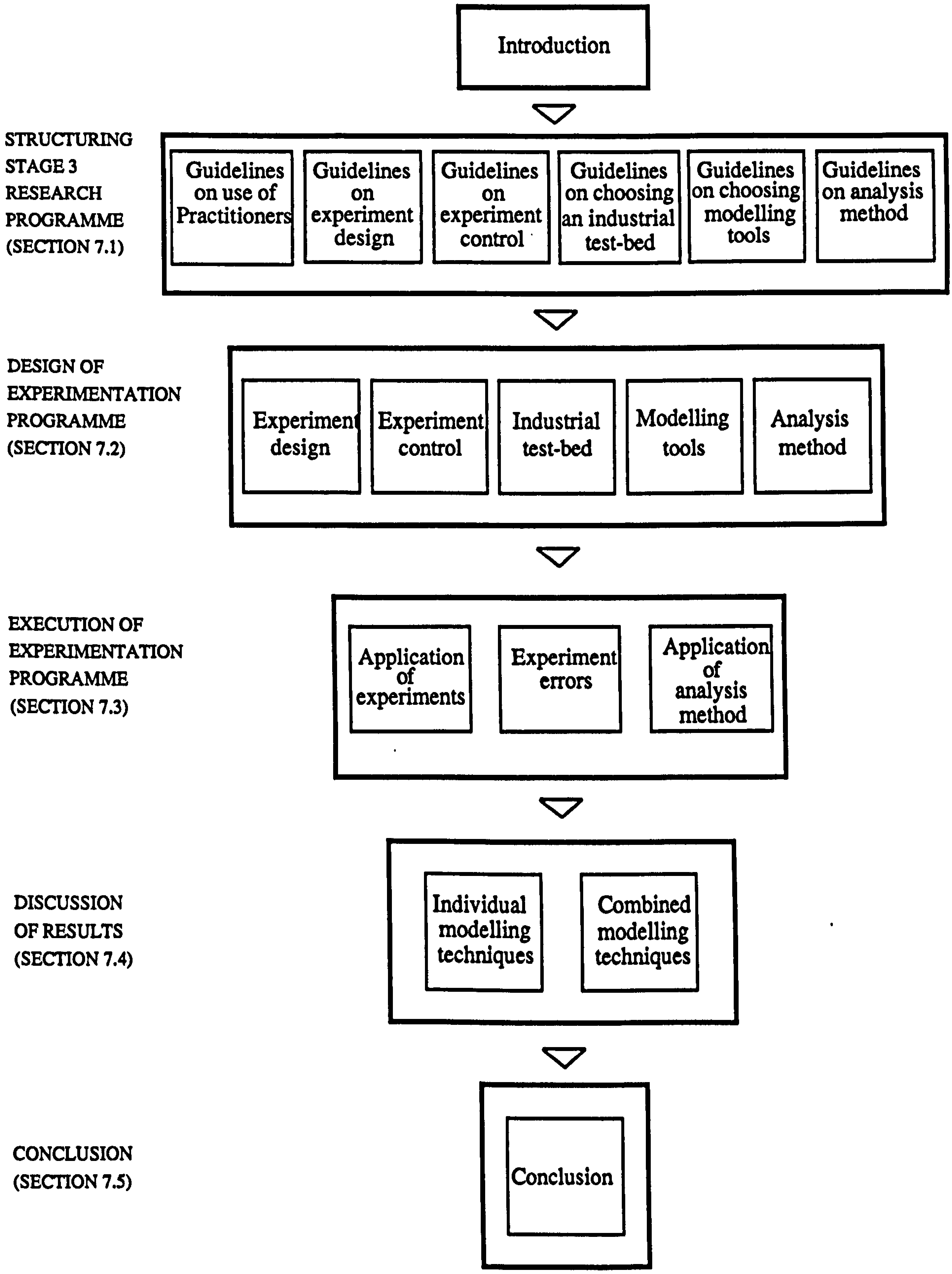


Figure 7.1: Structure of Chapter 7

appraisal through experimentation so as to accurately determine their capabilities. This section is concerned with the design and execution of such an experimentation programme.

Whilst the work of Chapter 4 has outlined the research activity at this stage, a number of other issues need to be addressed to convert this intention into a practical experimentation programme. Of particular concern here are the following issues:

1. Method of gaining input from modelling practitioners.
2. Experiment set to be conducted.
3. Choice of industrial test-bed on which to perform these experiments.
4. Choice of modelling tools to use in the experimentation.
5. Method of performing deduction to establish the capabilities of combined modelling techniques.

Guidelines for addressing each of these issues are presented in the remainder of this section.

7.1.1 Guidelines on the use of practitioners

To support the experimentation programme, the work in Chapter 4 advocates soliciting the opinions of practitioners with modelling expertise to assist in the verification of experiments and generalisation of the capabilities of modelling techniques. Chapter 5 successfully solicited the views of practitioners through an in-depth interview approach structured around a presentation document. On the basis of this success the same approach will be used at this stage. Application of this mechanism is described in Section 7.3.1.

7.1.2 Guidelines on experiment design

Chapter 4 has established that an appropriate test of a modelling technique is experimentation in the same context as it would be applied in practice, namely, with the experiments synthesising the evaluation of a manufacturing strategy in an industrial situation. On the basis of the work in Chapter 4, a hypothesis can be formed for each of the seven generic modelling techniques, in that, each technique satisfies all the requirement set. Experimentation must now seek to disprove each of these hypotheses by searching for the limitations of the modelling techniques.

To efficiently realise this objective a pre-defined programme is necessary to orchestrate experimentation. The activity of defining this programme is referred to as experiment design. The task in this section is to determine guidelines that provide an approach to carrying out this design.

The capabilities of a generic modelling technique that are of interest to this study are given by the requirement set in Table 5.1. These requirements fall succinctly into four categories with a number of criteria in each. Attempting to simultaneously design experiments that consider all criteria in each category of the requirement set appears to be an arduous task because of the number and variety of criteria involved. Smith (1990) provides useful advice to this situation when suggesting that a successful approach to complex experimental problems is to break them up into smaller experiments, and to complete the work in parts. Therefore, to simplify the task of experimental design, it is proposed to initially consider each category of requirements independently, and in each case design an appropriate experiment. This work should provide four experiments, or groups of experiments, to test a generic modelling technique against all of the requirement set. If such experiments can be defined, some amalgamation and rationalisation of experiments may then be possible. The outcome of such rationalisation will complete the experiment design and be termed the 'experiment set'. Section 7.2.1 applies this guideline and develops the experiment set.

7.1.3 Guidelines on experiment control

For the experiment set to be effective, a number of other issues also need to be examined as part of the experimental programme. These issues are highlighted by Beveridge (1950) who points out:

> "An experiment usually consists in making an event occur under known conditions where as many extraneous influences as possible are eliminated and close observation is possible so that relationships between phenomena can be revealed."

This view is common in the literature on experiment design. Leedy (1980) argues that:

> "All research is conducted within an area sealed off by given parametric limitations. By such control, we isolate those factors which are critical to research."

An insight into the extraneous influences anticipated in this case can be provided through assuming that the experiment set will involve testing models of a manufacturing system. Through exploring how model construction should be conducted, a number of control factors are apparent.

A variety of authors offer their opinion as to the stages in model construction, for example, Sargent (1987), Mihram (1972), Balci (1990), and Law and Kelton (1991). Of these, Law and Kelton offer a succinct view of model construction which is consistent with the general view of the literature. This process is as illustrated in Figure 7.2. From this process a number of prominent procedures are evident in modelling, namely, data collection to provide a conceptual model; model construction; model execution; model verification and validation. Establishing credibility is also an activity in this process, however this is actually a criteria being explored by the experiment set, and cannot therefore be a control. Each of these procedures need to be explored, and a method established of controlling their effect on the results. On the basis of this guideline, development of such control procedures is discussed in Section 7.2.2.

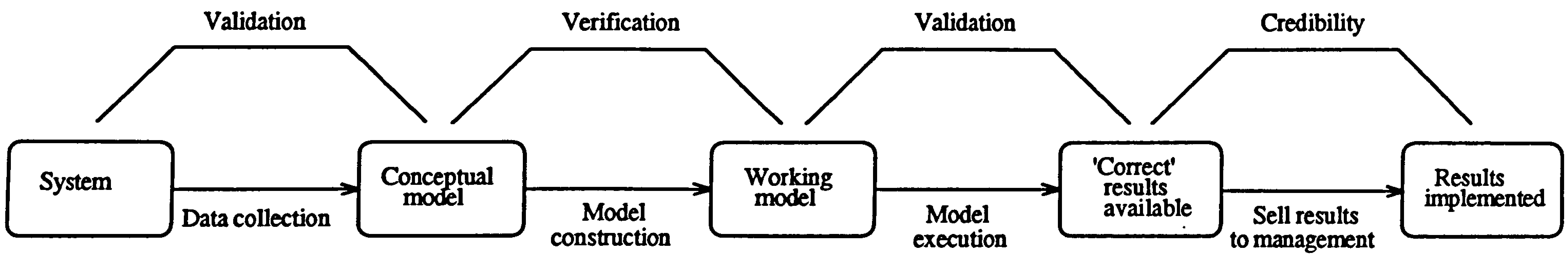
7.1.4 Guidelines on choosing an industrial test-bed

The chosen approach to experimentation requires a manufacturing company to act as an industrial test-bed. The type and sector from which a company is to be chosen is considered to be an issue for which guidelines must be developed.

Experimentation is intended to seek out the limitations of generic modelling techniques. Therefore, it could be argued that a diverse and obscure type and sector of manufacturing would be appropriate, as it may be more arduous to test a modelling approach than with common types and sectors of manufacture. However, it is quite possible that a common form of manufacturing may provide a sufficiently searching test-bed. If this is the case then the results of experimentation will be relevant to more practising managers, than if experimentation is based on an obscure form of manufacturing. Therefore, Section 7.2.3 chooses a test-bed from a common type and sector of manufacturing.

7.1.5 Guidelines on choosing modelling tools

Chapter 4 has stated that modelling techniques are often applied in practise using modelling tools. In the case of the generic modelling techniques chosen for experimentation, the literature frequently refers to their application through computer based modelling tools. Therefore, prior to experimentation, appropriate computer modelling tools must be chosen. In Chapter 4 a preference is given for contemporary, commercially available modelling tools. However, as argued in Section 4.1, no verified modelling tools have been found to exist that are explicitly tailored to the task of manufacturing strategy evaluation. Therefore, as



Note 1: Law and Kelton (1991) are particularly concerned with discrete event simulation studies. Therefore, the terminology has been changed to reflect a broader concern with modelling in this thesis.

Note 2: Law and Kelton (1991) omit feedback loops to enhance readability.

Figure 7.2: Stages in a modelling study (Source:Law and Kelton, 1991)

manufacturing strategy is concerned with the development of manufacturing systems, it is appropriate in this instance, to seek tools that are associated with manufacturing system modelling.

Finally, practitioners with modelling expertise are sought to assist in the verification of experiments and generalisations of the capabilities of generic modelling techniques from the performance of computer modelling tools. Section 7.1 has highlighted the use of sales and support staff from companies that supply modelling tools. It is important therefore, that when choosing a modelling tool, a suitable collaboration agreement is set-up with the supplier to facilitate such input. On the basis of this guideline, the choice of modelling tools is carried out in Section 7.2.4.

7.1.6 Guidelines on analysis methodology

The experimental results gained will be for individual modelling techniques, and from these results deductive reasoning is intended to be applied to predict the capabilities of combined modelling techniques. As stated in Section 4.2.1, the number of possible combinations of modelling techniques takes the form:

$$Cn = 2^n - 1 - n$$

Where : Cn = The number of possible experiments.
n = The number of modelling techniques under consideration.

As experimentation will explore seven generic modelling techniques, this means that there are 120 possible combinations. Therefore, some analysis methodology is required to efficiently orchestrate the deductive reasoning.

To deduce the capabilities of a combination of modelling techniques, knowledge is required as to how the modelling techniques interact with each other. In the simplest case a number of techniques may combine, each providing unique capabilities, and the total capability is the sum of the capabilities of the individual modelling techniques. Alternatively, a more complex case is where a combination of modelling techniques gives a total capability that is greater than the sum of the capabilities of the individual modelling techniques. In this sense, two forms of interaction are apparent. The first is termed here a symbiotic relationship of combining techniques, and the second is termed here a synergistic relationship. Of these two forms of interactions, the former is easier to assess as it only requires a summation of the capabilities of individual modelling techniques within a combination, to determine the capability for the whole combination. In the latter case, a careful consideration of the interactions of modelling techniques is necessary to determine the capability of the whole combination. Section 7.2.5 develops an analysis methodology on this basis.

7.2 DESIGN OF EXPERIMENTATION PROGRAMME

The previous section has provided guidelines for the detailed design of an experimental programme. This section performs this design by developing a set of experiments and controls, choosing an industrial test-bed and modelling tools, and arranging for the analysis of results. The outcome of this section is the complete experimental procedure.

7.2.1 Experiment design

It has been determined in Section 7.1.2 that experiment design should proceed by first considering experiments necessary to test each category of the requirement set for a generic modelling technique, and an attempt should then be made to provide a rationalised experimentation programme by amalgamating such tests.

Testing for flexibility to consider the structure and infrastructure of a manufacturing system

This flexibility is concerned with the span of changes to a manufacturing system, across which, a strategy formulator is likely to require evaluation to be performed, and can be defined in terms of the policy areas illustrated in Table 5.1. An experiment is required that will expose the inability of a modelling technique to consider developments to a manufacturing system in each of these areas.

An immediately apparent test is to use a modelling tool in an attempt to construct models across the breadth of the policy areas. The policy areas are convenient frameworks for organising the diversity of manufacturing decisions that must be made over time (Hayes and Wheelwright, 1984), but a typical development scenario could be chosen at a test-bed company to represent each policy area. Hence, because there are nine policy areas, nine scenarios can be used. Such scenarios would need to be consistent with the literature yet be in the context of the industrial test-bed. Each scenario is likely in practice, to bridge a number of the policy area categories because, as pointed out by Hayes and Wheelwright (1984), the decision categories are closely interrelated. They explain, for example, that workforce policies interact with location and production process choices, and purchasing policies interact with vertical integration choices. Therefore, it may be difficult to identify industrial scenarios that succinctly fit into each category, and as a consequence, it will require careful consideration to determine the capabilities of a modelling technique against each policy area.

This approach raises an issue with model validation. Methods of validating a model are discussed in Section 7.2.2. However, it is necessary to briefly pre-empt this later section in order to provide a cohesive explanation of how testing for flexibility can proceed.

The work in Section 7.2.2 argues that an appropriate validation procedure for models constructed in this study are tests for 'reasonableness' and 'structure'. This means testing the configuration of a model to ensure that it is structured to take account of a manufacturing scenario, and checking that the model behaves in a reasonable manner.

To facilitate these validation tests, an estimate needs to be made of the implications of the nine strategic development scenarios, on the structure and behaviour of a model. As a wide variety of estimates can conceivably be made some form of rationalisation is required, and this can be achieved by making estimates from a perspective of market, finance or manufacturing performance measures, for each strategic development scenario.

Testing for performance measures

A model is required to provide internal and external measures of manufacturing system performance (Section 5.4), these measures are given in Table 5.1. An experiment is required that will establish the performance measures supported by each modelling technique.

In this case, there is a particular concern that the capabilities of modelling techniques will be significantly influenced by computer based modelling tools, as such tools are likely to have the capability to manipulate data, or even import from, and export data to, other computer tools. This feature could corrupt an interpretation of the capabilities of a modelling technique as, given sufficient time and expertise, each tool could probably be configured to give the required performance measures.

A solution to this situation lies with the two variables of time taken and expertise available. If the expertise of the model builder is controlled during experimentation, then model build time becomes a measurable factor in determining the performance measurement information that a tool supports. However, it is probably impractical, and certainly inefficient, to attempt to establish the time taken to reach the absolute limits in performance measurement capabilities of a computer tool. This situation can be overcome to some extent by questioning what performance measurement information a tool focuses on providing within a reasonable amount of time. The emphasis being on establishing the focus, and not on definitive limitations of the capabilities of a modelling technique.

A suitable experiment therefore, is to limit the modelling time available and to require that as many performance measures as possible are provided. In such a situation the modeller can be instructed to add performance measures in order of ease of application, so as to make best use of the time available. The measures that are provided initially will be taken to be the 'focus' of the modelling technique.

The main concern with this experiment is that some techniques may provide several performance measures whilst others may provide fewer, but at a higher level of integrity and hence accuracy. This however is an issue concerned with serviceability and will be subsequently addressed.

Testing for system transition and content change

The behaviour of a manufacturing system, along with changes to the content of the system, needs to be evaluated as time advances (Section 5.5). An experiment is required that reveals whether a model can be constructed that accounts for the advance of time, and that can have content changed as time advances. Such an experiment is to construct a model of a manufacturing system, and then test to see whether time transition is provided. If transition can be provided, content change can be investigated by attempting to modify the model at an instant in time.

Testing for serviceability

A strategy formulator will require a modelling tool which provides credible and accurate models, with short application time, and low application cost (Section 5.6). An experiment is required that will test the performance of a modelling technique against each of these factors.

Accuracy is a measure of how the results gained from the model matched those gained from the real system. Consequentially, accuracy can only be stated for a model for which a comparable system exists. Law and Kelton (1991) offer an approximate experiment in this case, which is referred to as the 'correlated inspection approach' (Figure 7.3), and is concerned with assessing the behaviour of a model to the system under study. However, there is a concern here that accuracy may depend on the time, effort and expertise involved with model construction. Therefore, it may only be appropriate to compare the accuracy of different modelling approaches where these features are consistent. A method of providing this consistency is to control the expertise of the model builder and to measure the relationship between model build time and accuracy. In this manner, different modelling approaches can be compared by examining model accuracy and build time profiles.

To form such profiles a policy is required on the stages in a model's construction of which the recording of accuracy is appropriate. The researchers previous experience of a consultancy project (Section 4.2.1), revealed that model construction can be performed in an incremental manner, with each stage associated with a distinct addition to the model content. On this basis, a measurement of model accuracy and build time can be made at the completion of a number of major stages. Commensurable with the number of modelling techniques under experimentation, and the resources available in this study, three major stages will be chosen for each model constructed. These stages will be referred to as initial, intermediate, and final model build. On completion of each stage the time taken, and the level of accuracy against the real system can be recorded.

Credibility is a measure of how believable the results of a model are (Section 5.6). A potential experiment to test credibility is to build a model of the industrial test-bed, and then request personnel who are familiar with the collaborating company to score each model as to which is most believable. In this case a scale of '1 - 10' can be used, where a score of '1' can mean that the model is felt to be fictitious, and a score of '10' can mean that the model is totally believable. This test will require that the participating personnel are not involved in model construction, otherwise their opinion may be inadvertently influenced by the model building procedure, and also that the numerical values of model behaviour are not disclosed as these may cause personnel to confuse accuracy with credibility.

Section 5.4 has defined application cost as being based on the expertise and resources required to construct and apply a modelling tool. On this basis many physical modelling techniques have been discounted in Chapter 6 from further consideration in this research. Unfortunately, a number of concerns are now apparent with this criteria that render it unsuitable for direct assessment through experimentation.

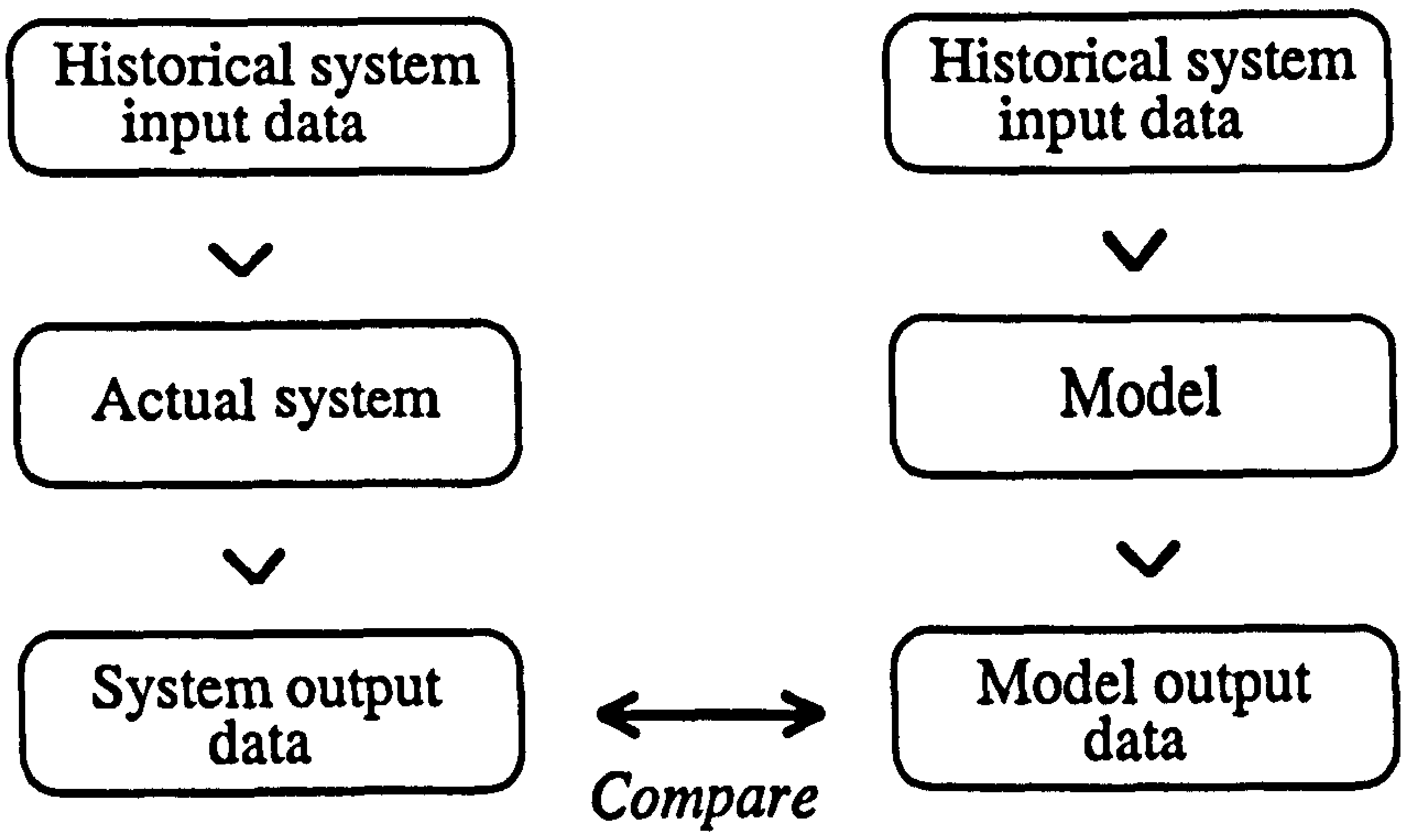


Figure 7.3: The correlated inspection approach (Source: Law and Kelton,1991)

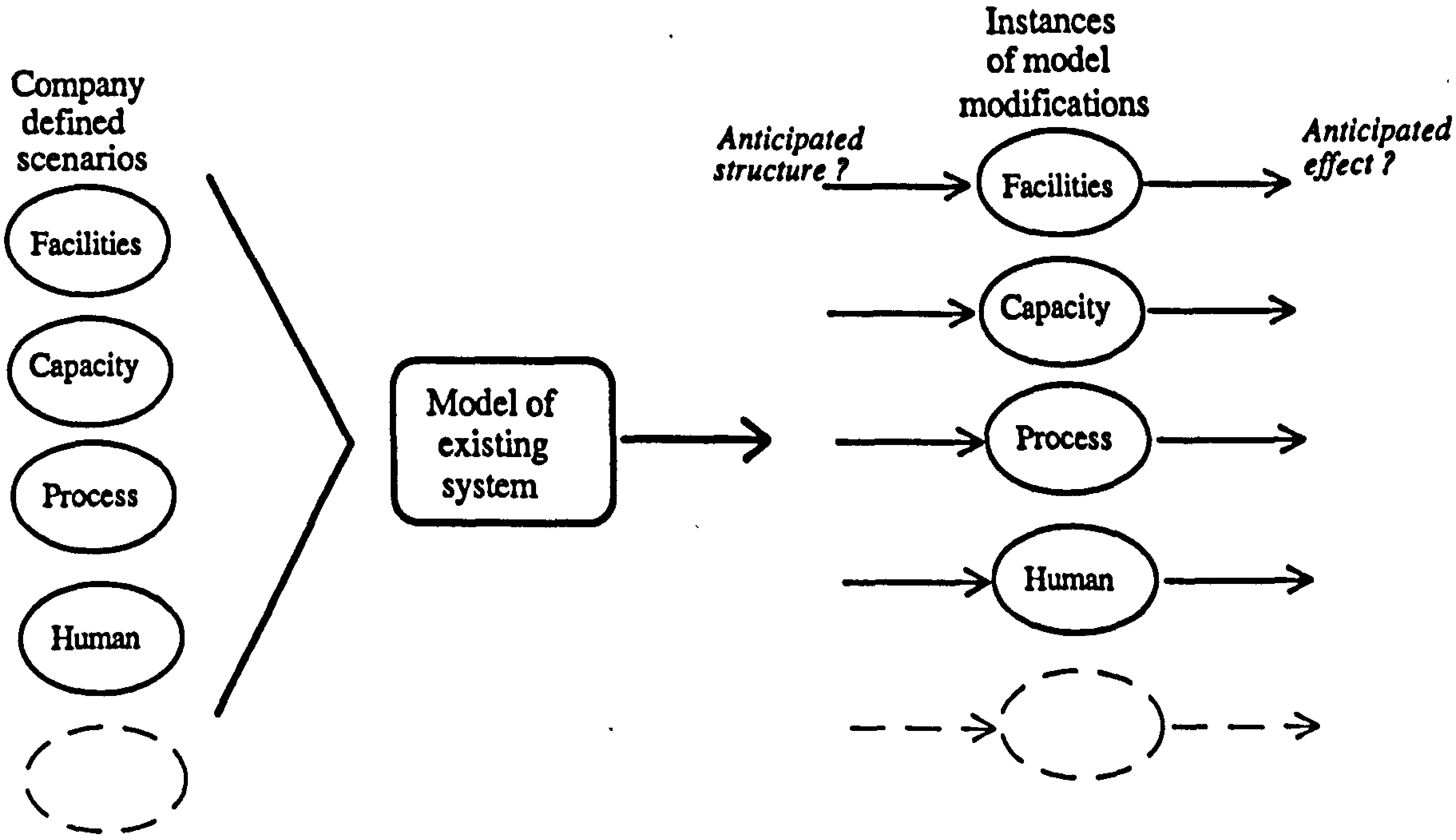


Figure 7.4: The flexibility test

Each modelling technique is represented by a modelling tool that has a number of features that can be attributed to the modelling medium rather than the modelling technique. It is not possible through experimentation to precisely establish the effort that has been consumed providing these features, compared to that required by the underlying modelling technique. Furthermore, the reasoning given above requires the expertise of the model builder to be kept constant during experimentation, hence allowing the complexity of applying a modelling tool to be measured in terms of the time taken in model building. Therefore, the approach taken here will be to recognise that application cost is important, and that the model building implications will be measured in terms of time. However, the cost of constructing a modelling tool will only be investigated if a distinction is necessary between two modelling approaches which are similar in all other respects.

Finally, experimentation is required to assess model build and execution times. A measure of model build time can be gained as part of the experiment to measure accuracy, as discussed earlier in this section. On completion of this test a complete model should be available for each modelling technique, which can then be used to assess model execution times. For such comparisons to be objective, comparable platforms of computer hardware are necessary.

Combining tests to provide an experimentation programme

A number of tests have been developed above to explore the capabilities of each generic modelling technique against the requirement set. An attempt can now be made to amalgamate and rationalise these experiments.

First, it is apparent that the outcome of establishing the accuracy to build time relationship for a modelling technique will be a complete model. This presents an opportunity to record the time taken to execute a model. For the purpose of comparing modelling approaches, the model execution time will be measured over a time period equivalent to one year. At this stage, a model can also be explored to establish whether a dynamic change to the content of the model can be made. Likewise, an assessment of model credibility can be made through seeking the opinion of employees at the test company, in the manner described above.

The process of generating the accuracy and build time profile gives an opportunity to assess the performance measures that a modelling technique is focused at supporting. In this case an emphasis on achieving short model build times can be made during model construction, hence encouraging the model builder to provide only those performance measures most supported by a modelling approach[1]. The factors discussed so far in this section succinctly form one experiment. This experiment has been adopted and termed the 'functionality test'.

The functionality experiment does not consider the flexibility of a modelling technique. However, the basic test of flexibility established above, can be performed on the complete model resulting from the functionality test. This model can be tested against nine scenarios of strategic manufacturing developments. This second experiment has been termed the 'flexibility test' and is illustrated in Figure 7.4.

On the basis of the investigation in this section, the experiment set will consist of the functionality and flexibility tests.

7.2.2 Experiment control

Section 7.1.3 has identified a number of prominent procedures that should be controlled so as not to influence the experimental results, namely, data to provide a conceptual model; model construction; model execution; model verification and validation. This section develops methods to control these procedures so that their affects are consistent throughout experimentation.

Data collection for the conceptual model

The conceptual model is a representation of the system being modelled in terms of data and assumptions[2]. For objective evaluation of a number of generic modelling techniques the conceptual model needs to be the same in each case; each modelling tool should be set the same task. To complement the experiments designed above, first a conceptual model of the existing manufacturing system at the test-bed company is required against which the functionality test can be executed, then a number of modifications to this model are necessary to execute the flexibility test. The conceptual model, and associated modifications, should

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[1] As product features, design flexibility and quality are inputs and conditions for model execution (Section 5.4.3), they will not be considered here. However, the receptiveness of models to this approach is considered in the conclusion (Section 7.5). Likewise, the measure of contribution, as defined in Section 5.4.2, will be assessed in terms of the capability of a modelling technique to provide some performance measures at a sub-system level.

[2] A conceptual model is considered by Balci (1990) to be the model that is formulated in the mind of the modeller. Law and Kelton (1991) however consider that the conceptual model can be represented formally in terms of flow diagrams and data. This description is more consistent with what Balci, and others, refer to as a communicative model; a model representation which can be judged or compared against the real system. For consistency with Figure 7.2 the term conceptual model will be retained with an acceptance that some authors interpret such a model to be a communicative model.

also be in a form that reflects a strategy formulation exercise, for example, product families formed in the manner of a manufacturing audit (DTI, 1988).

It is essential that the conceptual model is a valid representation of the real system; if the data and assumptions are invalid so too will be the working model. Therefore, a method is required of validating the conceptual model. Law and Kelton (1991) advise the involvement of company personnel in such validation. Hence, the approach chosen here is to define the data and assumptions typically required of a conceptual model using each generic modelling technique, collect the necessary data from the participating company, and then present the conceptual model to company personnel to ensure that the gathered data is valid. To complement this approach, data will be fed back to company personnel in a different form from that collected. In this case, 'material flow charts' (Currie, 1959) will be used to present the manufacturing sequence and associated times of product families.

Constructing a valid conceptual model may take a substantial amount of time. It can be argued that a measurement of model build time should include some account of the time taken for data collection, for each modelling technique. This however, would require carrying out a number of independent data collection procedures at one company, and as such would require the control of a wide variety of factors to remain objective. For example, the evolving knowledge gained of the company by the data collector, and the difficulty in maintaining a consistent employee response to what may be repetitive questions. Therefore, while the time taken to collect data will be omitted, the time taken for analysis specific to a modelling technique, such as time taken to choose cost drivers with ABC, will be recorded.

Model construction

Model construction is defined by this thesis to be concerned with transposing the conceptual model, into a valid working model, using the modelling medium under consideration. Section 7.2.1 has highlighted the need for consistent model builder expertise to form comparable tests of modelling techniques If, for example, the model builder has greater familiarity with one particular modelling technique or tool, it is likely that the progress made on model building will differ to a situation where the modeller has no previous knowledge. Likewise, the familiarity of the modeller with the conceptual model is likely to increase as a greater number of models are constructed, with a probable consequence of reducing model build time. Furthermore, if the modeller approaches model building with different procedures in each case, it is likely that the application time will again be influenced. Fortunately, the issue of model building procedure is addressed by the form of the functionality test (Section 7.2.1).

Maintaining a consistent level of modeller expertise is more difficult, as it raises the question of 'who should be the modeller?'. This issue can be addressed by questioning the role of the researcher. Platts (1993) considers three main categories of research method that might be appropriate in researching manufacturing strategy, namely:

- Direct observation: the researcher endeavours to remain totally detached and records what happens without influencing events. The initial aim being to obtain a record of events as free from interpretation as possible so as to obtain a set of 'pure' data.
- Participant observation: the researcher takes part in the activity under study and adopts two roles, one is as a member of the group being studied, the other is as a recorder of the processes and behaviour occurring within the group.
- Action research: here the researcher seeks to direct and influence the way in which the activity is conducted, being not so much concerned with gaining a better understanding of current approaches to tasks, as with changing those approaches and observing the facts.

Platts argues that his work on testing a manufacturing audit is concerned with an approach which prescribes a process different from that which organisations would normally use and for this reason action research is clearly an appropriate method. In this case the primary role of the researcher was to guide and structure the process; he did not try to impose his views over those of the company. However, Platts does caution that because of the direct nature of the researchers involvement it is necessary to recognise that his or her background and previous experience will have an impact on the research process.

There is an argument that to evaluate a modelling technique in the context of a manufacturing strategy evaluation exercise it is appropriate to directly observe an industrialist, or group of industrialists, apply the generic modelling techniques. Unfortunately, this does present a problem of controlling the effect of the industrialists previous experience, as the industrialist could still have greater familiarity with particular approaches. Furthermore, there is a danger that the extent to which such familiarisation is affecting the study will not be known.

Similarly, as computer based modelling tools are to be applied in the study (Section 7.2.4), the opinion of an industrialist may be influenced by the features of a modelling tool rather than the underlying capabilities of the modelling technique.

To ensure consistent modeller expertise, and also to gain a better understanding and insight into the generic modelling techniques, the researcher's role in this case will be one of 'participant observation'. Hence, the researcher will take on the role of model builder and strictly adhere to the experimentation programme. In an attempt to reduce the effect of the researcher's expertise[3], familiarisation of modelling approaches will be gained by constructing a pilot model with each modelling tool. Furthermore, the first modelling tool to be applied will be that with which the researcher is most familiar, in this way the familiarity with the tool will be offset to some extent by unfamiliarity with the conceptual model. Likewise, the modelling tools applied later will be .those with which the researcher is less familiar, but model build time will be offset by a greater familiarity having been gained of the conceptual model.

Model execution

Model execution is concerned with how a model is used to generate results. Because some of these results will be used in the measurement of accuracy, as formerly established in experimental design, it is important that a consistent approach to model execution is maintained.

A potential for error in this situation is exposed by Law and Kelton (1991) who consider that one of the major pitfalls in carrying out a modelling study is in making a single replication of a particular system design and treating the output statistics as true answers. If a statistical content is included in a model, then following the advice of Law and Kelton, a number of model runs will be necessary to carry out a sensitivity analysis and to provide valid results. Sensitivity analysis is concerned with testing the sensitivity of the model's output, to small changes in input parameters, when an input probability distribution is changed (Law and Kelton, 1991). This presents a dilemma when considering consistency across experimentation with a number of generic modelling techniques, in that, if statistical elements are included in a modelling approach

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[3] It is important to emphasis the expertise of the researcher. In this case the researcher has eight years experience of conducting Discrete Event Simulation projects within manufacturing industry, having constructed models of machining and assembly facilities across a range of manufacturing environments. Furthermore, over the past four years the researcher has taught manufacturing system modelling using Discrete Event Simulation to engineering students at undergraduate and postgraduate levels.

then the necessary sensitivity analysis may have an adverse effect on model execution time. However, a modelling approach that contains statistical elements may provide greater accuracy if a number of model runs are carried out.

The following policies will be adopted to overcome this dilemma. Firstly, to reduce the potential of these factors to a minimum, the data that describes the conceptual model should contain the least amount of statistical elements possible. Secondly, when comparing the execution time of models, the time for only one model run should be considered, as this will allow a consistent comparison but also allow the time required for multiple model runs to be estimated, Finally, if a model contains statistical elements a limited sensitivity analysis should be conducted. If the variance in results is small then one set of results should be chosen as representative. If however, a large variance is recorded the experimentation procedure must be interrupted and a detailed investigation and search for causes conducted before proceeding with further testing.

Model verification and validation

Verification is concerned with ensuring that a model performs as intended, whilst validation ensures that the intended model is an accurate representation of the system being modelled (Sargent, 1987). This is illustrated in Figure 7.2 where verification is concerned with comparing the conceptual and working models, whereas validation compares the working model and the real system. This description ignores validation of the conceptual model that has previously been discussed in Section 7.2.2. The experiments designed above require a model to be constructed of an existing manufacturing system, then once complete, modified to represent a number of strategic manufacturing developments. Hence, verification and validation methods must be available for models in both of these cases.

Verification can be carried out by applying three approaches offered by Gass (1983) in this case, namely:

1. Ensuring that the program, as written, accurately describes the model as designed.
2. Ensuring that the program is properly mechanised on the computer.
3. Ensuring that the program as mechanised runs as intended.

Validation however, requires consideration of a number of factors. If the conceptual model is absolutely valid, and the working model fully verified, then in theory, no validation of the working model is necessary. Although this state is desirable the practical implications of an industrial study mean that absolute validity of the conceptual model may not be possible. Therefore, validation is necessary for each working model formed.

Validation in this case can be carried out using a number of methods, Sargent (1987) lists several approaches, and Balci (1987) gives 24 validation techniques. However, Pegden et al (1990) argue that most methods of validation show a mixture of testing from the view point of 'reasonableness', 'structure', and 'behaviour', each having a description which can be summarised as follows:

- Reasonableness: exhibiting reasonable or realistic behaviour that resembles that of the real world.
- Structure: testing the structure of a model for adequacy and verification; assessing correspondence between basic modelling assumptions and the referent system.
- Behaviour: studying the behaviour of the model in relation to the behaviour of the referent system.

Pegden et al (1990) provide a number of validation approaches for each of these categories. Hence, a validation procedure for this study can be determined by considering the suitability of each category, and then adopting the approaches contained within.

Pegden et al (1990) consider that tests for behaviour are usually most convincing in validation. Unfortunately, inspection of the requirement set shows that accuracy of a modelling technique is an experimental factor and cannot therefore be used in validation. Furthermore, tests for behaviour can only be conducted where a real manufacturing system exists. If a future development of a system is under consideration, as is the case for the flexibility test described in Section 7.2.1, then such tests cannot be used because no system exists against which to make comparisons. Hence, only validation tests for reasonableness and structure are appropriate in this study. For example, to evaluate the effects of a new warehouse within a factory, a model structure may need to be changed to include the new materials handling procedures. Such a change of structure may be estimated to increase the manufacturing lead time of products. To validate this particular model it would be necessary to ensure that changes to the materials handling procedures and the resulting product lead time can be related to the anticipated real world situation. Such an approach distinguishes between situations where, for example, data may be entered into a model but due to limitations of the technique under consideration there is no internal mechanism to relate this change to the behaviour of a model.

A number of tests are offered by Pegden et al (1990) in each of the reasonableness and structure categories. These are consistent with approaches advocated by authors such as Balci (1987) and Sargent (1987). Therefore, although other tests do exist, this common group will be used in this study to ensure model validity. These tests are summarised in Table 7.1.

Concluding comments on experimental control

This section has explored methods of controlling the potential effects of perceived prominent extraneous factors in the experimentation programme. In this case control has been sought in the data collection for the conceptual model, model construction, model execution, model verification and validation. There may be some factors not taken into account at this stage that influence the results gained, therefore it will be necessary to explore possible errors on completion of experimentation, and to consider their affects on the validity of the recorded results.

7.2.3 Selecting an industrial test-bed

Section 7.1.4 has provided guidelines as to the form of an industrial test-bed. These guidelines have been followed in this section while seeking to attract a suitable collaborating company.

Several manufacturing companies were identified which satisfied those characteristics laid down in Section 7.1.4. An initial letter briefly outlining the project, and requesting an opportunity to visit them and give a short presentation, was sent to either the senior manufacturing manager or director at these companies. These letters were followed by a telephone call to the senior manager or director one week later. After several visits and telephone conversations a test-bed company was identified and formally invited to participate in this study.

The participating company chosen for this study was AUTOPRESS-COMPOSITES LIMITED, Staffordshire, England. This company manufactures thermo-setting plastic products for a variety of markets, and is felt to be typical of a multi-product batch manufacturing environment. This company is described in more detail in Appendix B.

Tests for reasonableness	Tests for structure
• Continuity: Small changes in the input parameters should cause consequent small, but appropriate, changes in the output state of the system variables. If the changes are disproportionate, the analyst should understand why and be able to justify the behaviour. • Consistency: Essentially similar runs of a model should yield essentially similar results. • Degeneracy: When certain features of a model are removed, the output should reflect their removal. • Absurd conditions: This test has two aspects. First, absurd inputs should not get equally absurd outputs. Second, absurd conditions should not arise during model execution.	• Face validity: Achieved by asking persons familiar with and/or knowledgeable about the referent system whether the model and/or its behaviour appear reasonable. • Parameters and relationships: Tests of the underlying assumptions about parameter values and variable relationships. • Structural and boundary verification: Ensuring that the structure of the model does not obviously contradict reality. Need to ensure that there is a mapping or homomorphism between the model and the real system.

Table 7.1: Validation tests for reasonableness and structure (Source: Pegden et al, 1990)

7.2.4 Selecting suitable modelling tools

This section reviews modelling tools that are available for each generic modelling technique and chooses a representative tool in each case. The emphasis at this stage is to justify the modelling tools chosen. This complements the description of modelling techniques cited earlier in Appendix A. The tools chosen in this study are summarised in Table 7.2.

IDEF$_0$

IDEF$_0$ can be applied manually using pen and paper, however some computer tools exist which automate the application of IDEF$_0$. One such example is a computer based tool called DESIGN/IDEF supplied by Micro-Match Ltd. This tool principally assists in the drawing of diagrams and also offers a variety of functions to support modelling, for example consistence checks to ensure that all arrows and decomposition nodes are connected. Furthermore, DESIGN/IDEF extends the IDEF$_0$ functionality by allowing the assignment of numerical attributes to activities by encapsulating a static mathematical model. A pedantic view would ignore this mathematical functionality as it does not pertain to the true nature of IDEF$_0$. However, such functionality may provide a valuable method of evaluating a manufacturing strategy and will therefore be considered for the purpose of this study to be an extension of the IDEF$_0$ methodology. As a consequence, DESIGN/IDEF has been acquired for evaluation, and collaboration in this study agreed with Micro-Match Ltd.

Integrated Enterprise Modelling

Few tools have been found which apply the concepts of this approach. A particularly significant contribution is provided by a product called ENTERPRISE MODELLER (EM) supplied by Business Integration Technologies Ltd.

This tool adopts the less abstract characteristics of 'materials flow charts', relaxes the strict rules associated with IDEF$_0$, but offers a decomposition approach. EM provides a graphical representation of a system in terms of activities, flows, stores, data, material, functions, human and physical resources and links these to identify business processes. Furthermore, a mathematical and data capture functionality is offered in the same manner as described for IDEF$_0$. A copy of this tool has been acquired for this study and collaboration agreed with Business Integration Technologies Ltd.

Categories of modelling techniques	Definition	Generic modelling techniques	Representitive modelling tools
Schematic	A graphical representation of a system using symbols.	$IDEF_0$ Integrated Enterprise Modelling	DESIGN/ IDEF ENTERPRISE MODELLER
Simulation	A model of the behaviour of a system as a whole by defining in detail how various components interact with each other.	Discrete Event Simulation System Dynamics	WITNESS STELLA
Mathematical	Explicit analytical formulae describing known relationships.	Queuing Theory Business Planning Activity Based Costing	MPX/ Manuplan II ABP BPS-ABCM

Table 7.2: Modelling techniques and tools considered in experimentation

Discrete Event Simulation

There are a wide variety of computer tools that enable the construction of DES models, as illustrated by Carrie (1988) who gives a general taxonomy of tools available. Included in this taxonomy are tools such as SEEWHY, WITNESS, OPTIK, GENETIK, SIMON, SIMAN and SLAM. Carrie points out that some of these tools are intended for general purpose system simulation, and others are focused at manufacturing system modelling. For the purpose of this research, a tool that was focused at manufacturing system modelling was favoured. On the basis of this criteria a tool called WITNESS was acquired. WITNESS is supplied by a company called AT&T ISTEL Ltd. This company was approached, a copy of WITNESS was acquired for evaluation, and collaboration in this study agreed.

System Dynamics

There appear to be three main computer tools that are currently available for automating the SD technique, namely, DYNAMO, DYSMAP, and STELLA. Towill (1993a) makes the following comments about STELLA in particular:

- Methodology is well established.
- 'User-friendly' software leads to easy interaction with industrialists.
- There are many published case studies available for cross referencing.
- 'User-friendly' software aids the modeller.
- System modellers need know no servotheory.
- Useful self checks and balances are built into the software.
- Simulation modelling becomes very easy.

Towill also points out that in the USA in particular, there is a move towards the use of the STELLA package. Likewise, Wolstenholme (1990) believes that the most recent and perhaps significant development in SD software has been that of STELLA. Wolstenholme (1990) states that STELLA's major innovation is that pipe diagrams representing models can be drawn directly on the computer screen using a pre-defined tool kit. STELLA is supplied by a company called Cognitus Ltd. This company was approached, a copy of STELLA was acquired for evaluation, and support in this study agreed with company personnel.

Queuing Theory

There are a number of computer based tools that can be used to apply the principles of QT to manufacturing system analysis. Snowdon and Ammons (1988) suggest the packages CAN-Q, RESQ, PANACEA, QNA, MVAQ, PMVA, MANUPLAN, and MANUPLAN II. The earliest package referenced by Snowdon and Ammons (1988) is Computer Analysis of Networks and Queues

(CAN-Q). They point out that this tool was developed in 1977 to mathematically model work flow in a flexible manufacturing system for machining.

Haider et al (1986) review the general criteria that a QT based tool should satisfy in order to be generally appropriate to manufacturing systems analysis. These criteria include, for example, that the technical details on the QT should be masked from the user. On the basis of these criteria Haider et al (1986) advocate the use of MANUPLAN.

MANUPLAN and MANUPLAN II were developed by Suri and Diehl of Network Dynamics Inc., USA, and combine the theory of a network of queues with reliability modelling (Snowdon and Ammons, 1988). More recently MANUPLAN II has been superseded by a tool named MPX. MPX has been designed to be applied to general manufacturing system's, and it is believed to be the only commercially supported QT based tool for such applications. On the basis of these factors a copy of MPX was obtained from the USA for analysis, and collaboration with Network Dynamics Inc., agreed.

Business Planning

In reviewing the computer tools available, a number of business modelling packages were considered. Some tools can be adapted to particular financial situations while the most common tools are spreadsheet based and are sold for general applications. For this review a tool was chosen which was specifically intended for application at a manufacturing company. This tool is called APPLIED BUSINESS PLAN (ABP) and is supplied by Applied Business Software Ltd, with whom collaboration in this study was agreed.

Activity Based Costing

There are currently few computer tools that automate the application of ABC to manufacturing system analysis. After a thorough review, a product named BPS-ABCM was identified as being an appropriate tool for this application. BPS-ABCM is a computer based tool that enables the application of ABC to manufacturing systems. The supplier is a company named BPS Software Ltd, with whom collaboration in this study was agreed.

Conclusion on modelling tools

Seven modelling tools have been identified in this study, and collaboration has been agreed with the vendor company in each case. Fortunately, the choice of tools has not been governed by their availability, with the most suitable tools being acquired for experimentation in each case.

7.2.5 Analysis methodology

To complete the experimentation programme design, a method of deducing the result of combining modelling techniques is required. Section 7.1.6 has determined that both symbiotic and synergistic relationships need to be considered.

Considering symbiotic relationships, these exist where the result of combining two modelling techniques is the sum of the capabilities of the individual modelling techniques. Hence, a method is required of rigorously and efficiently summarising the capabilities of each possible combination of modelling techniques, from the results that will be gained through experimentation. The routine established in this case is as follows. First, a two dimensional matrix is constructed that consists of unique squares for specific capabilities of a modelling technique. Then, on the basis of the experimental results, where a capability exists the associated square on the matrix is blanked out. By constructing this matrix on an 'overhead transparency', the capabilities and limitations of a combination of modelling techniques can be measured by overlying the associated transparencies.

All possible combinations of modelling techniques need to be identified. As 120 combinations exist (Section 7.1.6), the possible combinations can be identified by counting to 127 in binary code and then ignoring instances where the number '1' features alone. Each remaining binary code can then be considered to represent a unique combination which can then be tested by the transparency overlaying method. This simple comparative mechanism is illustrated in Figure 7.5. The results from this analysis can then be entered on to a computer spreadsheet package that will allow the capabilities of modelling techniques to be quickly sorted and ranked in order of performance.

A synergistic relationship is considered to exist where the capability of a combination of modelling techniques, is greater than the sum of the capabilities of the constituent modelling techniques. In an instance where a synergistic relationship exists, it will mean that the performance of the combined modelling techniques will be greater than if only a symbiotic relationship existed. Therefore, if a combination of modelling techniques have a symbiotic relationship, but satisfy all the requirement set, they need not be considered for a synergistic relationship. Hence, only combinations that exhibit limitations against the requirement set, after being tested for a symbiotic relationship, need be considered for this further analysis.

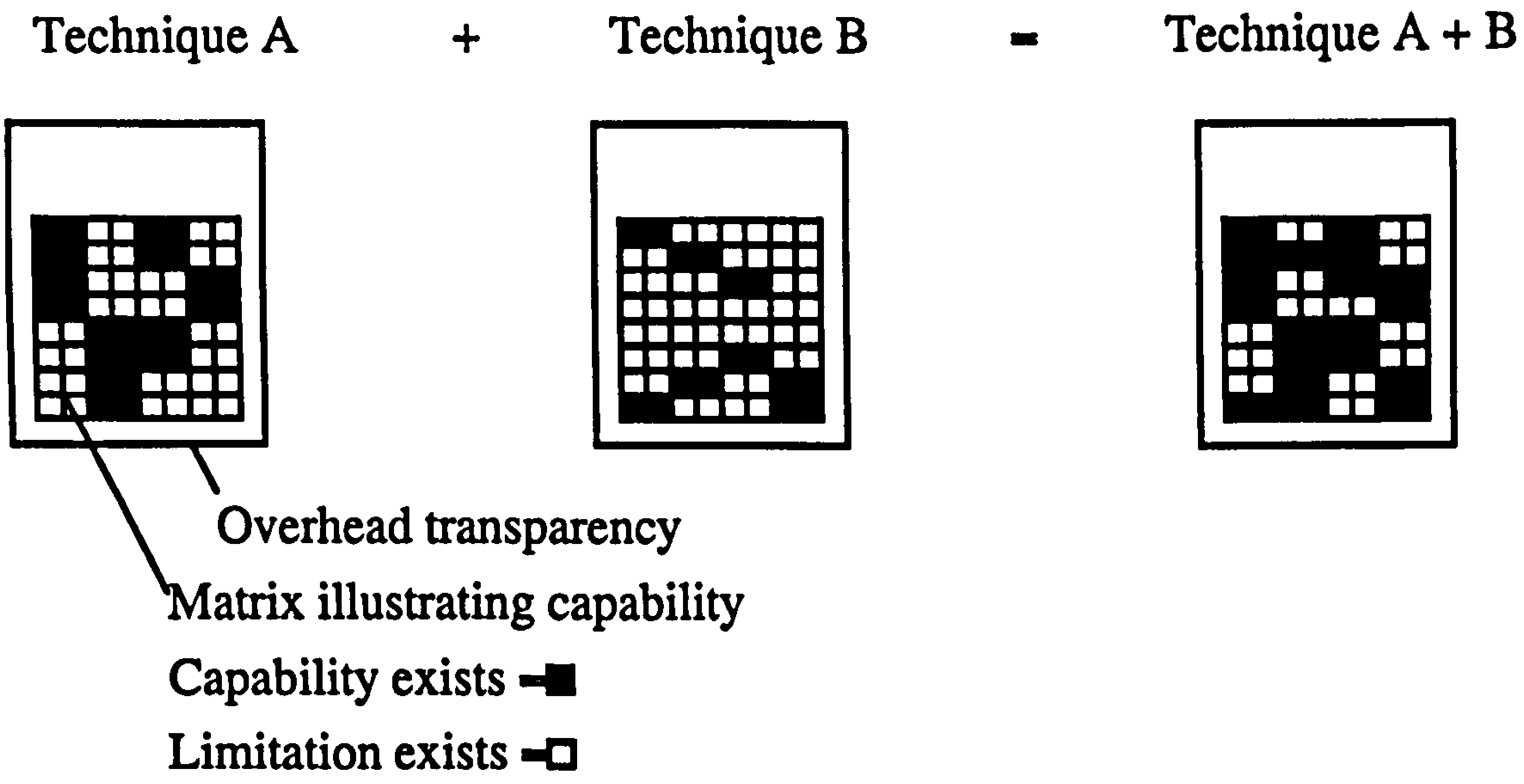


Figure 7.5: Evaluating the symbiotic effect of combining modelling techniques

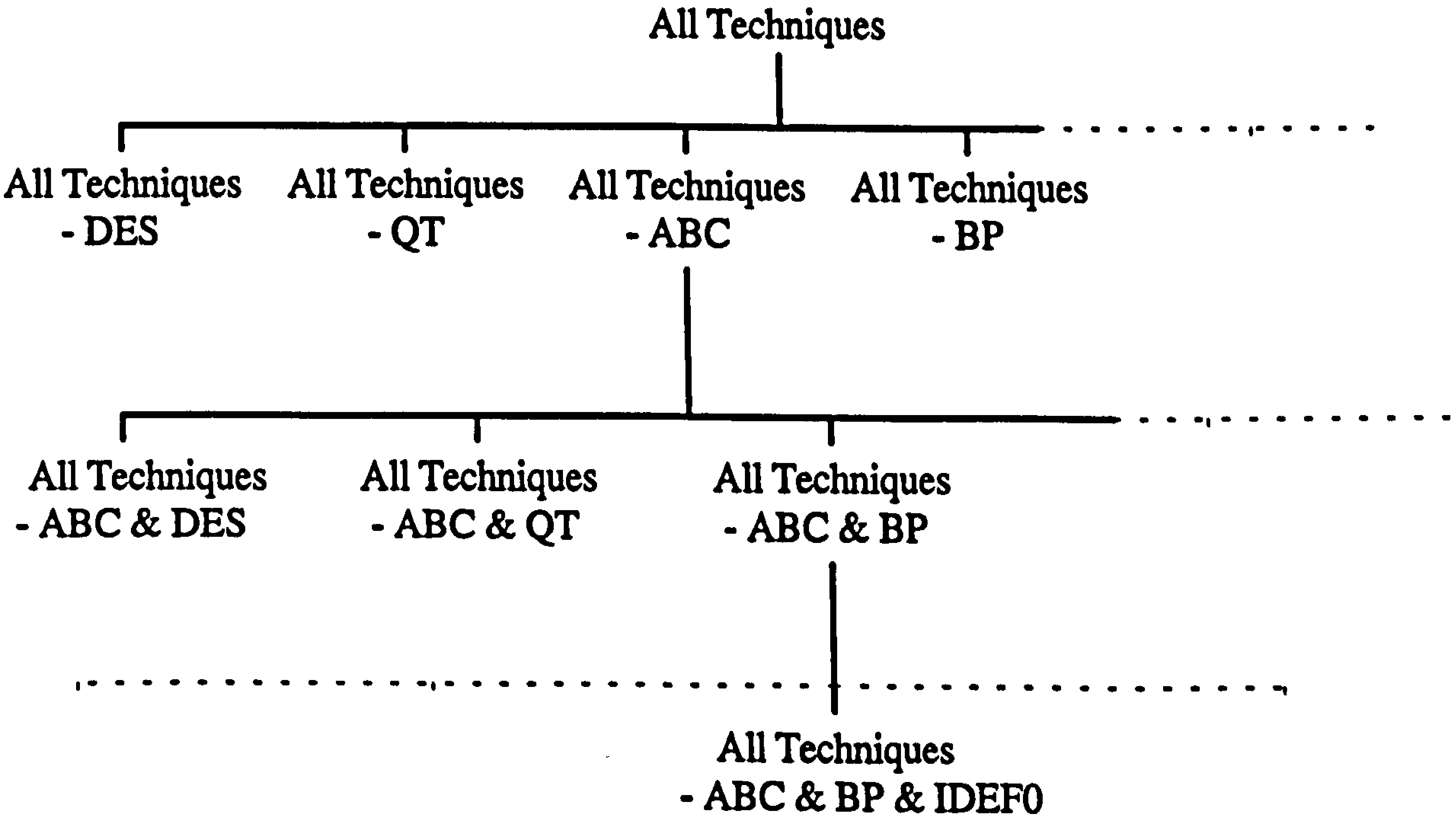


Figure 7.6: Evaluating the synergistic effect of combining modelling techniques

To determine whether a combination of techniques will have a synergistic effect, a detailed investigation is necessary into the manner by which the associated techniques interact with each other. If all combinations of techniques were to be reviewed in this manner a tremendous amount of analysis would be required. However, such analysis can be economised by assuming that where a combination of techniques fails to satisfy the requirement set, any other instances of the same combination or less, will also fail. For example, if a combination of ABC, BP, and $IDEF_0$ failed to give the necessary capabilities, then a combination of only $IDEF_0$ and BP, will also fail.

Applying this method means that the required analysis can be considered as a hierarchy as shown in Figure 7.6. If for the moment it is assumed that no symbiotic relationships satisfy the requirement set, then the highest level of this hierarchy is a combination of 'all techniques', and if this combination is found to be successful then a second level of analysis is considered. At this second level, the combination of 'all techniques' is tested with each contributing technique sequentially omitted. For example, ABC is temporarily removed, the resulting combination tested, and then ABC returned. The sequence is followed at every level, and at each level an additional technique removed, until the combination fails. Once a combination fails, then no further analysis is considered for that set of techniques. Unfortunately, there is a danger that all possible combinations of techniques may have to be considered.

7.2.6 Summary of experimentation programme

The work in this section has described the detailed preparation of an experimentation programme to assess generic modelling techniques against the task of analytical evaluation of a manufacturing strategy. An overview of the main stages in this programme is given in Figure 7.7. On the basis of this design, execution of experiments can now proceed.

7.3. EXECUTION OF EXPERIMENTATION PROGRAMME

The experimentation programme illustrated in Figure 7.7 has been applied at the collaborating company. This section presents this application and the results obtained.

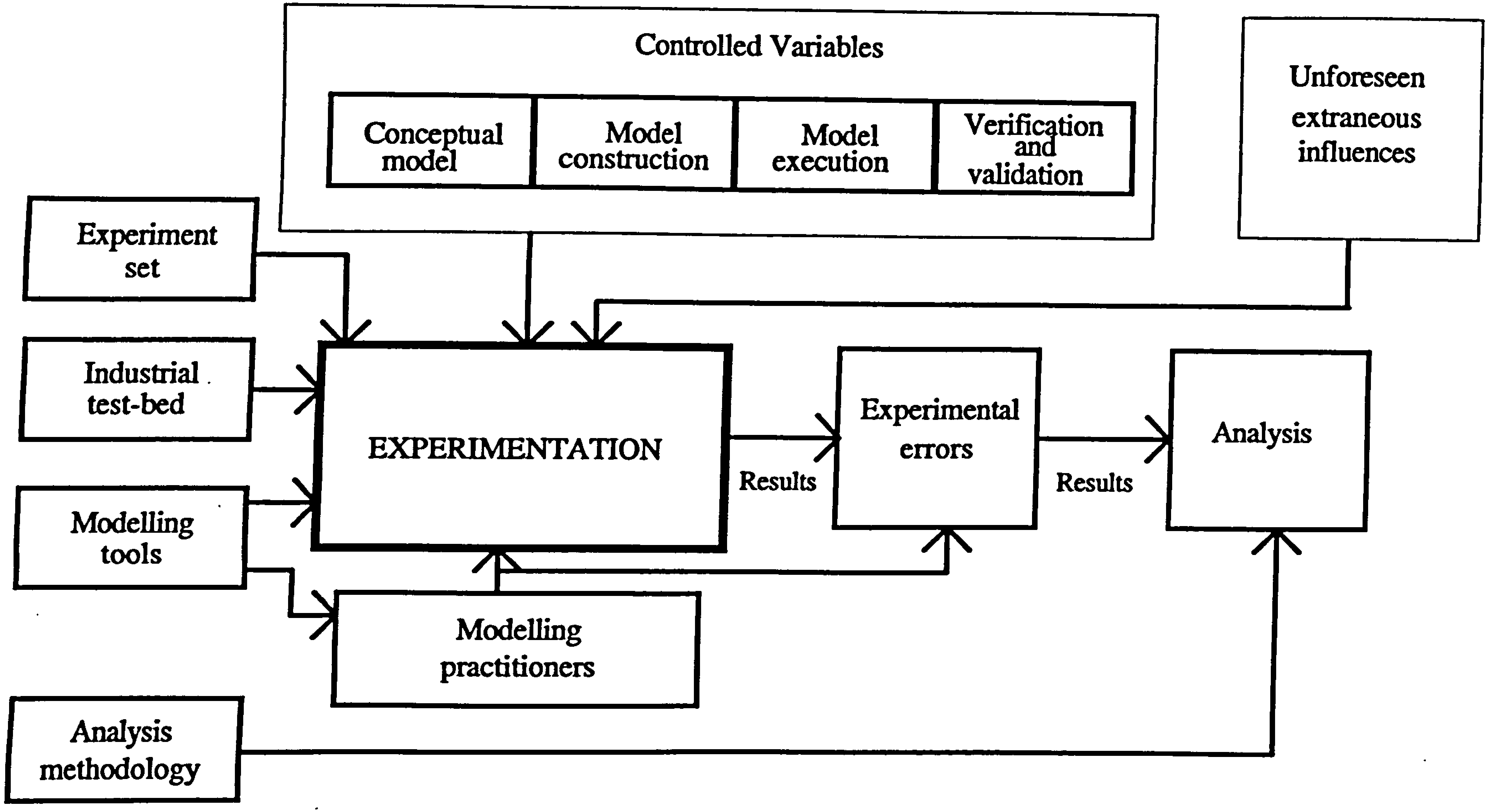


Figure 7.7: Overview of first experimentation programme

7.3.1 Experimentation

The first phase in experimentation was to collect and analyse data to form a valid conceptual model of the existing manufacturing system at the test-bed company. Initially, the earlier stages of the manufacturing audit offered by DTI (1988) were applied to identify product families, and to set an appropriate context for the personnel at the test-bed company. The manufacturing cycle of the product families was transposed on to material flow charts, an example of which is shown in Figure 7.8. Subsequently, the latter stages of the manufacturing audit process were applied to assist in the formation of the nine scenarios of strategic manufacturing developments, required to assess the flexibility of modelling techniques. In this case an effort was maintained to choose manufacturing developments that were representative of the intentions of the literature, rather than appeasing the desires of management at the company. The chosen strategic manufacturing development scenarios are summarised in Table 7.3. The anticipated effects of these scenarios, as required for validation, are given in Table 7.4. Validation of the conceptual model concluded this phase of the study. This was achieved by presenting the collected data, after transposition into a different presentation form than originally received, to the participating personnel at the test-bed company, and thereby attempting to identify omissions and inaccuracies.

The second phase of experimentation was application of the chosen modelling tools according to the functionality and flexibility tests (Section 7.2.1). The modelling tools were ranked in order of the researchers familiarity with the modelling approach, as justified in Section 7.2.2. The subsequent sequence was DES, IDEF$_0$, IEM, ABC, BP, QT, and SD. In each case a pilot model was first constructed to familiarise the researcher with the modelling tool, and to determine logical stages in model build. This model was then discarded, and modelling of the existing manufacturing system at the test-bed company commenced. This model was constructed in three stages of initial, intermediate, and final (Section 7.2.1), with the accuracy and associated model build time recorded at the end of each stage. The content of each model constructed at each of these stages, is summarised in the results presented later. On completion of the functionality test, the completed models were carried forward to the flexibility test. In this test, an attempt was made to form valid models of each pre-defined scenario of strategic manufacturing development.

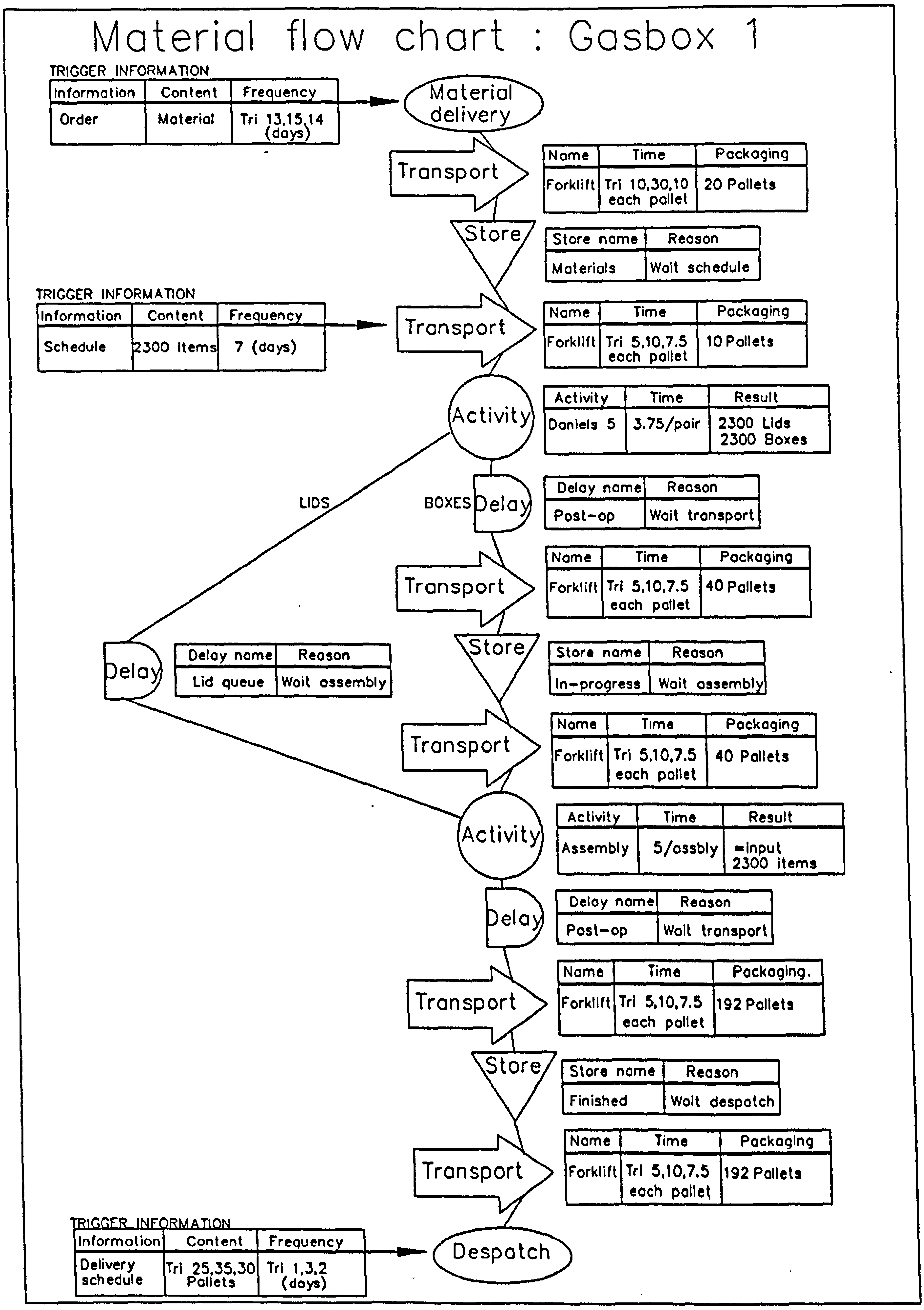


Figure 7.8: Material flow chart for a typical product family

Decision category represented	Strategic manufacturing developments to the test-bed company
Facilities	Purchasing a dedicated warehouse for storage of finished product stock.
Capacity	Increasing capacity of high volume product manufacture to deal with fluctuations in product demand. Production capacity increased by reorganising machine availability.
Span of process	Separation of primary product processing from the main manufacturing facility.
Processes	Automation of high volume product manufacture.
Human resources	Setting up employee quality circles to address issues of machine tool reliability.
Quality	Introduction of final colour inspection activity for all products.
Control policy	Introduction of a MRP II manufacturing planning and control system.
Suppliers	Purchase of all raw material from external suppliers on a lowest cost basis.
New products	Modification of new product introduction procedure.

Table 7.3: Representative manufacturing strategy scenarios

Facilities: Purchasing a dedicated warehouse for storage of finished product stock

Prominent structural change	Significant anticipated effect
Change in lorry service times	*Market based:* Reduced lead times
Change in materials handling and lorry loading procedure	*Manufacturing based:* Reduced materials handling utilisation
Financial acquisition of warehouse	*Financial based:* Decrease in ROI

Capacity: Increasing capacity of high volume product manufacture to compete with fluctuations in product demand

Prominent structural change	Significant anticipated effect
Change in production control rules	*Market based:* Reduction in lead time
Increases in the number of production machines	*Manufacturing based:* Reduction in machine tool utilisation
Stock reduction	*Financial based:* Improved cash flow

Span of process: Separation of primary product processing from the main manufacturing facility

Prominent structural change	Significant anticipated effect
Manufacturing awaiting the delivery of material in batches	*Market based:* Increase in lead time
External orders used to fill excess capacity of autonomous facility	*Manufacturing based:* Increased utilisation of processing machinery
Increase in quantity of products through facility	*Financial based:* Improved profit

Processes: Automation of product manufacture

Prominent structural change	Significant anticipated effect
Reduction in manpower	*Market based:* Reduction in product cost
Introduction of automated machinery	*Manufacturing based:* Utilisation of the automation
Financial acquisition of automation	*Financial based:* Reduction of ROI

Human resources: Setting up employee quality circles to address issues of machine tool reliability

Prominent structural change	Significant anticipated effect
Reduced waiting of parts at broken machines	*Market based:* Reduction in lead time
Improvement in machine reliability	*Manufacturing based:* Increase in press utilisation
Increase in employee overtime costs	*Financial based:* Reduction in profit

Table 7.4: Anticipated effects of strategic scenarios

Quality: Introduction of final colour inspection activity for all products

Prominent structural change	Significant anticipated effect
Additional inspection process in the manufacturing route	*Market based*: Increase in lead time
Additional materials handling activity	*Manufacturing based*: Increase in utilisation of materials handling equipment.
Purchase of inspection equipment	*Financial based*: Reduction in ROI

Control policy: Introducing of a MRP II manufacturing planning and control system

Prominent structural change	Significant anticipated effect
Use of stock based reordering	*Market based*: Reduced lead time.
Reduction of management involvement with scheduling	*Manufacturing based*: Reduction of manpower utilisation
Introduction of a M.R.P.II push system	*Financial based*: Reduction in cash flow

Suppliers: Purchase of all raw material from external suppliers on a lowest cost basis

Prominent structural change	Significant anticipated effect
Reliability of raw material deliveries	*Market based*: Reduction in delivery performance
Additional material acquisition activity	*Manufacturing based*: Utilisation of material acquisition facility
Removal surplus machinery	*Financial based*: Improved profits

New products: Modification of new product introduction procedure

Prominent structural change	Significant anticipated effect
Change in procedure	*Market based*: Reduced lead time
Employment of technical assistant	*Manufacturing based*: Utilisation of manpower
Employment of technical assistant	*Financial based*: Reduction in profit

Table 7.4: Anticipated effects of strategic scenarios (cont'd)

The final phase of experimentation was a presentation of the results gained for each modelling tool, to the participating personnel at the collaborating commercial suppliers. This was performed by despatching two written reports to each company. The first report described the context of the research, whilst the second described the experimentation and the subsequent results for the modelling technique supported by the company. The results of other modelling techniques were purposely withheld so as not to violate confidentiality agreements that some companies required on the preliminary results, and to ensure that responses were objective. The participating personnel from each modelling company were asked to comment on whether they felt that the performance of their modelling tool was a true reflection on the capabilities of the underlying modelling technique. Each company was then visited and discussions held with personnel, on the experimentation programme, the results gained, and their comments. Unfortunately, one company, Network Dynamics Inc., was based in North America and could not be visited. In this case the communication was in writing and the letter of reply from this company is given in Appendix C. Through this procedure the experimental work was validated and the capabilities of modelling techniques generalised, these results are presented in Appendix D and are summarised in Table 7.5.

The tables that are given in Appendix D are given a prefix letter 'D' when referred to in the main text. Hence, Table D.1 gives the results of attempts to model the strategic development scenarios with each modelling technique. In these tables the first column refers to the policy area being considered, the content of the policy area, and the representative scenario chosen in each case. The following seven columns contain the result recorded for each modelling technique against each scenario. In each case a brief summary is given of the changes made to the model of the company's existing manufacturing system. Attempts to validate these changes from a market, manufacturing and financial perspective are then made using the procedure described in detail in Section 7.2.1. In brief, 'X' indicates that a valid model could be constructed from the perspective under consideration, whereas 'O' shows that a valid model was not achieved. For example, in the case of DES the results show that the implementation of a warehouse could only be modelled from a manufacturing and marketing perspective.

Table D.2 shows the capability of each modelling technique to provide performance measurement information. The left hand column of these tables

Requirement set criteria		IDEF$_0$	IEM	DES	SD	QT	ABC	BP
Performance measurement	Lead time	X	X	X	X	X	O	O
	Delivery	O	O	X	X	O	O	O
	Volume	X	X	X	X	X	O	O
	Cost	O	O	O	O	O	X	O
	Contribution	X	X	X	X	X	X	O
	Utilisation	O	O	X	X	X	O	O
	Profit	O	O	O	O	O	X	X
	Cash flow	O	O	O	O	O	O	X
	Turnover	O	O	O	O	O	O	X
	ROI	O	O	O	O	O	O	X
Structural and infra-structural changes		M m F	M m F	M m F	M m F	M m F	M m F	M m F
	Facilities	X O O	X O O	X X O	X X O	X X O	O O O	O O X
	Capacity	O O O	O O O	X X O	X X O	O X O	O O O	O O X
	Span of process	O O O	O O O	X X O	O X O	X X O	O O X	O O X
	Processes	O O O	O O O	O X O	O X O	O X O	X O O	O O X
	Human resources	O O O	O O O	X X O	X X O	X X O	O O X	O O X
	Quality	X O O	X O O	X X O	X X O	X X O	O O O	O O X
	Control policy	O X O	O X O	X X O	X X O	X O O	O O O	O O O
	Suppliers	O X O	O X O	X X O	X X O	O O O	O O X	O O X
	New products	O O O	O O O	X X O	X X O	X X O	O O X	O O X
System transition	Time dependency	O	O	X	X	X	O	X
	Content change	O	O	X	X	O	O	X
Serviceability	Accuracy (1) %	80	80	63	60	64	No value	No value
	Accuracy (2) %	80	80	92	72	75	No value	No value
	Accuracy (3) %	80	80	94	88	86	No value	No value
	Build time (1) hrs	40	35	68	30	24	40	22
	Build time (2) hrs	68	59	116	50	32	No value	No value
	Build time (3) hrs	90	79	156	64	42	No value	No value
	Execution time min	0	0	21 (for 11 weeks)	Variable	1 (for 1 year)	0	0
	Credibility score	5	6	9	7	3	3	2

X / O: Supportive / unsupportive of requirement set criteria. M m F: Structure to consider market, manufacturing of financial perspective of change. (a): Assessed as a capability to provide some performance measures at a sub-system level. (b): Calculated as the average of the absolute differences, between the values provided by the model and the real system, for the performance measures given by a model.

Table 7.5: Summary of experimental results gained for individual modelling techniques

gives the measurement of concern, for example lead time, and how the measure was intended to be recorded within a model. The subsequent seven columns present the results of each modelling technique in the same general format as described above.

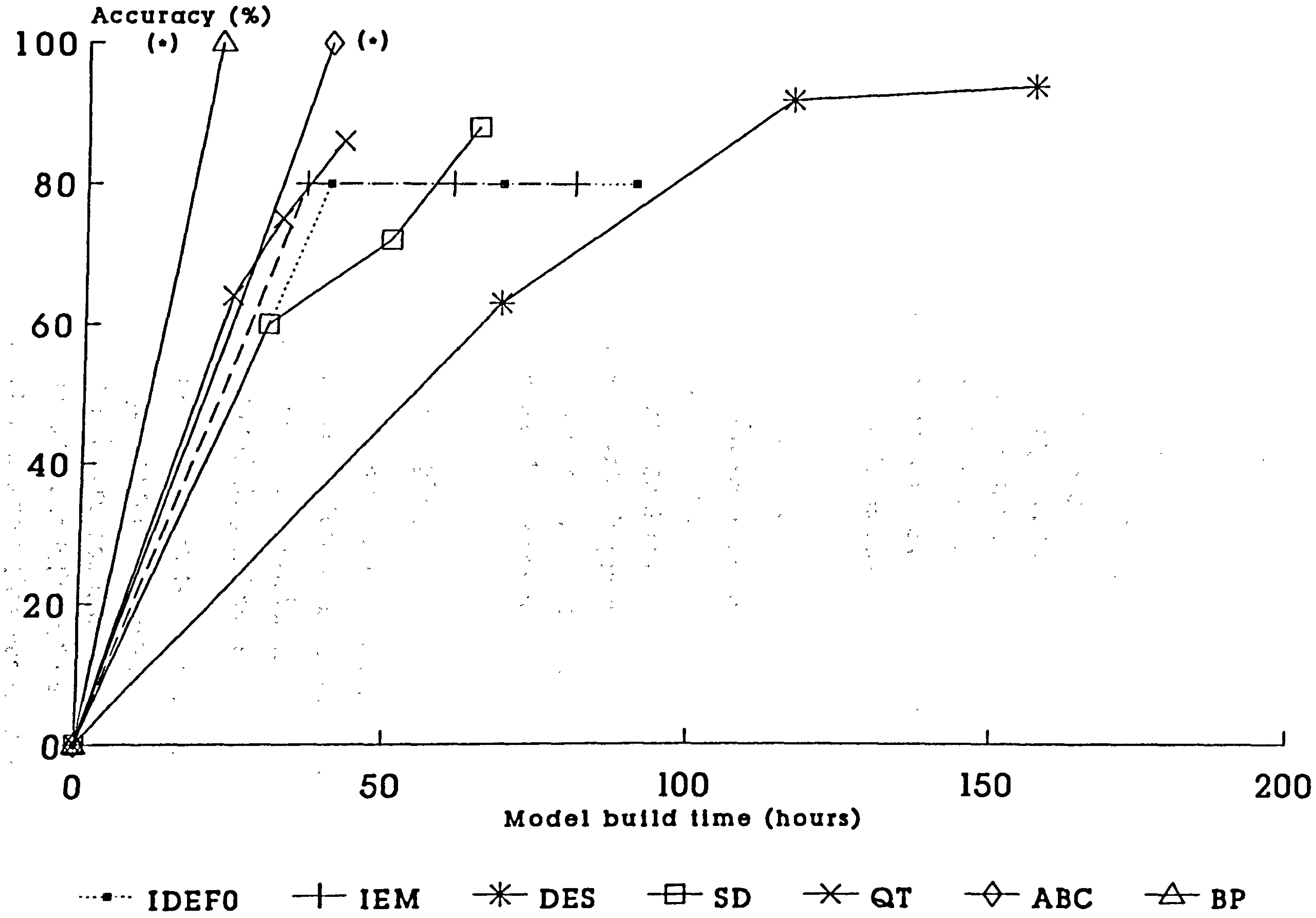
Table D.3 shows the capability of each model to exhibit time dependent behaviour, and to allow model configuration to be changed at an instant in time. Again, the layout of this table follows the basic format described above.

Finally, Table D.4 presents the performance of modelling techniques against the requirements of accuracy, credibility and model build time. To complement the values for model build time and accuracy, Figure 7.9 is constructed. It should be noted that the model build times recorded, are precisely the time taken in transposing the conceptual model into a working model. This time does not include data collection or similar interruptions, but does include time taken for data analysis specific to the modelling technique. For example, model build time with ABC included the time taken to determine cost drivers, and with QT and BP, the time to manipulate the data into an appropriate form was included.

7.3.2 Experimental errors

During experimentation, a number of potential sources of error were observed which could have influenced the results gained. This section briefly presents the most significant of these sources.

The model build time recorded for the DES modelling tool WITNESS was particularly long when compared to other modelling techniques. After experimentation with WITNESS there was a concern that the model build time could have been reduced if a model had been constructed which contained less detail and simpler graphics. To reduce detail a greater stochastic content could have been included in the model, meaning that the behaviour of some activities would have been represented by a statistical distribution. Such an approach would have required some time to be spent transforming data into a suitable form for the model, but would have probably given a reduced model build and execution time because of the reduced model content. Likewise, less complex graphics could have reduced model build time, though run time would not be affected as the modelling tool WITNESS allows graphics to be disabled during model execution. In support of the experiment approach adopted, discussions had been held prior to experimentation with personnel from AT&T ISTEL, the company supplying WITNESS. This was in an attempt to capture the flavour of



(•) = Accuracy measurement not appropriate, model complete.

Figure 7.9: Model build time and accuracy relationships

model building with DES in industry. The approach taken in model building was based on such advice. Therefore, whilst some potential reduction in model build and application time appears to exist, this was not felt to be significant by either the researcher or personnel from AT&T ISTEL, and is justifiably offset through the attempt to emulate industrial practice.

The model build time with ABC was much shorter than the researcher expected, this expectation being based on perceptions gained from manufacturing strategy practitioners. Hence, after experimenting with ABC there was a concern that the modelling process had been over simplified through choosing ten cost drivers and allocating as many costs as possible on this basis. Each individual cost could have been allocated using a cost driver. However, after careful consideration and discussions, with personnel from the company supplying the modelling tool, this approach was judged to be acceptable, as modelling was required at a strategic rather than operational level.

Finally, when working with BP, some financial information from the collaborating company was deemed sensitive and therefore unavailable to this study. This meant that estimates had to be substituted in the model, thus threatening model accuracy. This would have been unacceptable if the model was to be used for the purpose of evaluating manufacturing development for the collaborating company. However, as it was the technique rather than the company that was being assessed, this approximation of data was considered acceptable.

7.3.3 Application of analysis methodology

Analysis is necessary to deduce the performance of combinations of modelling techniques. This section applies the analysis methodology developed in Section 7.2.5, and commences by considering symbiotic relationships, and then synergistic relationships between modelling techniques.

Consider first symbiotic relationships, all possible combinations of techniques have been considered by the following process. First, all possible combinations were established, and then assessed as proposed in Section 7.2.5. These results were then sorted in terms of the total capability offered by a combination, and showed that no combinations of modelling techniques fulfil all the requirements of manufacturing strategy evaluation. Some combinations though, only narrowly missed fulfilling all these requirements, and in each case the contentious requirement was in the policy area of control. An investigation into this issue revealed that it was caused through attempting to evaluate the effect of a 'push' manufacturing control rule on cash flow. The modelling technique of SD and DES could equate a change of control rule to a change in product stock, but lacked the structure to calculate cash flow. However, BP could provide a measure of cash flow, but because a manufacturing system is only considered at a superficial level, the control rule could not be evaluated. This reflects the weakness of assuming a symbiotic relationship, as when a synergistic relationship is reviewed, then issues such as this are resolved.

Further analysis has then considered synergistic relationships. Using the hierarchical approach developed in Section 7.2.5, each relationship in the hierarchy was considered where appropriate. However, on completion of this analysis some redundancy was apparent amongst the successful combinations. This redundancy was exposed by identifying instances where a combination of modelling techniques offered no greater functionality, than the same combination with a particular technique omitted. In such situations the redundant modelling technique was identified and removed from the combination. The combinations that satisfy all the requirements of manufacturing strategy evaluation with no redundancy were ABC and BP forming a synergistic combination with either DES or SD.

7.4 DISCUSSION OF RESULTS

The previous section has described the execution of the experimentation programme and presented the subsequent results. This section discusses these results and draws out conclusions on the suitability of individual and combined modelling techniques to the role of manufacturing strategy evaluation.

7.4.1 Individual modelling techniques

Table 7.5 shows that none of the generic modelling techniques satisfy all the requirements of manufacturing strategy evaluation. This section summarises the capabilities of each generic modelling technique and focuses on the limitations in each case. For each modelling technique, the discussion is structured to consider assessment of structural and infrastructural changes to a manufacturing system, performance measurement, assessment of system transition, and serviceability.

IDEF$_0$

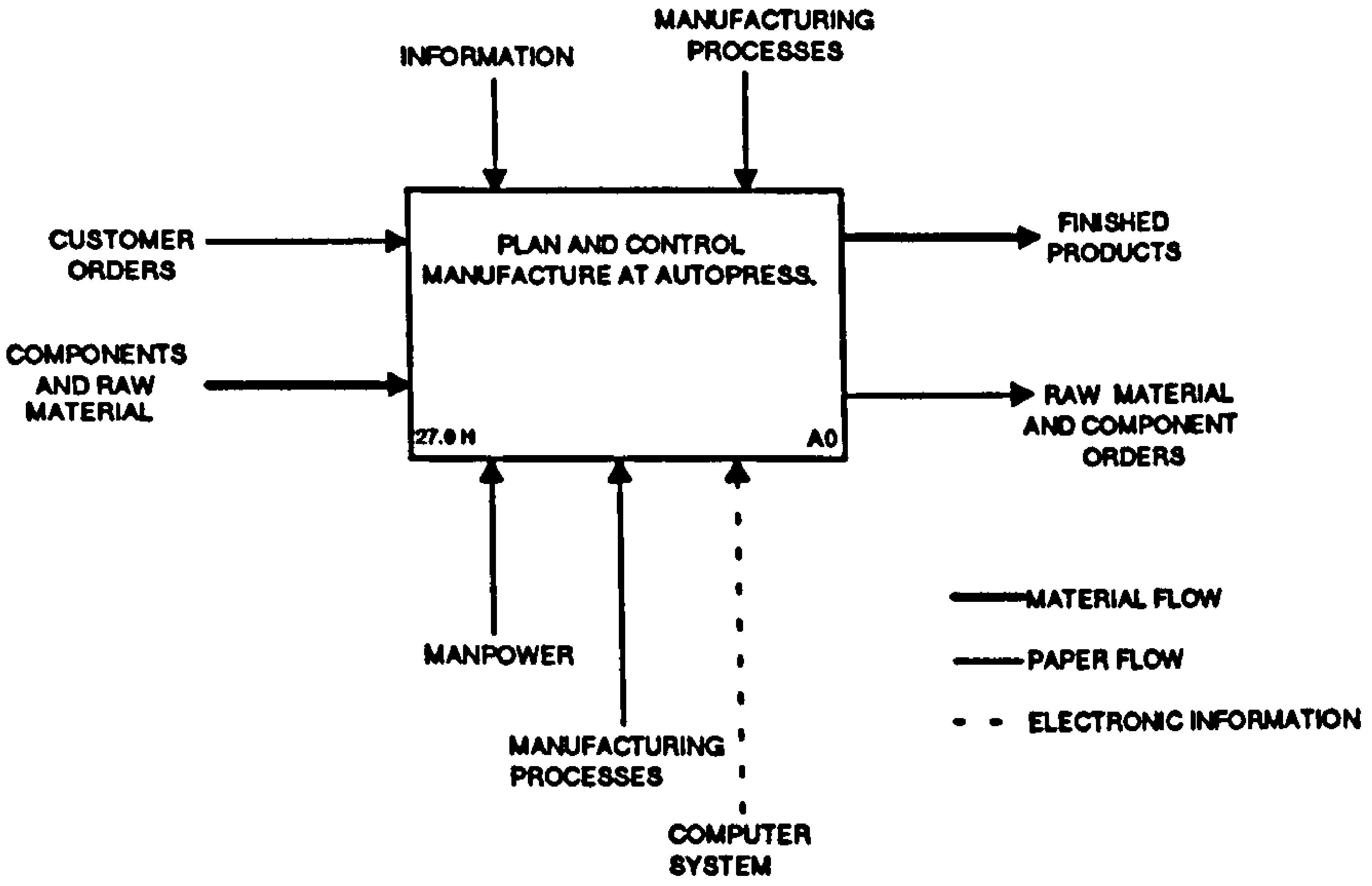
The IDEF$_0$ technique enables the construction of a form of flow chart that illustrates the activities resident within a system. This representation is characterised through a specific diagrammatic syntax and a hierarchical structure (decomposition) for illustrating varying levels of detail in a systems description (Section 3.4.4). The modelling tool chosen to represent $IDEF_0$ in this study is DESIGN/IDEF (Section 7.2.4). A portion of the $IDEF_0$ model produced using this tool is given in Figure 7.10. DESIGN/IDEF automates the drawing of an $IDEF_0$ model and also provides some mathematical functionality. This functionality allows numerical attributes to be assigned to each activity in a system. These attributes are then aggregated to one value at the highest level of the hierarchical structure. Although strictly $IDEF_0$ contains no mathematical features these have been considered as this increases the potential of the technique (Section 6.3).

Table D.1 shows that the flexibility of $IDEF_0$ is poor, and this can be attributed to the inflexibility of the mathematical functionality of DESIGN/IDEF. $IDEF_0$ is capable of expressing many of the strategic development scenarios under consideration, however DESIGN/IDEF cannot relate such an expression to a valid change in model behaviour. For example, the change in the manner by which material is routed around a system can be altered from an activity called push to one called pull, though this cannot be transposed to an effect on lead time. The main reason for this lack of functionality is that interactions between activities are not accounted for in the mathematical model. This issue is explored further when discussing accuracy below.

Performance measurement capabilities are illustrated in Table D.2 and consist of lead time, volume, and the contribution of each activity to these measures. However, the user needs to be cautious as to the accuracy with which these means are provided, as also discussed further below.

The time dependent behaviour of a manufacturing system cannot be represented by $IDEF_0$; an $IDEF_0$ model is a snapshot of the content and configuration of a system at an instant in time, and this remains the case even if the numerical functionality of DESIGN/IDEF is considered. A pseudo view of time dependent behaviour of a manufacturing system can be gained by constructing a series of models at sequential time instances. This method is generally referred to by modelling practitioners as 'time slicing'. Likewise, to complement this approach, time averaged numerical values can be input into a DESIGN/IDEF model to represent the time dependent behaviour over each time phase. However, this approach is limited, as the history of a systems behaviour cannot be accumulated

Manufacturing system description at the highest level:



Manufacturing system description decomposed to a second level:

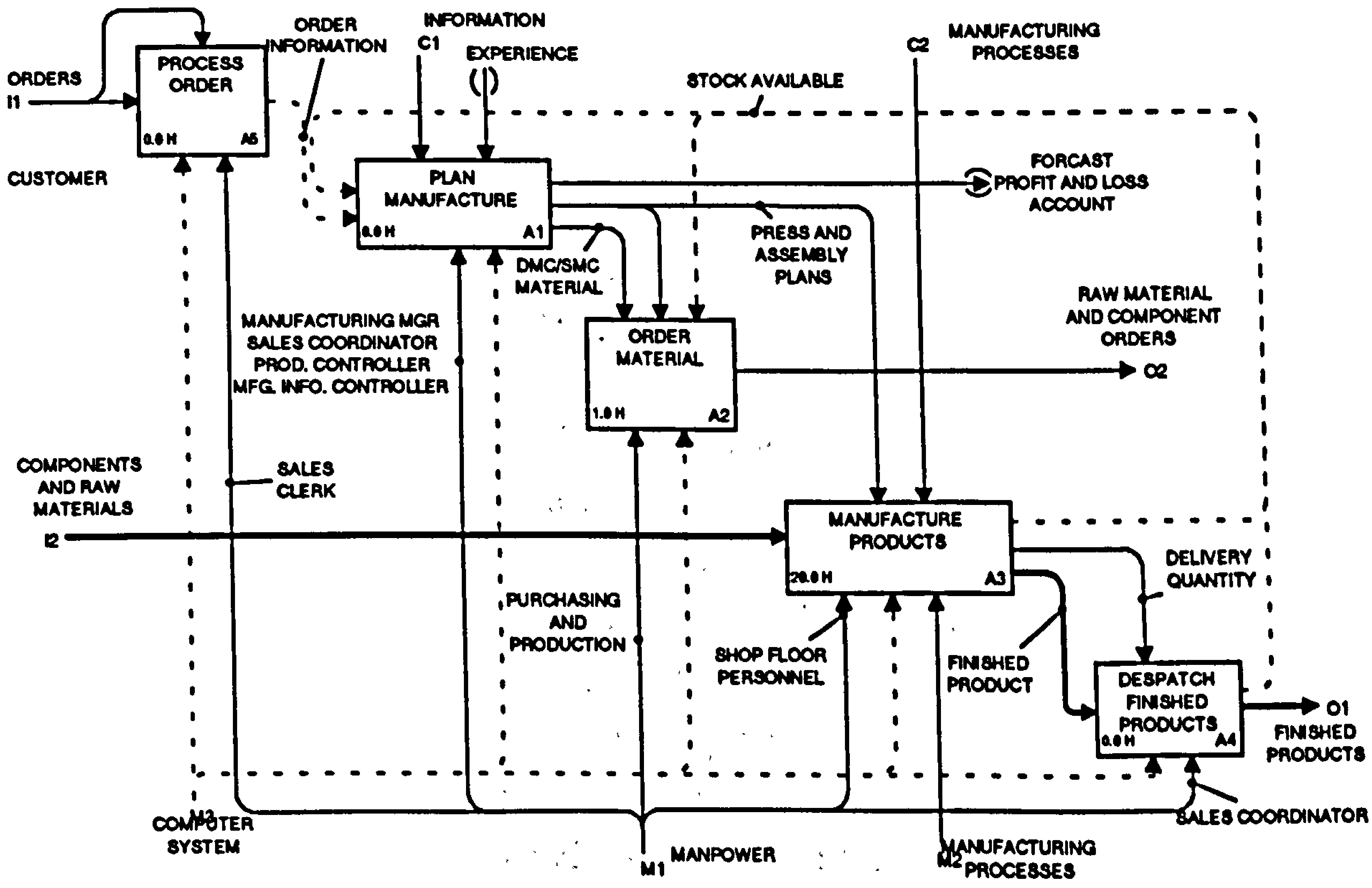


Figure 7.10: A portion of the IDEF$_0$ model of the test-bed company

as time phases are executed, and hence cannot be used to influence the behaviour of successive time phases.

Serviceability results of $IDEF_0$ are given in Table D.4 and Figure 7.9. Particularly intriguing in these results is the relationship between accuracy and model build time. $IDEF_0$ showed a relatively good model accuracy, though this accuracy appeared to be independent of model size. On further investigation, the reason for this phenomena appeared to be that although the level of detail increased as a model was developed, the nature of the conceptual model meant that the quality of information remained constant. Hence, the model accuracy remained constant. This may not have occurred if such a valid conceptual model had not initially been constructed. If only a coarse conceptual model had been constructed then, as the $IDEF_0$ model was decomposed to increasing levels of detail, more precise information about the real system may have been revealed. In this sense the mathematical capability can be used as a mechanism to capture and refine, through decomposition, the model builder's anticipation of a system's content.

The discussion above raises the question as to why, if $IDEF_0$ provides a data capture mechanism, is there a discrepancy of 20% between the values of performance gained from the model to those of the real system? This can be explained, along with the difficulty in producing valid changes in model behaviour during the flexibility test, through considering that the conceptual model contained a description of the content, characteristics and interactions of the manufacturing system at the test bed company. Such interactions are described in the $IDEF_0$ model by 'control arrows', but these are not transformed into a contention between activities in a model, and hence do not reproduce the delays and queues in product manufacture associated with many manufacturing systems. Some compensation for queue times was introduced in the DESIGN/IDEF model, because generally the manufacturing system was treated at a departmental rather than individual machine level, and corresponding lead times rather than process cycle times were used. However, this failure to model the factors which caused queues and delays meant that the results of a modification to a model were often invalid.

The DESIGN/IDEF modelling tool featured an ongoing calculation facility so that model execution time was effectively instantaneous.

Considering credibility, the diagrammatic syntax did raise some issues because to 'read' a model the 'reader' has to be conversant in this syntax. This initially caused some confusion when presenting and discussing models with personnel at the test-bed company. However, once personnel were conversant with this syntax a credibility score of 5 was recorded.

In conclusion, the principal limitations revealed through the experimentation programme were mainly concerned with mathematical functionality. If this functionality is ignored, then it can be concluded that IDEF_0 provides a strong mechanism for illustrating the activities in a system, and their interactions, at an instance in time. The problems with the numerical features are that the mathematical functionality is only superficial.

Integrated Enterprise Modelling

IEM techniques have been designed to bridge the features of IDEF_0 and less abstract techniques such as material flow charts (Section 3.4.4). A representative tool in this case is EM (Section 7.2.4), and a portion of the EM model of the test bed company is shown in Figure 7.11. The performance of this technique is very similar to IDEF_0 in many ways, with only the factors of model build time and credibility being distinct. These are discussed as follows.

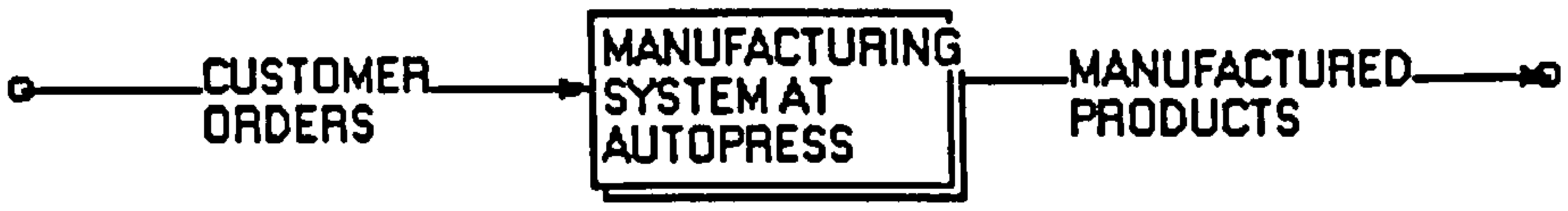
Compared to IDEF_0, IEM modelling with EM provided a model that could be termed less abstract, as the modelling syntax was more easily related to the real system. As a consequence, models were understood and better accepted by personnel at the test-bed company. Furthermore, the relaxed modelling syntax constraints meant that model building was faster. These distinctions are clearly apparent in the results where model build time is generally faster with EM and the credibility score was better at 6 (Table 7.5). However, this relaxation in syntax did mean that there was less distinction between, for example, information controls on an activity and information processed by an activity. In this sense IDEF_0 could be considered to provide a richer system description.

The results for IEM and IDEF_0 are similar in many respects, with only model build time and accuracy values differing significantly. While other differences do exist, when taken in a broad context of models, as with this study, these differences are insignificant.

Discrete Event Simulation

DES models attempt to emulate the time dependent behaviour of a real system by acting through the activities that occur in the real system (Appendix A). As discussed in Appendix A, invariably, the number of activities will be rationalised to improve modelling efficiency, and the model execution time is reduced by

Manufacturing system description at the highest level:



Manufacturing system description decomposed to a second level:

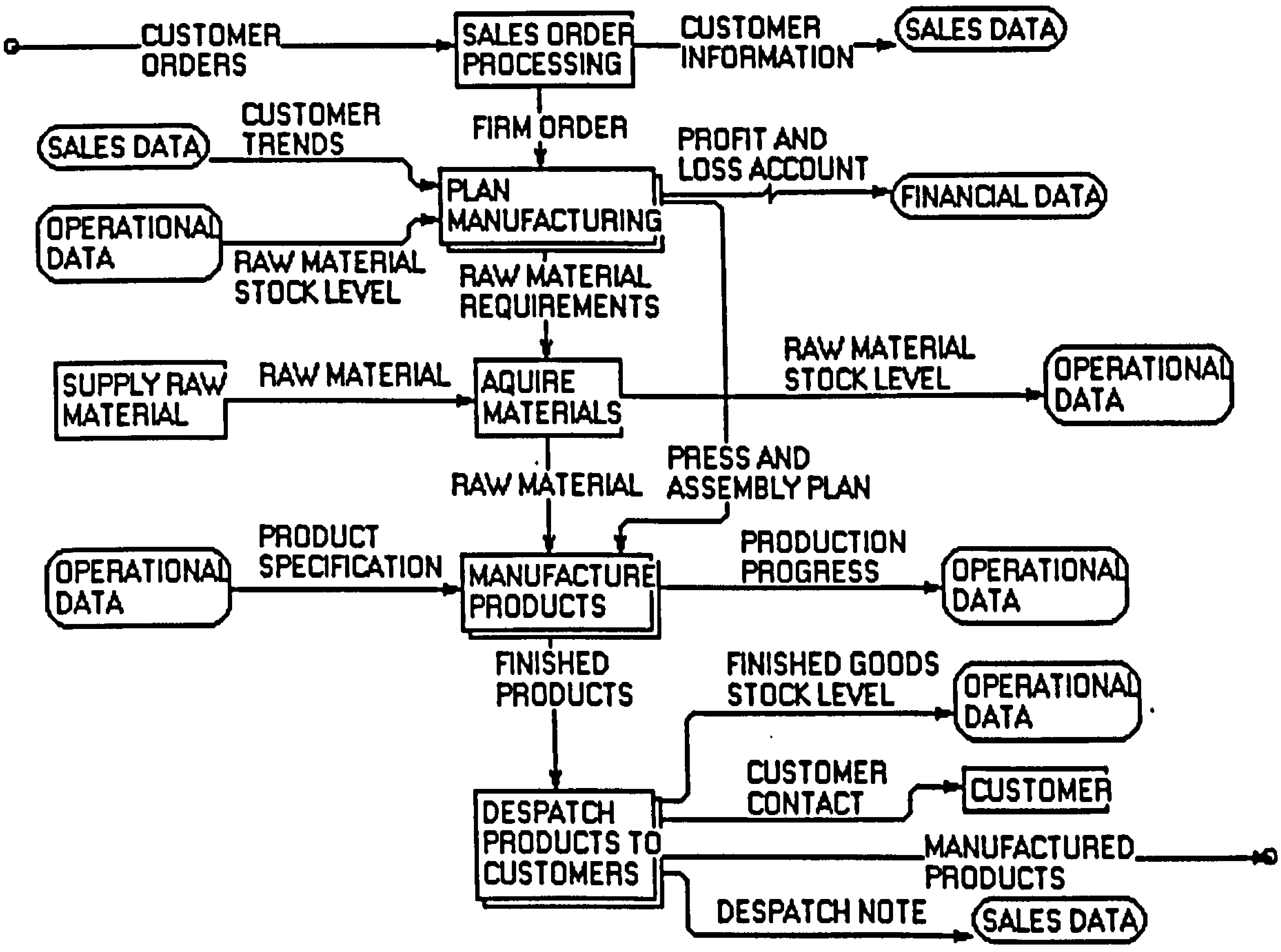


Figure 7.11: A portion of the EM model of the test-bed company

approximating actual activities to discrete events, time is then scaled down, and skipped forward according to an event list.

Table D.1 shows the flexibility of DES. Most aspects of the strategic development scenarios could be incorporated into the WITNESS (Section 7.2.4) model. The most significant limitations were when manufacturing system developments that manifested predominantly as changes in financial performance were being considered. This potentially contentious observation is discussed in more detail below when considering performance measures. A second limitation was apparent where information availability to an activity, or information processing issues, had some effect on the flow of materials. For example, the consequences of an additional order processing activity on product lead time had to be addressed by incorporating an additional 'machining process' to cause a delay in the flow of materials. However, after discussions with practitioners, it became apparent that this limitation was concerned with the modelling tool, which inherently focused the modeller on shop floor material flow, rather than the modelling technique.

The focus of the performance measurement capabilities of DES are illustrated in Table D.2. This technique focuses on product flow and can provide product lead time, delivery, and volume, along with resource or process utilisation and contribution. However, there is limited capability to provide financial based performance measurement information, an issue that caused contention with some modelling practitioners.

Financial performance values can be provided by the WITNESS modelling tool, however this does not mean that DES is focused at providing this facility and it is important to appreciate the modelling mechanisms that are being intertwined. The financial values are provided by encapsulating and integrating the structure of a financial model into the WITNESS computer package. The DES and financial models are then executed simultaneously. This situation can be more clearly explained by considering the operation of a non-computer based DES model, such as an activity cycle diagram (Carrie, 1988). In this case a DES manufacturing system model may consist of machines, human resources, and product, the movement and interactions of which are carried out manually. If financial measures are required from such a model, then calculations have to be carried out independently, based on information from the model. Hence, while financial performance measures can be provided by a DES modelling tool, the

DES technique is focused at emulating the dynamic behaviour of a real system rather than financial modelling.

A DES model exhibits time dependent behaviour and can be re-configured at an instant in time, as summarised in Table D.3. For example, during experimentation, the DES model was modified to reflect the introduction of a new press facility at the collaborating company. The model was configured to carry out this change automatically, by re-routing products after several weeks of production had elapsed within the model.

Serviceability results of DES are given in Table D.4 and Figure 7.9. The time required to configure the WITNESS model of the existing manufacturing system was 156 hours. This is lengthy when contrast against the model build time of other modelling approaches. However, when consideration is given to the records kept of the model build activity, it is apparent that approximately one third of the model build time was taken by entering data and computer code, a further third was spent developing the computer model, and the remainder was spent developing and modifying the graphical animation.

The graphical animation provided a high value for credibility to be recorded for the DES model. However, it was found that the high level of graphical animation provided by the DES modelling tool had an intriguing effect on the amount of animation perceived to be desirable by personnel, in that it perpetuated, rather than fulfilled their expectations of animation. An example of this situation occurred when, during modelling, an iconic representation of a shop floor worker was shown in the model as wearing blue overalls. This model was criticised by some personnel at the manufacturing company because the worker, a charge-hand operator, should have worn overalls with a red collar! In contrast, the personnel had been quite content with a numerical value to represent workers in other modelling approaches. To some extent, these personnel were confusing improving model accuracy with an increased the level of detail within the model.

The amount of detail in a DES model appears to be high because it is easy to add such detail compared to other modelling approaches. In this sense DES encourages a modeller to build a more precise replication of the real system than do other techniques. As a consequence, the technique can appear to be 'data hungry'. Other techniques have inherent approximations that reduce model build time.

An accuracy of 94% was achieved when the performance of the completed DES model was compared to the real system. This was significantly better than most other modelling approaches and was hence independently assessed and subsequently supported by colleagues of the researcher and personnel from AT&T ISTEL, the supplier of WITNESS. It was generally felt amongst these personnel that an absolute limit on accuracy with DES, was with the inherent assumption that all real world activities can be approximated to a discrete event.

Model execution time was significantly slower than other modelling techniques, taking 21 minutes to execute the equivalent of 11 weeks. This time was recorded whilst the modelling tool was in 'batch' mode, an option where model execution takes place without graphical animation. The implications of this relatively slow model execution time are significant on model building time. If an error in model behaviour occurs at a particular run time, then the model will probably need to be executed several times to that run time during debugging. As model execution time increases then the time taken for debugging, and hence model building, also increases. For this reason the DES model was verified to the equivalent of 11 weeks of production. This particular time allowed model execution speed and accuracy to be assessed, without recording a large content of model build time that was based on model execution speed and hence computer hardware.

In conclusion, experimentation revealed three significant strengths of the DES modelling technique. Firstly, the technique can be applied to evaluate a wide variety of changes to a system. Secondly, the technique can provide accurate information on the dynamic performance of a system. Thirdly, by computer animation of manufacturing system operation, the models produced by this technique have good credibility. The most predominant limitation of DES was found to be the time taken to build and execute a model, recorded as considerably longer than for other modelling techniques in a similar situation.

System Dynamics

As described in Appendix A, SD represents the progress of materials or information through a system as a continuous flow. A system is described in terms of 'resources' which flow through a variety of 'states' according to 'rates'. An example of a resource is a product family, a state could be work in progress stores, and rates could be a representation of machines. Once the content of a system is defined a mathematical expression is constructed to link rates with states. This expression is then executed at various time intervals and performance of the system is recorded.

Experimentation with STELLA (Section 7.2.4) revealed that SD is inflexible in some situations. During experimentation and discussions with practitioners it became apparent that this limitation is caused by the inherent approximation that manufacturing systems can be represented by continuous product flows; the severity of this approximation is dependent on the detail to which a system is being modelled. For example, the SD model in the study could not cope at its lowest level of detail, with the sequencing of products. However, at a more general level of model detail or aggregation, complex issues such as materials control rules, could be evaluated. Hence, this does encourage the model builder to view a system at a high level of aggregation.

The performance measurement capabilities of SD are given in Table D.2. As with DES, a SD model focuses on product flow and can provide product information on lead time, delivery, and volume, along with element utilisation and contribution. However, as discussed previously for DES, SD focuses on the dynamic behaviour of a real manufacturing system, and financial performance measures are gained by encapsulating and integrating a financial model within the SD modelling tool.

A SD model exhibits time dependent behaviour and the model content can be re-configured at an instant in time, as summarised in Table D.3. As discussed below, the size of the increment by which time advances is pivotal in determining the precision of model behaviour and execution time. A change to manufacturing systems content can be modelled by, for example, incorporating a pulsation in a flow. This pulsation can directly represent product manufacture, or indirectly influence production by representing a resource that is required for flow to commence.

Serviceability results of SD are given in Table D.4 and Figure 7.9. The model execution time with SD can be varied to reflect either a priority for either precision in model behaviour or shorter model execution time. This is achieved by altering the time increment value of 'DT', in the STELLA package. A smaller value of DT causes the mathematical expressions within the model to be calculated more frequently in a time period. As a consequence more values of model behaviour are available allowing, for example, greater precision in constructing graphical outputs. The trade-off in this case is that the computer is required to perform many more calculations per time period, and hence model execution time is longer.

The value of DT was particularly critical if elements of a model were described as having a discrete, rather than continuous behaviour. In this case, although an activity may be described in a discrete manner, the state of an activity is only considered for update by the model at instances of DT. Hence, a discrete activity may be effectively complete after a portion of a DT time increment, but the state of the activity will only be changed after the full time increment has elapsed. For this reason, discrete elements were purposely avoided in the experimental models. In all cases discrete manufacture was approximated to a rate of product flow. A further advantage of this approach was that it was felt to better capture the philosophy of SD modelling, as described by Forrester (1958).

The credibility of the SD model was significantly influenced by the graphical representation of the test-bed manufacturing system as a 'pipe diagram'. This diagram could be animated to show flows and the levels of stocks in a system. Generally this was well received by personnel at the manufacturing company, though a prominent feedback was that an iconic representation that better reflected the activities within manufacture would have been favoured. Furthermore, a second issue with credibility occurred because product flows needed to be modelled separately, and with the SD modelling tool a number of flows cannot be routed through the same activity. This can be overcome by representing a machine that receives several product flows, as several machines that are linked in such a way that they behave as one machine. This caused some duplication and confusion in the graphical display.

In conclusion, SD is relatively flexible if the model builder can approximate the effect of a development into a constraint on product flow. The predominant concern is that model accuracy and flexibility is limited by the inherent approximation of product manufacture to flows.

Queuing Theory

As described in Appendix A, QT is based on a mathematical determination of a manufacturing systems performance. The technique consists of a number of mathematical expressions of a standard form. These expressions are then populated with information about the characteristics of the manufacturing system being modelled. Execution of these equations then provides values on the predicted performance of the manufacturing system.

The recorded flexibility of QT is given in Table D.1. During experimentation a number of limitations were apparent, for example it was particularly difficult to consider control policy decisions, as the rules concerning material flow between activities are limited to percentage based routing information. Likewise, the technique was limited when modelling conditional situations such as linking the behaviour of a part to the conditions of the system. For example, if a queue is too long when parts arrive at a machine, then some of them may be re-routed, but with QT there is a need to estimate the number of products being re-routed rather than setting up the conditions for such re-routing to take place. It was also apparent that while the modelling tool MPX (Section 7.2.4) could be used to address structural changes to a manufacturing system quite easily, with many infrastructural changes the researcher needed to estimate the effect of the change on product and material flow. However, this was felt to be a reflection on the characteristics of MPX introducing the model builder at a shop floor level, rather than an inherent limitation of QT.

The performance measurement capabilities of QT are given in Table D.2, and it is clear that MPX is focused at the analysis of product and material flow within a manufacturing system. Consequently, product volume and lead time performance measures are well supported. However, in this case the volume required is actually set as an input parameter for the model. If with the manufacturing system capacity specified, the value of product volume required cannot be achieved during the model execution period, then model execution will halt. The user then has to adjust some of the model's characteristics in an attempt to set-up an acceptable condition for model execution.

A QT model provides performance values on the basis of steady state conditions within a manufacturing system. Hence, as summarised in Table D.3, the transients associated with the start-up or major disturbances to a manufacturing system are not considered. Likewise, a model cannot be reconfigured at an instant in time to reflect a change in manufacturing system content. A time slicing approach, as formerly discussed for $IDEF_0$, was attempted during experimentation. However, as with $IDEF_0$, QT does not account for system history. For example, the stock built up at the end of one time slice, is not considered in the subsequent time slice. This issue is a concern with the supplier of the QT modelling tool, as illustrated in the response from Network Dynamics Inc., given in Appendix C.

The QT modelling tool MPX gave relatively accurate results in a very short time, as shown in Table D.4 and Figure 7.9. Within 24 hours of model building a reasonably accurate model was constructed, and of this time, a considerable amount was actually spent converting the information describing the characteristics of the real system into an appropriate statistical form. The completed model gave an accuracy of 88% when compared to the real manufacturing system. Furthermore, this model did not include material handling characteristics, the inclusion of which may have improved the accuracy further. At this stage however, the model was becoming difficult to expand, as the limitations of QT required an increasing number of assumptions to be necessary. For example, shift patterns or specific labour could not be assigned to activities. Likewise, there is an inability to assign different labour to a set-up activity rather than an operating activity. Similar constraints were revealed with products, for example, no priority could be placed on the production of particular products. This limitation was particularly apparent in the industrial study where one short lead time product, was always given priority on manufacturing operations in the real system, but a similar situation could not be achieved in the model.

In credibility tests, the MPX technique scored relatively low. Discussions revealed that this was primarily an issue with the difficulty in describing the model operation without some form of graphical animation. Finally, the MPX modelling tool performed the model execution· calculations almost instantaneously.

In conclusion, there are a number of concerning limitations with the QT modelling technique. The predominant concerns are that performance measures are given for conditions of steady state system behaviour, that the inherent approximations restrict the depth and breadth to which a manufacturing system can be modelled, and that credibility is weak because graphical animation cannot be provided. The advantages are that a reasonably accurate model can be constructed relatively quickly.

Business Planning

Business planning techniques focus on giving information that describes the financial performance of an organisation, and consists of a series of projected financial statements about anticipated company performance (Appendix A).

Initially BP appeared to be flexible and able to consider a wide variety of manufacturing scenarios relatively quickly. However, as experimentation proceeded it became apparent that the researcher had to carry out considerable synthesis and estimates to provide data of a sufficiently high level for the model. For example, information about the performance of the test-bed manufacturing system, such as product lead times and costs were required to be entered into the model. After discussions with vendors of business planning tools, this characteristic appears to be typical of this form of model and not specific to the modelling tool used in this study. Hence, valid flexibility of BP was limited, as shown in Table D.1.

The performance measurement capabilities of BP, as shown in Table D.2, are predominantly the financial measures of profit, cash flow, turnover, etc. Hence, stock reduction, a change in lead time, or debt payment timing, can be directly calculated as an improvement in cash flow. Likewise, manpower quantities and payment rates can exist in a model, and consequently a change in manpower within the organisation can be equated to such measures as a change in profit. As noted above by the requirement to introduce lead time and cost, manufacturing or market based implications of a development are not considered.

The BP technique exhibits time dependent behaviour and allows consideration of a change in content of a manufacturing system, as summarised in Table D.3. For example, during experimentation a change in fixed assets at a specific date was introduced into the BP model. Furthermore, a sequence of changes to the model could be considered, along with associated funding to represent a manufacturing strategy. The sensitivity of these investments could then be tested against, for example, sales growth or increases in loan interest rates.

With serviceability, the time taken to build a complete model was 22 hours, as shown in Table D.4 and Figure 7.9. As also highlighted later with ABC, a valid BP model is based on a financial convention and hence it is inappropriate to consider an issue of model accuracy. During experimentation, most of the model build time was spent interpreting standard accounting information into an appropriate form. However, approximately 30% of the features of the modelling tool were unused, and not necessary for this study. Examples of such information are royalties and the company's financial arrangements. It is felt that a more precise modelling tool may have reduced model build time.

In credibility tests the BP technique received low scores relative to other modelling approaches. It became apparent from discussions with the participating personnel, that this score was caused by a lack of graphical animation representing the structure of the model. Furthermore, some employees were sceptical as to how realistic the predictions of the model were. For example, the model could be configured to show a 100% increase in the throughput of the manufacturing system without further capital investment, even though such a scenario was just not possible within the test-bed company.

The computer based BP modelling tool (Section 7.2.4) featured an ongoing calculation facility so that model execution time was effectively instantaneous.

In conclusion, the strength of BP is that it provides a business perspective of manufacturing developments. The predominant weaknesses are that valid flexibility and credibility are limited because the capabilities of a manufacturing system are only superficially considered.

Activity Based Costing

The principle of ABC is to precisely apportion the costs of an organisation to the products packed or services provided (Appendix A). The approach to model building with ABC is to divide overheads into activity based cost pools, and to assign these to products on the basis of consumption of their resources.

The flexibility of ABC is shown in Table D.1, and it is apparent that only developments where there is a significant effect on product cost can be evaluated.

Table D.2 shows that ABC is focused at establishing product and management information as to where costs exist in an organisation. Such is the extent of the bias to the latter capability, that the BPS-ABCM (Section 7.2.4) modelling tool does not actually provide an individual product cost, but a cost of producing a product family over a period of time. This information has to be augmented with sales volume data in order to provide individual product costs. Although strictly this is a limitation of BPS-ABCM, as subsequent discussions with practitioners revealed, it is not a constraint of the ABC technique and has hence been ignored as a limitation.

The ABC model provided a snapshot of the performance of a manufacturing system. However, there is a degree of pseudo-dynamic behaviour as in the calculation of individual product cost an average production rate is required.

Considering serviceability, as with BP, ABC is based on an accounting convention and as such it is inappropriate to consider model accuracy. In this case the issue is with the model validity, and this is achieved by ensuring that the assumptions that underpin a model are acceptable to personnel at the collaborating company. In this case 40 hours were required to reach this state, this being illustrated in Table D.4 and Figure 7.9. In this study the model build time was found to principally consist of two activities, data interpretation from the company accounts, and the choice of appropriate cost drivers. The management accounts at the collaborating company contained cost centres that were mainly convenient groupings of costs and not necessarily cost pools in the

ABC sense. Choosing the appropriate cost drivers was simplified by only attempting to accurately apportion larger costs and keeping the number of cost drivers down to a reasonably small number. In this case ten cost drivers were used. This approach is justified as the completed model was intended to support strategic decision making, as discussed in Section 7.3.2.

In credibility tests, the ABC technique scored relatively low. As with BP, this was found to be primarily due to the difficulty in describing the operation of a mathematical model without some form of graphical animation.

The computer based ABC modelling tool featured an ongoing calculation facility so that model execution time was effectively instantaneous.

In conclusion, ABC is focused at providing product cost, and has the flexibility to assess a range of strategic developments in terms of this measure. Contrary to some evidence in the literature, see for example Cooper (1990), this modelling technique can be applied in a reasonably short amount of time if restricted to a strategic level.

7.4.2 Combined modelling techniques

On the basis of the experimental results, the analysis methodology developed in Section 7.2.5, has been applied as described in Section 7.3.3. This section discusses the results gained from analysis, and draws a number of conclusions.

Firstly, two combinations of modelling techniques satisfy the requirements of analytical evaluation of a manufacturing strategy. Common to each combination are the financial modelling techniques of ABC and BP. An alternative is then provided, based on whether a SD or DES is considered. However, during the analysis a combination of QT and IDEF_0 was carefully considered before being discounted. The capabilities of this combination were such that the decision not to pursue this solution further requires an explanation.

QT and IDEF_0 were identified as potentially fulfilling the requirement set if a synergistic relationship was considered to exist between the two techniques. The mathematical functionality of the tool DESIGN/IDEF has been seen to be superficial. However, IDEF_0 itself has provided a rigorous mechanism for illustrating the contents, characteristics and interactions within a manufacturing system. Likewise, experiments showed that typically a QT model could be constructed in 1/3 of the time taken for a DES model of comparable accuracy. With the model execution time, under comparable conditions, being only 1% of the time taken by a DES model. During these comparisons it was very surprising to discover that when limits of model accuracy were explored, contrary to what was expected from the relatively large DES model, on average the QT model was only slightly less accurate.

There are however, a number of concerning limitations with QT. In particular, the performance measures are given for conditions of steady state system behaviour, and while the transition of a system can be modelled in time phases, this is crude as the system history has not been considered. The routing of parts through a system is approximated to a percentage rule, and cannot be dependent on conditional situations. Finally, there is a lack of graphical animation which limits credibility.

A thorough investigation was subsequently conducted as to how these limitations may be overcome. For example, the graphical features of $IDEF_0$ can be used to counteract the credibility issue with QT. However, the limitations in flexibility of QT are considerable, and this research has failed to establish how these limitations can be overcome whilst maintaining short model build times. This argument is supported through correspondence with Rajan Suri of Network Dynamics Inc., (Appendix C). Therefore, to conclude, a potentially valuable contribution exists in combining $IDEF_0$ and a powerful mathematical modelling approach such as QT, though a number of significant developments are required to enable such a combination to be realised.

Finally, $IDEF_0$ and IEM are absent in the combinations that fulfil the requirements set. These techniques did feature in a number of successful combinations, but in each case a combination was being formed with either DES or SD. In each case, if either $IDEF_0$ or IEM were discarded, the functionality of the combination was unaffected. Hence, it became clear that neither of these techniques were essential and were subsequently discounted.

7.5 CONCLUSION

The research in this chapter has critically appraised the support that generic modelling techniques give to the task of analytical evaluation of a manufacturing strategy. These techniques have been investigated using a rigorous experimental programme to apply contemporary computer tools at a collaborating industrial company. Practitioners who are knowledgeable of modelling have been used extensively to verify experimentation, generalise results, and to assist in interpretation of capabilities of modelling techniques from the performance of modelling tools. Although some minor concerns were highlighted with the experiments conducted, the results decisively show that none of these modelling techniques fully support the activity of manufacturing strategy evaluation.

Some modelling techniques, such as Activity Based Costing and Business Planning, do give the appropriate financial perspective of a manufacturing strategy. However, these techniques suffer from constraints such as a lack of manufacturing and market based information. Indeed in some instances, performance measures that are required as an output from an evaluation model have to be input into these forms of model. Similarly, modelling techniques such as $IDEF_0$ lack an appropriate numerical functionality. Conversely, Discrete Event Simulation, Systems Dynamics, and Queuing Theory techniques focus on material flow and have relatively high numerical functionality. This is particularly true of Discrete Event Simulation, which also has good credibility, though models can be slow to build and execute. Queuing Theory gives much shorter model build and execution times but fails to consider such issues as system transition and complex manufacturing control rules. However, these approaches have limitations when the financial impact of a strategy needs to be assessed.

The experimental results have been analysed in order to predict the capabilities of combining modelling techniques to form a modelling tool, and two combinations provide the necessary functionality. In both cases, Activity Based Costing and Business Planning are required to give the necessary financial perspective of a manufacturing strategy. Two combinations are then formed on the basis of including Discrete Event Simulation or System Dynamics.

The experimental approach taken for each modelling technique in this section, has been to form a hypothesis that the modelling technique fulfils the requirement set. This approach has meant that evidence about the limitations of a modelling technique, rather than capabilities, has had to be apparent. This approach has proved successful, as the conclusions above indicate.

To be critical of this research, it is important to recognise that this study has been based at one company, the generic modelling techniques have been represented by a relatively small number of modelling tools, and a number of experimentation concerns have arisen. Hence, there is a danger that the results gained are only true for the manufacturing system at which the experiments have been applied. However, this should be contrast against the thoroughness of the experimentation programme, the use of practitioners in generalising the results, and the significant differences in the capabilities of the modelling techniques.

Finally, the performance measurement facilities required by a strategy formulator include a need to assess product features, design flexibility and quality (Section 5.4.3). The work in Chapter 5 has argued that such measures can be provided indirectly by a model. Therefore, these measures have not been included in the requirement set on which this experimentation programme has been based, and hence have not been considered in this chapter. However, during the work described in this chapter, an opportunity arose to test the validity of the argument in Chapter 5. This was achieved by testing various models to see whether the desired performance measures could be provided indirectly. These tests were successful and supported the principles developed in Section 5.4.3.

The contribution of the critical appraisal, described in this chapter, is a comprehensive and in-depth knowledge about modelling techniques. From this knowledge, the principles can be formed of a modelling tool tailored to manufacturing strategy evaluation.

CHAPTER 8

FORMING THE PRINCIPLES OF A STRATEGY EVALUATION TOOL

The objective of the research described in this chapter is to form the principles of a modelling tool for the analytical evaluation of a manufacturing strategy. This objective is realised by establishing the most suitable modelling approach to manufacturing strategy evaluation on the basis of the critical appraisal of modelling techniques carried out in Chapter 7.

The first section of this chapter reviews the programme developed in Chapter 4 for this stage of research, and develops this programme on the basis of the results in Chapter 7. The second section summarises the capabilities of the favourable modelling techniques, and from this the third section chooses the most suitable modelling solution to the strategy evaluation task. The structure of the resulting strategy evaluation tool is then discussed. Finally, conclusions are drawn on the work conducted in this stage of research.

8.1 STAGE 4 RESEARCH PROGRAMME

Chapter 4 has argued that if possible, the principles of a modelling tool should be established from existing modelling approaches. The results of the critical appraisal carried out in Chapter 7 show that each of the seven generic modelling techniques has limitations when considered for the task of analytical evaluation of a manufacturing strategy. However, subsequent analysis has deduced that two combinations of modelling techniques do fulfil the requirements of this task. Common to both combinations are the modelling techniques of ABC and BP. The modelling technique ABC is required to allow the impact of a manufacturing strategy on product cost to be determined, whereas BP is necessary to provide a business perspective on the implication of a manufacturing strategy. Two combinations are then provided on the basis of whether SD or DES are chosen to complement ABC and BP. Therefore, as two combinations of existing modelling techniques satisfy the strategy evaluation task, research at this stage must focus on these.

Whilst the principles of a modelling tool can be based on either of the two combinations, in practice, only one approach is necessary. Therefore, a choice needs to be made as to which combination to develop as the modelling solution. As ABC and BP are common, a choice can therefore be made by ranking SD and DES in terms of suitability to the task of manufacturing strategy evaluation. The remainder of this chapter chooses a modelling solution on this basis.

8.2 CONTRASTING THE EXPERIMENTAL RESULTS OF DISCRETE EVENT SIMULATION AND SYSTEM DYNAMICS

As a precursor to choosing between SD and DES modelling techniques, this section examines the experimental results to clearly distinguish between the capabilities of the techniques, for each category of the requirement set.

8.2.1 Assessment of structural and infrastructural changes to a manufacturing system

Table 7.5 shows that the flexibility of SD and DES are similar, both are able to consider most aspects of manufacturing system development covered by experimentation. A common weakness was an inability to give the financial impact of a manufacturing strategy. Stating this limitation may appear to contend with some of the literature where financial performance measures are provided from such techniques. However, as argued in Section 7.4.1, such an approach gives a clear perspective of the capabilities of modelling techniques.

It was observed that SD did exhibit limitations when detailed system design was being considered. This initially became apparent when testing for model accuracy and build time, when an inability to appraise the sequencing of product families was highlighted. Towill (1993a) makes a similar observation, and cites Forrester (1975) for implying this when arguing, that a system under consideration has to be viewed from a "...very particular distance". He goes on to say that this is not too close to be concerned with the action of one single individual, but not so far away to be ignorant of the internal pressures in a system. Hence, a limitation with flexibility is exhibited with SD relative to DES.

8.2.2 Performance measurement

The limitations of DES and SD are comparable, with both techniques failing to support all the performance measures in the requirement set. Again, some contention arose in experimentation because by using the modelling tools it was possible to set up numerical outputs named after each of the performance measures of concern. However, as argued in Section 7.4.1, such capabilities are a reflection on the features of the modelling tools, and not the focus of the modelling technique.

8.2.3 Assessment of system transition

There are no distinct issues when considering system transition. During experimentation it was observed that the STELLA model could be configured to take account of the start-up conditions of a manufacturing system, for example, allowing product stock to be assigned to the queue before manufacturing processes. Such functionality supports a consideration of manufacturing system transition. However, it became apparent that such a capability is a reflection on the modelling tool, and could also be provided in principle with DES.

8.2.4 Serviceability

Serviceability differs from the other categories of the requirement set, because the limitations of modelling techniques are of a relative rather than absolute nature (Section 6.1). For this reason a strength in one technique can be perceived as a weakness in the second, and therefore care must be taken to avoid duplication when searching for distinctive performance. Hence, it is important here to focus at strengths and leave the corresponding weakness of each technique to be implied.

Consider first the issues of model build time and accuracy, the experimental results of which are summarised on Figure 8.1. Prior to appraising these results it is important to reiterate that it was not an objective of this study to investigate extremes of model accuracy during experimentation, rather as explained in Section 7.2.1, it was to explore model build rate at three stages of model construction. In this way a model build time to accuracy relationship was established for DES and SD. From these results there are clear distinctions between the capabilities of DES and SD, and these are apparent for both the model accuracy to build time gradient, and the maximum values of accuracy achieved.

Figure 8.1 shows that for SD, the model build rate is faster than for DES. Hence, for most of the range of accuracy considered, in a given amount of time a more accurate model could be constructed using SD than DES. An intriguing observation made during experimentation, was that model construction time with DES was significantly effected by the time taken to construct a detailed graphical

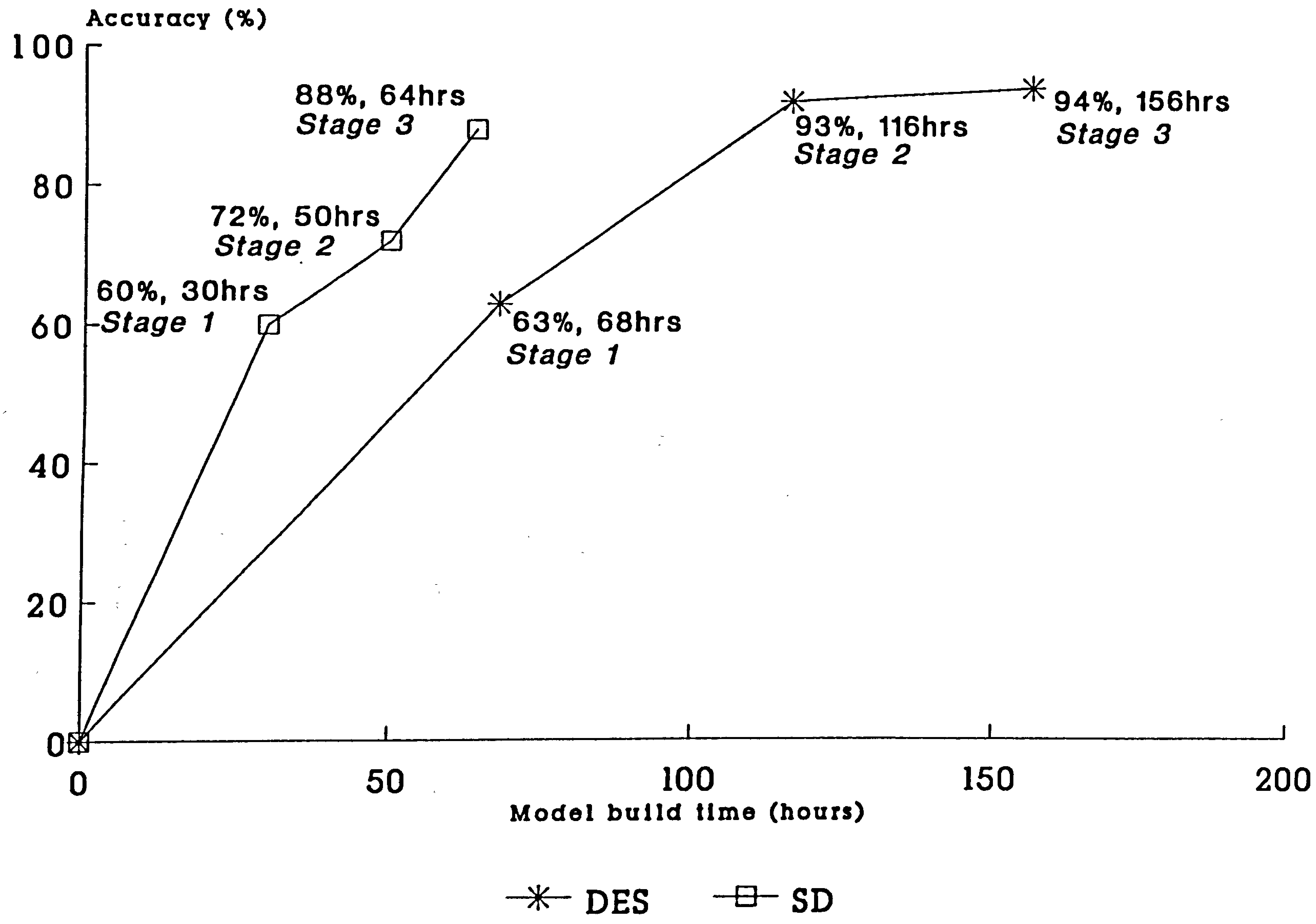


Figure 8.1: Discrete Event Simulation versus System Dynamics model build time and accuracy relationship

animation. Such work was felt to account for roughly 30% of model build time (Section 7.4.1), and furthermore SD was not effected in the same manner. An enlightening comparison between SD and DES can be gained by discounting the time taken in providing the graphical animation, and reducing the model build time associated with DES by 30% as illustrated in Figure 8.2. However, as this graph shows, the model build rate for DES is still slower than SD, thus demonstrating a fundamental distinction between the capabilities of the two modelling approaches.

Model accuracy has been observed to be higher with DES than SD in the final stages of model build. This observation is less meaningful than those for model build rate because, as mentioned above, it was not an intention to attain absolute limits of accuracy. If, for example, the profile for SD shown on Figure 8.1 is extrapolated it suggests that a model of 100% accuracy could be attained before that of DES. However, this is unrealistic because at the final stage of model build with SD, the model builder had reached a point where a considerable effort would be required to pursue further accuracy. The DES profile illustrates the effect of pursuing ever greater model accuracy, in that more and more effort is required to achieve ever smaller improvements. Model building with DES could have stopped earlier to give a similar profile to SD. However, model building continued because it was relatively easy to do so. Therefore, it can be concluded that, as Figure 8.1 shows, DES will provide a more accurate model where extremes of accuracy are considered.

To summarise the issues of model build time and accuracy, model construction is faster with SD for comparable levels of model accuracy, although DES will eventually provide a more accurate model. An explanation for the faster model build rate experienced with SD, is that discrete product manufacture is approximated to a flow, as discussed in Section 8.2.1. If this is the case, then it means that initially model construction is assisted, but subsequently restricted, by this approximation.

Considering the issue of credibility, which for the DES model was recorded to be higher than that of the SD model. This was achieved because the DES modelling tool provided an iconic representation of the real system that was less abstract than the equivalent SD graphical display. The modelling tools used in each case were felt to significantly influence the results received, with the quality of animation not wholly due to the underlying modelling technique. For example,

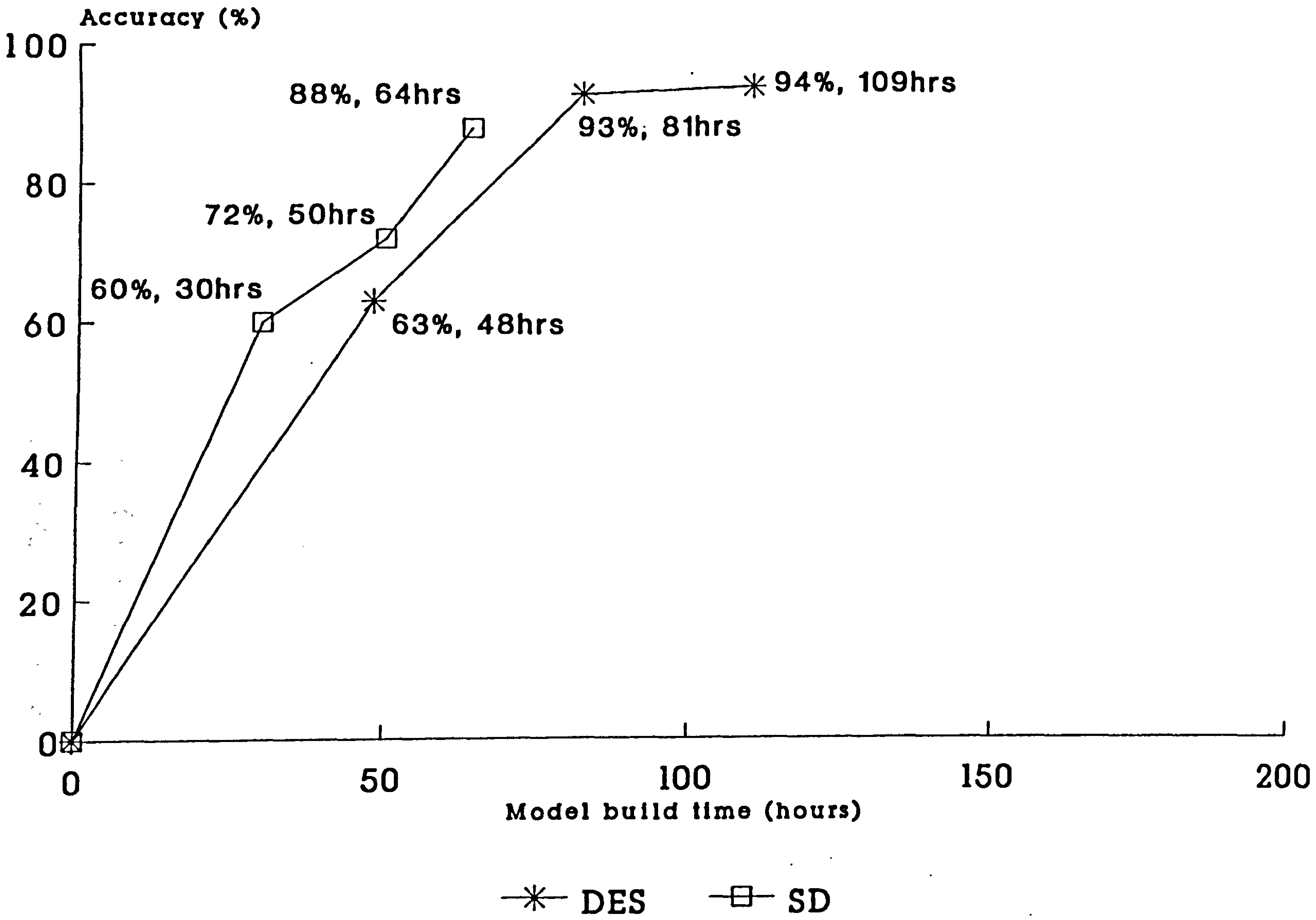


Figure 8.2: Modified profile of Discrete Event Simulation versus System Dynamics model build time and accuracy relationship

SIMON is an early DES modelling tool that initially lacked graphics (Carrie, 1988).

The underlying modelling techniques do, to some extent, enable animation to take place. Both DES and SD emulate the behaviour of a real system and can hence support the generation of some forms of animation during model execution. However, under closer examination, it becomes apparent that there is a distinction in the extent to which animation is supported in each case. With DES, discrete products can be represented individually because the technique can operate at such a level of detail, whereas SD is limited to representing product manufacture as flows. Therefore, irrespective of the graphical animation features of a modelling tool, there is a distinction in credibility between these two approaches because DES will enable a more detailed model to be created.

Finally, considering model execution time, SD was recorded to be faster than DES. A direct comparison is difficult because the model execution time with SD is dependent on the value of the time increment 'DT' (Section 7.4.1). The DES modelling tool could be used in a 'batch' mode where execution took place without graphical animation. This however differs from SD where the actual number of calculations performed in a time period can be reduced during model execution, providing a distinctive capability.

8.2.5 Summarising contrasting issues of Discrete Event Simulation and System Dynamics

The contrasting capabilities of DES and SD have been identified above and are presented in Table 8.1. The principal distinctions between these two techniques can be summarised as follows.

SD has the flexibility to address a wide variety of issues, it exhibits a relatively rapid model build rate and model execution time. However, because of the inherent approximation of treating a product as a flow, the depth of model detail, credibility, and absolute level of accuracy are less than for DES.

DES can also evaluate a wide variety of issues, to a low level of detail, with relatively high model accuracy, and good model credibility. However, the technique has a slower model build rate than SD, and the resulting model will take longer to execute.

Category of requirements	Discrete Event Simulation	System Dynamics
Structural and infrastructural changes to a manufacturing system	*Capability* • Considered most aspects of a manufacturing strategy represented by strategic scenarios. *Limitation* • Lacked structure to take account of financial impact of strategy.	*Capability* • Considered most aspects of a manufacturing strategy represented by strategic scenarios. *Limitation* • Lacked structure to take account of financial impact of strategy. • Incapable of considering detail system design such as sequencing of products.
Performance measures	*Capability* • Provides measures of product lead time, delivery performance, volume, contribution and utilisation. *Limitation* • Financial performance measures not provided.	*Capability* • Provides measures of product lead time, delivery performance, volume, contribution and utilisation. *Limitation* • Financial performance measures not provided.
System transition	*Capability* • Exhibits time dependent behaviour. • Can cope with change of model content and configuration at an instant in time.	*Capability* • Exhibits time dependent behaviour. • Can cope with change of model content and configuration at an instant in time.
Serviceability (Comments here are relative to the two techniques being considered).	*Strength* • Model accuracy. • Model credibility.	*Strength* • Model build time. • Model execution time; can chose between short model execution time or precision of results.

Table 8.1: Summary of experimental results for Discrete Event Simulation and System Dynamics

8.3 CHOICE OF MODELLING TECHNIQUES

The preceding section has highlighted the distinguishing issues associated with DES and SD. On the basis of these results this section chooses the most appropriate technique to carry forward to combine with ABC and BP to form a tool tailored to manufacturing strategy evaluation. In this case five issues are prominent from the work in the previous section, namely, model execution time, credibility, accuracy, build time and detail. A choice between SD and DES can be made by considering these factors in this order.

SD is initially favoured because of the shorter model execution times. However, this factor is dependent on the computer hardware on which a model is installed, and it is generally accepted that the performance of such hardware is being continually improved. Hence, improvements in the performance of computer hardware will themselves reduce the time taken for model execution. Whilst the execution time of both modelling approaches will be reduced, DES will benefit most significantly because of the associated larger model execution time. Therefore, the long term developments in computer hardware mean that this factor cannot be pivotal in the choice of a modelling technique.

The results show that DES supports credibility better than SD. This distinction has mainly arisen because DES enables the construction of a model to include more detail than SD. For example, a DES model can represent individual products in a queue before a machine, whereas a SD model will be limited to showing an accumulation of product flow. In this sense, higher credibility can be considered to be roughly proportional to an increase in model detail. On this basis however, the significance of the credibility issue depends on the level of detail necessary in a model for manufacturing strategy evaluation. This issue of model detail also arises when considering accuracy, and hence the credibility issue will be resolved, when accuracy is addressed shortly.

Model build time and accuracy present a dilemma; whether to choose an approach that provides faster model building rate, but to a lower level of accuracy, or a considerably slower model build, but eventually a better value of accuracy. A faster model build rate will mean that alternative strategies can be evaluated in less time. In this case SD consistently required less time to build a model, by approximately 30%, than the time taken for DES. However, if the model constructed is too inaccurate then the evaluation is worthless. SD is less accurate than DES, the experimental results show that the maximum accuracy achieved with SD is 7% less than the maximum value of accuracy attained for

DES. Unlike model build time, this distinction only becomes apparent in the latter stages of model construction, where the detail included in the DES is greater than the SD model. Therefore, a choice between model build time and accuracy can also be resolved by considering the level of model detail appropriate to manufacturing strategy evaluation.

Both accuracy and credibility of DES depends on building a relatively detailed model. Clearly, these benefits can only be realised if information available about the real system is itself sufficiently detailed. Indeed, if the information available prevents a model being sufficiently detailed to capitalise on the model accuracy and credibility, associated with DES, then SD is favoured because of shorter build times. Furthermore, the differences in flexibility between these techniques is dependent on model detail. Hence, the distinction between modelling approaches becomes pivotal on the level of model detail required in manufacturing strategy evaluation.

The literature holds little explicit guidance on the level of detail associated with a manufacturing strategy. Notable exceptions are authors such as Parnaby (1986) who cautions against becoming too overwhelmed in detail. However, Schroeder and Lahr (1990) have previously been cited for revealing that companies that undertake discussions at a general level, partly in the belief that strategy is not detailed in nature, often have a superficial outcome. Unfortunately, these authors give no guidance or clues as to what they consider an acceptable level of detail to be.

Some resolution to this situation is given by Mintzberg (1994) who sees that organisations often pursue what may be called umbrella strategies; the broad outlines are deliberate while the details are allowed to evolve within them. He does however go on to caution that details can eventually prove to be strategic. To place this caution in context, Quinn (1978) argues that a strategy must deal with unknowable factors. Therefore, it is apparent that a strategy should have a certain amount of robustness to some variances in details. Dealing with strategy in an umbrella fashion will also reduce the amount of detail considered by strategy formulators in practice, and hence strategy formulation is likely to be more manageable and the result easier to communicate within a company. On this basis, this thesis sees manufacturing strategy as a sequence and framework of deliberate actions that should be sufficiently robust to accommodate for some variance in detail, and indeed promotes the concept of tactical actions so as to assist in the management of the formulation activity.

This view of strategy favours the SD approach to modelling. The level of detail at which modelling is appropriate to manufacturing strategy evaluation is considered here to be such, that a distinction between SD and DES on accuracy and credibility cannot be pivotal. Hence, SD is most appropriate because of faster model build times.

A further benefit of SD is conjectured to be, that because the SD approaches force a modeller to consider a manufacturing system at an aggregate level, this will help to prevent the strategy formulation process becoming overwhelmed in detail. Invariably, this will lead to a criticism of inflexibility with SD, but this criticism itself may well reflect a practitioner who is taking an inefficient approach to strategy formulation.

In conclusion, this section has argued that SD is a more appropriate foundation on which to build a modelling tool for manufacturing strategy evaluation than DES. On this basis the complete principles of such a tool will be formed from SD, ABC and BP.

8.4 PRINCIPAL STRUCTURE OF THE STRATEGY EVALUATION TOOL

Section 8.3 has determined that the principles of a modelling tool for manufacturing strategy evaluation should be based on SD, ABC and BP. To complete the formation of these principles, this section describes how these modelling techniques could be integrated to form a modelling tool. This description is given by first declaring the required information outputs of the complete modelling tool, and then considering how each of the modelling techniques can contribute to these capabilities.

The information outputs of the complete manufacturing strategy evaluation tool, as illustrated in Figure 8.3, are the direct performance measures summarised in Table 5.1. These direct performance measurement outputs should be recorded against elapsed execution time, and could be presented as a time series profile of the form illustrated in Figure 8.4. To enable model configuration and execution a number of inputs will be necessary, as shown in Figure 8.3, the content of these inputs will become apparent later in this section.

The specific role of SD in the manufacturing strategy evaluation tool is illustrated in Figure 8.5. An SD model will provide the performance measurements of delivery reliability, delivery lead time, volume flexibility, activity utilisation and

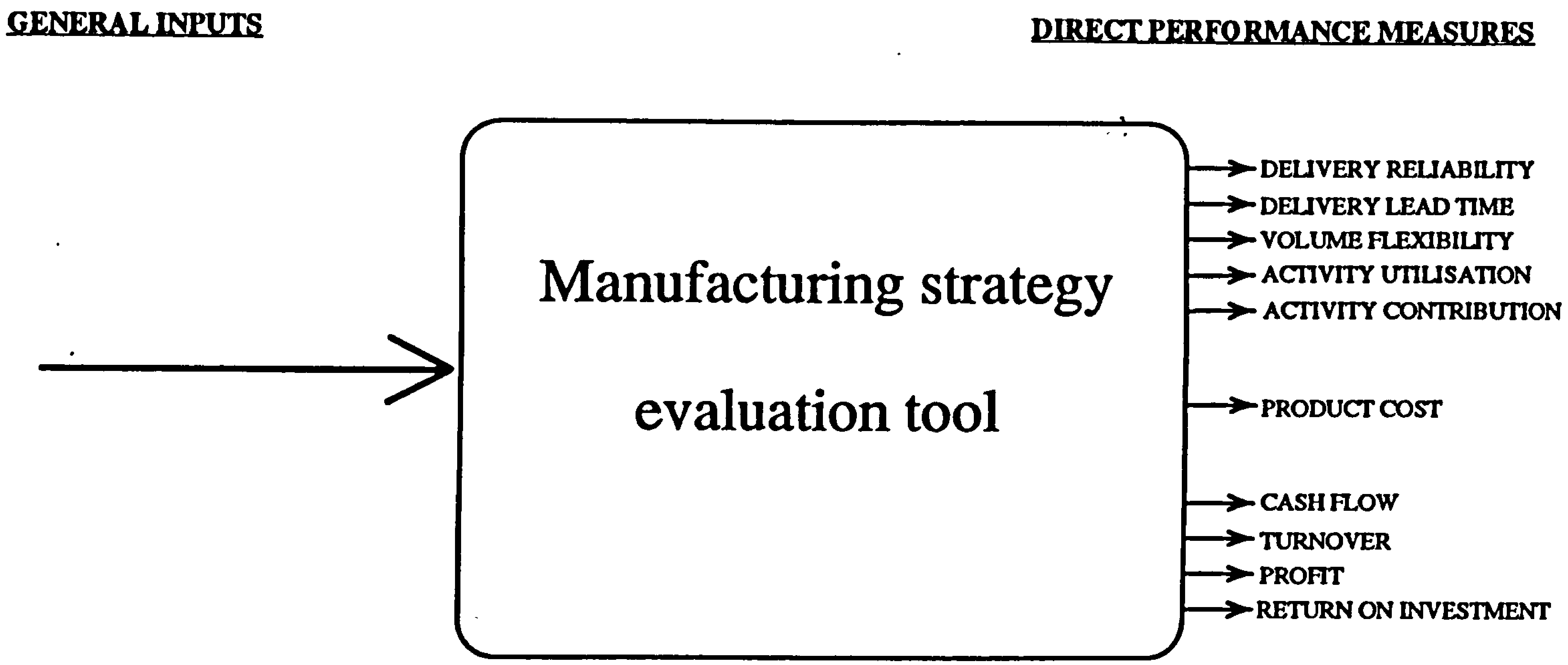


Figure 8.3: Information outputs of the complete manufacturing strategy evaluation tool

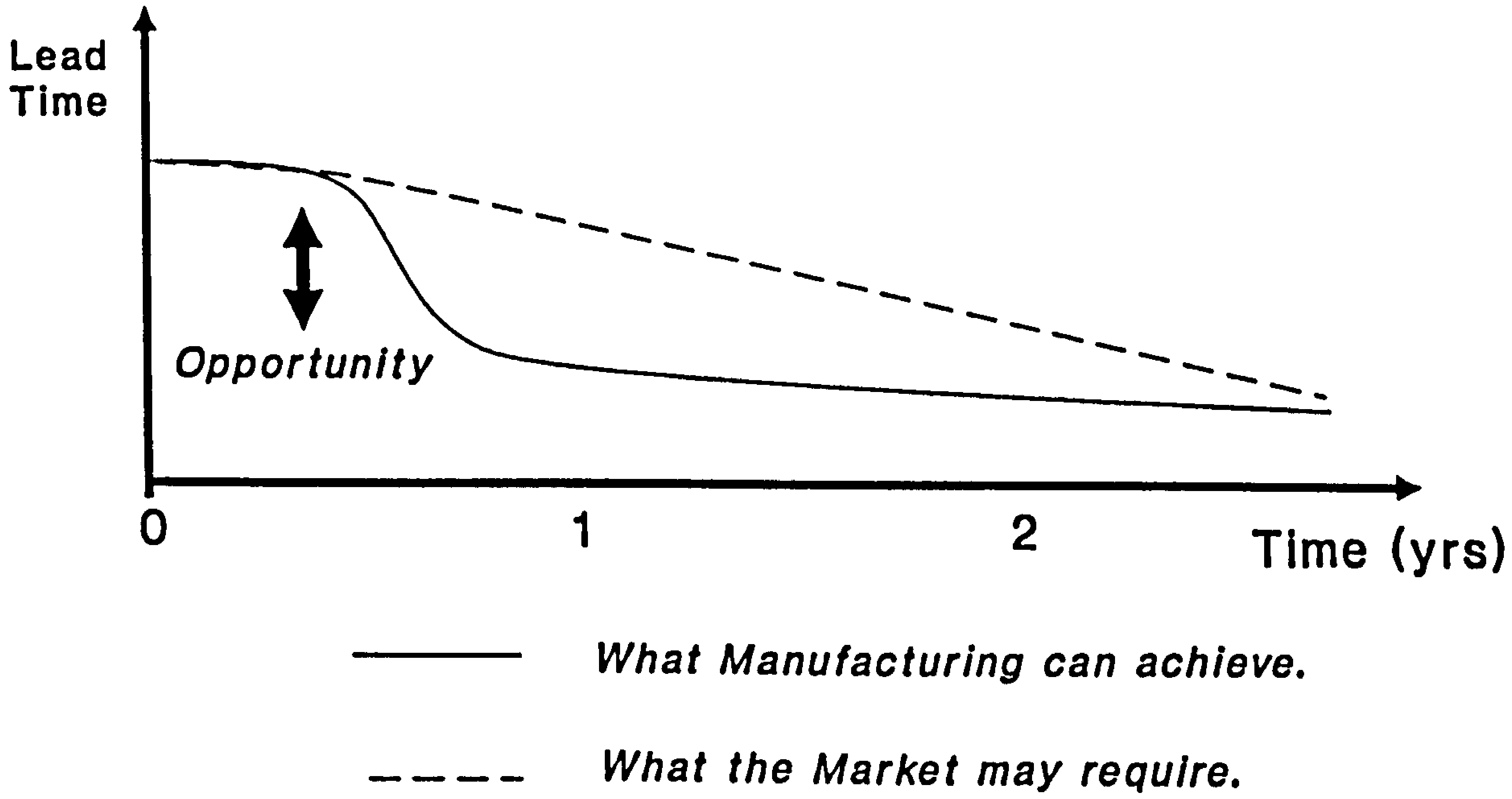


Figure 8.4: Time series profile for displaying performance measurement results

activity contribution. To provide these measures a number of specific inputs will be necessary. First, to configure the SD model a description of the manufacturing system under consideration will be required. This description will typically need to contain data about product families, manufacturing processes, information flows within the company, etc. A similar input will be necessary that describes the manufacturing strategy under evaluation. The manufacturing strategy may be described as an implementation schedule of strategic developments to the host company's manufacturing system. For example, how the flow in product families through a factory is intended to transform as a reorganisation of facilities or an investment in processes takes place. A proposed method of representing a manufacturing strategy is a PERT chart, as described in Section 5.3.3, and such a chart could be amalgamated into a modelling tool. However, besides specifying the time when a strategic development is intended to occur, a PERT chart will also need to contain a thorough description about the integration of strategic developments into the manufacturing system being modelled. For example, an introduction of a manufacturing cell into a model of a factory will require information about the implications on human resources.

To control the execution of the SD model a set of general configurations will be necessary. Such configurations will include the time increment (Section 7.4.1) and the duration of model execution. Furthermore, a forecast product demand will be required for the SD model to operate. Finally, an estimated product lead time will be needed, which can then be combined with the lead time information provided by the SD model, to produce a value for delivery reliability.

The role of ABC in the manufacturing strategy evaluation tool is illustrated in Figure 8.6. Primarily, a value of cost for each product family can be calculated through the ABC model. However, to provide a cost for individual products, values of product volume are required from the SD model. This is shown in Figure 8.6 by the vertical link from volume flexibility. Furthermore, as well as calculating total product cost, it will be possible to determine the contribution that an individual resource or manufacturing process makes to overall product cost. This facility is illustrated in Figure 8.6 as a vertical link from product cost to activity contribution.

A description of the host company's manufacturing system, and the manufacturing strategy under consideration, are also required in order to configure the ABC model. Principally, this description will be in terms of cost pools and cost drivers that are representative of the organisation being modelled.

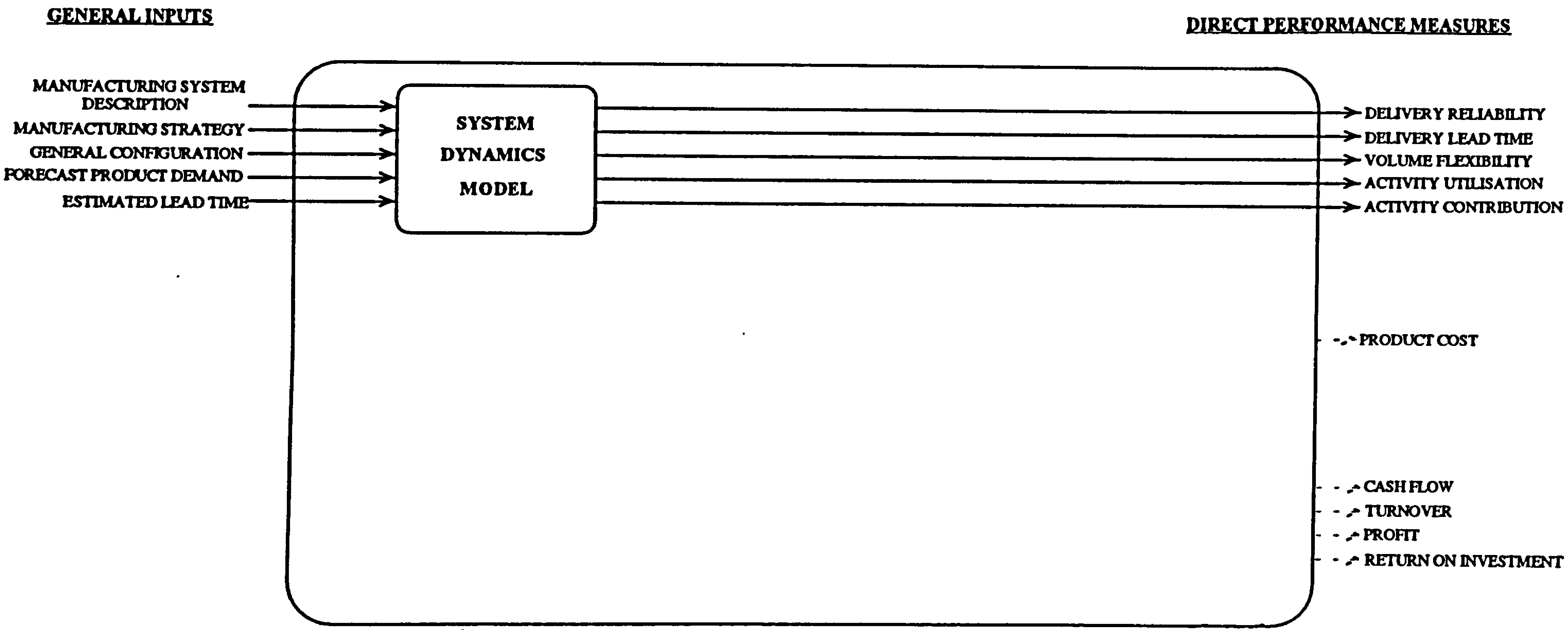


Figure 8.5: The role of System Dynamics within the manufacturing strategy evaluation tool

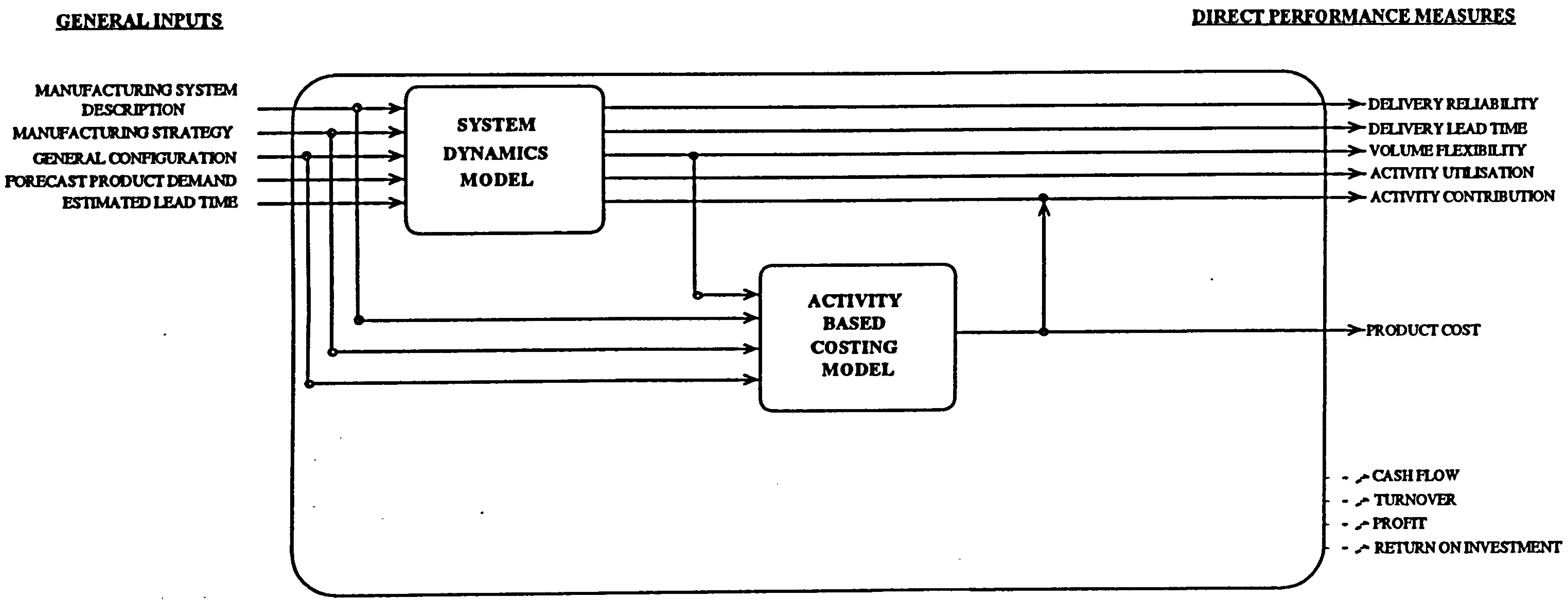


Figure 8.6: The role of Activity Based Costing within the manufacturing strategy evaluation tool

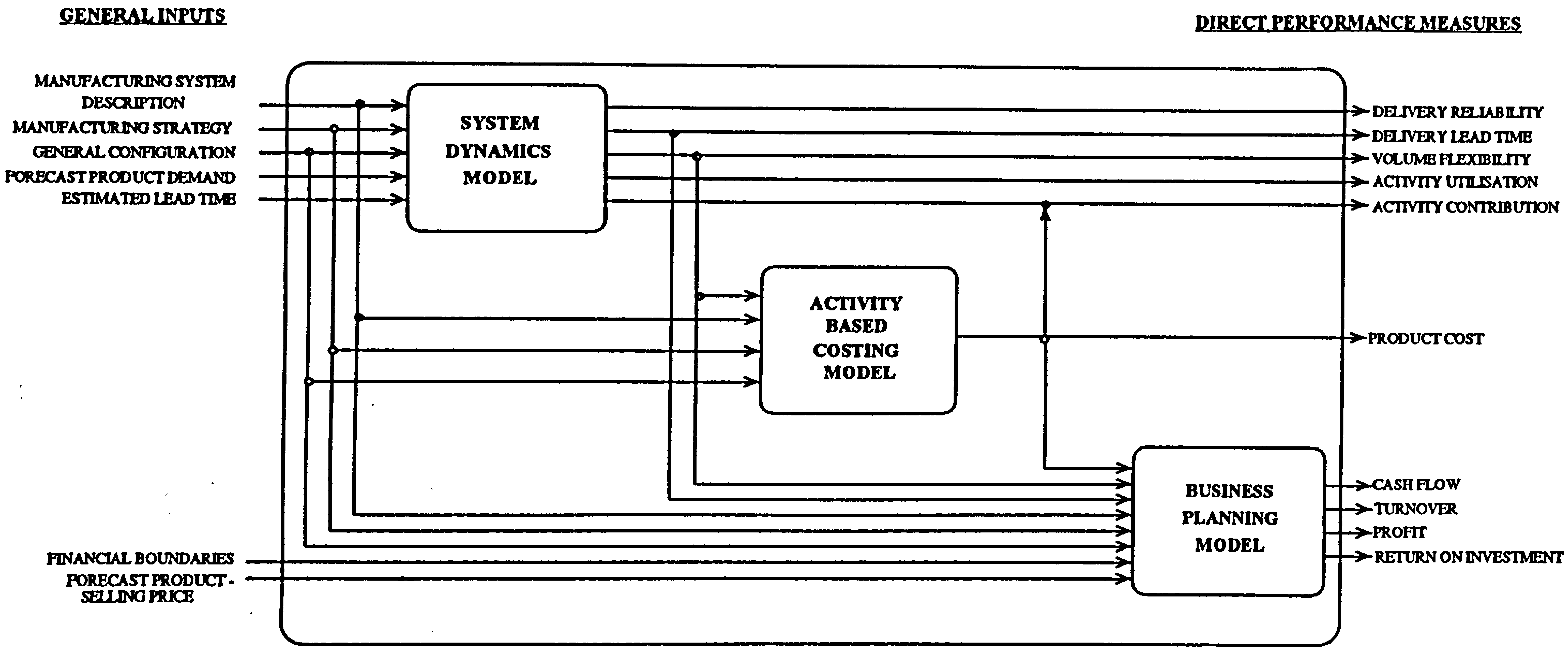


Figure 8.7: The role of Business Planning within the manufacturing strategy evaluation tool

For example, a company may contain a large production control department, where the primary task is to operate a computer based manufacturing planning and control system. If alternative forms of manufacturing control strategies are under consideration, it may be pertinent to group production control costs as a cost pool, and to link this cost pool to manufacture through a cost driver of computer generated production control information. The manufacturing strategy may then, through changes to the cost driver, describe how the role of the production control department will be changed as different strategies are considered.

The role of BP in the manufacturing strategy evaluation tool is shown in Figure 8.7. This model will directly provide measures of profit, cash flow and turnover, and return on investment. However, to perform these calculations values for product cost and volume are required from the ABC and SD models. A value of lead time is also needed from the SD model, as this is used in the calculation of cash flow. Likewise, estimates for product selling price are also required to be input into the BP model to enable calculations of profit, etc., to be made.

Descriptions of the manufacturing system and manufacturing strategy will be required to configure the BP model. The manufacturing system description may contain information about company assets, and the manufacturing strategy will indicate how such assets are intended to change as a strategy is implemented.

With the BP model, there are some boundaries of manufacturing system performance, such as credit limits, that in practice cause an abrupt halt to the operation of a company. A question arises as to whether a modelling tool should cease operation if, during model execution, such limits are exceeded. Ceasing model execution gives a very realistic view of a business situation, whereas allowing such limits to be exceeded will allow insight into the extent of a deficit, and hence may stimulate a redress of the situation. The solution favoured here is to provide within a modelling tool a facility whereby the mode of execution can be chosen by a practitioner prior to modelling.

In summary, the principles of the modelling tool are to be based on SD, ABC and BP, and these techniques are to be generally integrated as illustrated in Figure 8.7 and described above. The construction and application of a modelling tool of this form should make a valuable contribution to manufacturing strategy evaluation and hence formulation.

8.5 CONCLUSION

This chapter has developed the foundation of a modelling tool tailored to the task of analytical evaluation of a manufacturing strategy. This foundation has been formed by choosing the most suitable combination of modelling techniques on which to construct a modelling tool. This choice has been based on the comprehensive and in-depth knowledge of the capabilities of modelling techniques, that has been established through experimentation in the preceding chapter. On the basis of this analysis a combination of System Dynamics, Activity Based Costing and Business Planning have been chosen. Further experimental testing is now necessary to verify the suitability of this modelling solution in practice.

CHAPTER 9

TESTING THE PRINCIPLES OF THE MANUFACTURING STRATEGY EVALUATION TOOL

The preceding chapter has established the principles of a modelling tool for the analytical evaluation of a manufacturing strategy. The objective of the research described in this chapter is to attempt primary verification of the principles formed for the modelling tool, so that development into a robust prototype is justified, hence enabling extensive future testing.

The structure of this chapter is as illustrated in Figure 9.1. The chapter commences with a description of the research method at this stage. The second section designs an experimental programme that is based on the guidelines developed in Chapter 7 but within which, a number of parameters are changed. The third section then presents the execution of the experimentation programme, from which the fourth section draws a number of observations about the modelling solution. Finally, conclusions are drawn on the work carried out in this chapter.

9.1 STAGE 5 RESEARCH PROGRAMME

Two tasks have been established in Chapter 4 to realise the verification objective of this stage of research, namely:

1. Attempt to demonstrate that the principles of the modelling tool satisfy the requirement set.
2. Directly assess the usefulness of the modelling solution to practising managers in a strategy formulation role, and on the basis of this, consider the validity of the requirement set.

The experimentation programme needs to incorporate both of these tasks, and while the objective of this programme is different from that applied in Chapter 7, the basic principles and guidelines of experimentation developed in Section 7.1 remain appropriate here. Hence, taking into account these two tasks, and the content of the experimentation programme developed in Chapter 7, the design of the experimentation programme at this stage must address:

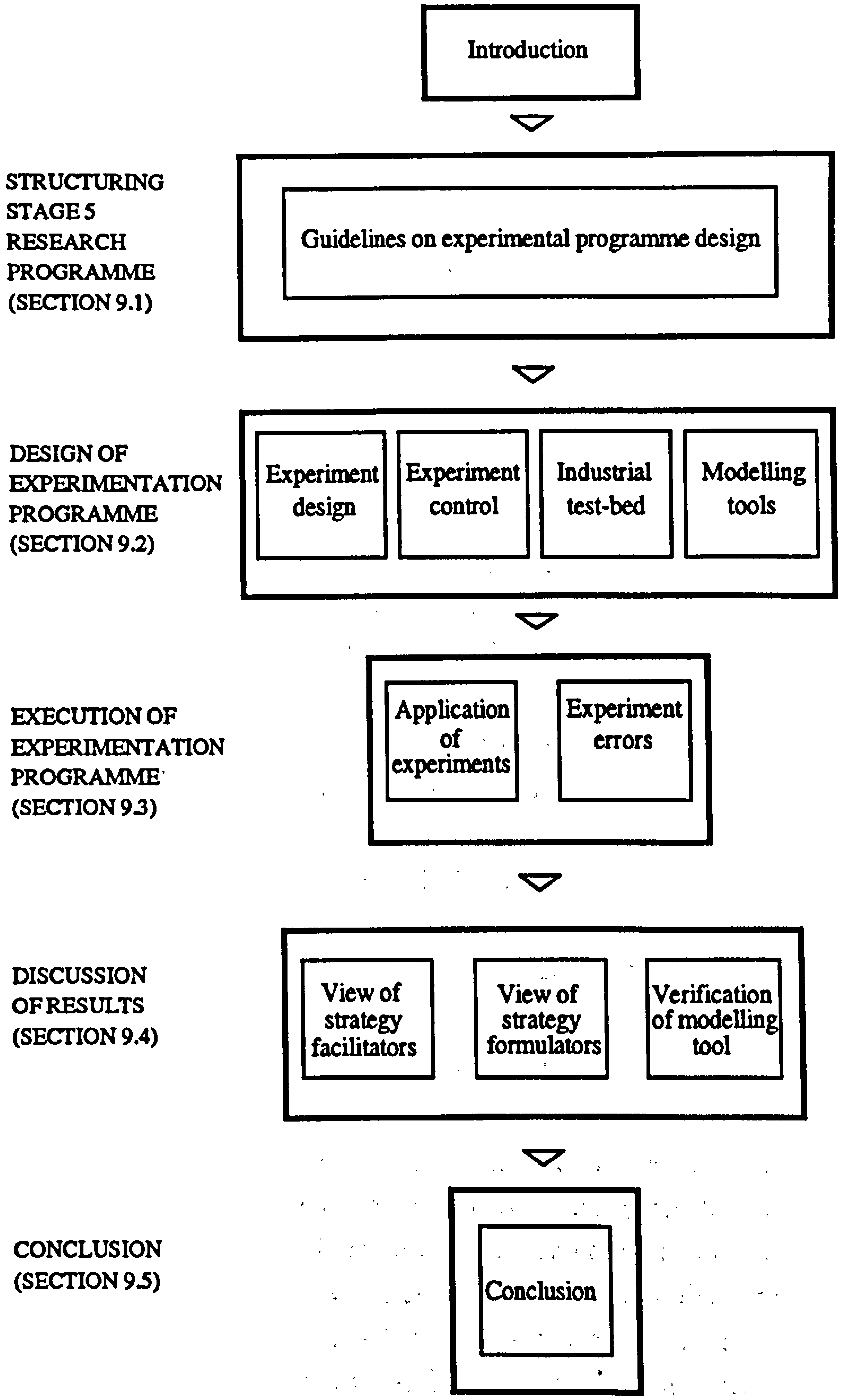


Figure 9.1: Structure of Chapter 9

1. Experiment design to test the modelling solution against the requirement set, whilst incorporating practising managers.
2. Experiment control incorporating choice of model builder.
3. Choice of industrial test-bed.
4. Choice of modelling tools.

On this basis, the design of the experimentation programme at this stage can proceed.

9.2 DESIGN OF EXPERIMENTATION PROGRAMME

This section develops the experimentation programme for this stage of research.

9.2.1 Experiment design

The experiment set used in Chapter 7 was designed by considering the tests necessary to expose the performance of a modelling technique, against the factors in the requirement set. Consequently, Section 7.2.1 has determined two experiments, respectively termed the functionality and flexibility tests. However, a number of test parameters require amendment to suit experimentation here.

The requirement set is summarised in Table 5.1. To assess the suitability of the modelling tool all the factors within the categories of structural and infrastructural changes to a manufacturing system, performance measures, and system transition still need to be assessed. However, as there is no longer a need to consider the relative performance of a number of modelling techniques, and hence the assessment of application time, accuracy and credibility will be effected.

In the case of application time, accuracy and credibility, no absolute values are available in the literature (Section 6.1) and so their performance has previously been measured in a relative manner (Section 7.2.1). Without a number of comparative tests against other techniques, precise measures for one modelling technique have little meaning. Therefore, the chosen approach in this study is to monitor the model build, accuracy and credibility, and rather than seeking precise numerical values, to investigate whether the performance gained generally correlates with that measured for each individual technique in Chapter 7. On this basis, the resulting requirement set of direct concern at this stage is given in Table 9.1.

Category of requirements	Requirements of evaluation
Structural and infrastructural changes to a manufacturing system	1. Facilities 2. Capacity 3. Span of process 4. Processes 5. Human resources 6. Quality 7. Control policies 8. Suppliers 9. New products
Performance measures	1. Delivery lead time 2. Delivery reliability 3. Volume flexibility 4. Cost 5. Activity utilisation 6. Activity contribution 7. Cash flow 8. Turnover 9. Profit 10. Return on investment
System transition	1. Time dependency 2. Content change

Table 9.1: Reduced requirement set

The reduced requirement set in Table 9.1 has direct implications on the content of the functionality and flexibility tests. The functionality test can be rationalised to consist of building a model of a company's existing manufacturing system to ensure that all the necessary performance measures are provided by the modelling tool. The flexibility test will remain unaltered and will still consist of attempting to modify the model of the existing manufacturing system to address nine scenarios of strategic manufacturing development.

Experiment design can be further extended to consider the second task of this research stage, namely, assessment of the utility of a modelling approach to practising managers in the strategy formulation role. The question to be answered is whether strategy evaluation will, in practice, benefit from the application of the modelling tool? To benefit from the application of a model based evaluation, strategy formulators must essentially. make 'better' strategic decisions than without such a facility. To determine whether a 'better' strategic decision has been made is fraught with difficulties, not least, defining what is meant by 'better'. The intended purpose of the strategy evaluation tool is to improve the understanding and prediction of a strategy formulator (Section 4.1.1). Some indication of benefit can therefore be gained by questioning whether any contribution has been made in either of these areas during strategy evaluation. To assess this contribution it is necessary to establish the strategy formulators basic understanding and prediction about a manufacturing strategy, and then to assess how this understanding and prediction changes through the use of a valid model.

A comparison between the views of practising managers and a model already exists in the procedure for model validation of the flexibility test (Section 7.2.1). Here, personnel who are knowledgeable of the industrial test-bed are required to anticipate the effect on performance of changes to the manufacturing system. Therefore, if a group of practising managers acting as strategy formulators are asked to provide estimates on the effect of a set of strategic developments to a manufacturing system, this can then be contrast against the predictions given by a valid set of models. The initial estimates of the strategy formulators will need to be formed through judgement and bargaining so that such influences are negated as far as possible, or can be directly attributed to the analytical contribution of the modelling approach. Such a procedure means that model building and strategy formulation need to be kept separate so that the extent of the contribution of modelling can be assessed as a final stage. This mechanism has been adopted by this research and is illustrated in Figure 9.2.

Finally, the validity of the requirement set needs to be ensured. Of particular concern are any omissions that might exist. Some indications can be gained by questioning strategy formulators on completion of experiments, as to whether modelling failed to provide the support they would have expected. Some omissions, that may be suggested, could be dependent on the previous experiences of the individuals involved. However, accepting these limitations, confidence in this research will be supported if few omissions are experienced.

9.2.2 Experiment control

Considered in this section are experimental control factors, as identified in Section 7.1.

Model construction

To demonstrate that the modelling tool is not only suitable to the test-bed through which it was created, and that the results are independent of the researcher, a different industrial test-bed will need to be chosen and the role of the researcher changed. In the previous experimentation programme the researcher played a significant role as the model builder (Section 7.2.2), and hence an alternative model builder must be chosen.

Platts (1993) advocates the use of graduate students in such experimental work. Fortunately, such a resource is available to this study, namely, a group of seven MSc students studying computer aided engineering. These students are available over an intensive twelve week period to study simulation of manufacturing systems. Furthermore, they have computing skills, a basic knowledge of manufacturing engineering and management, but no previous detailed knowledge of manufacturing system modelling. There is an additional benefit that the students are motivated as they share the common objective of successful completion of the simulation course. Hence, a relatively consistent knowledge base and associated motivation means that they are well suited to take on the role of model builders in this research. The researcher will hence be removed from direct production of the results, though some participation will still be necessary to guide and police the experimentation programme.

It is important that the students, who will subsequently be referred to as the facilitators, follow the same model build programme so that complex issues are addressed simultaneously and integration between the modelling tools is

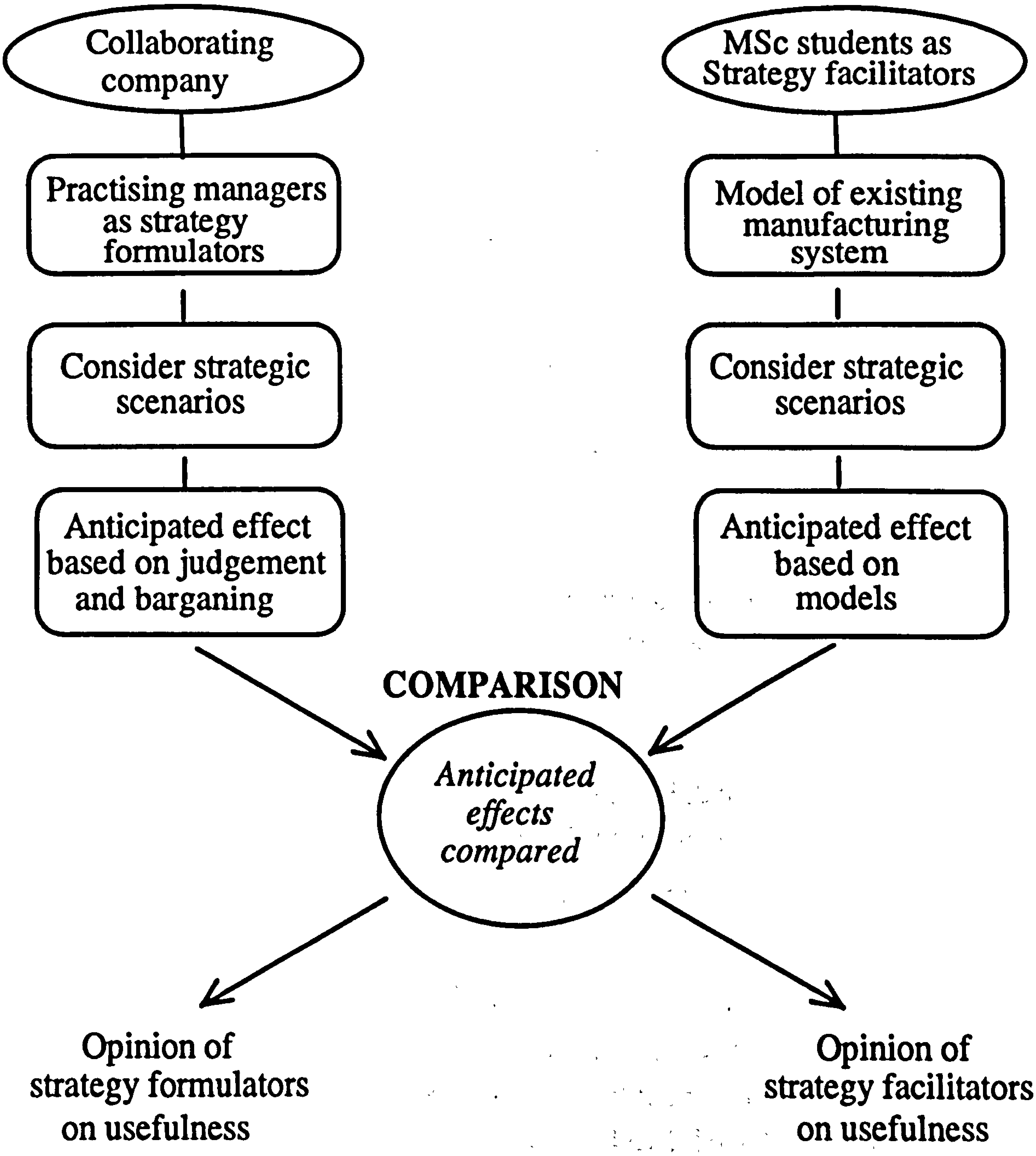


Figure 9.2: Measuring the utility of the modelling tool

maintained (Section 9.2.4). This will be provided by ensuring that regular meetings take place between the facilitators.

Data collection for the conceptual model
It is important to ensure that the facilitators are not disadvantaged by the lack of data about the existing manufacturing system and development scenarios at the industrial test-bed. Therefore, formal communication procedures need to be set up and policed to give general access to personnel at the test-bed company and allow data to be collected about the existing manufacturing system and strategic development scenarios. Likewise, it must be ensured that there is consistency between the strategy formulators and facilitators, on choice of product families and the making of general assumptions. Furthermore, the facilitators need to be given basic training on data collection techniques such as 'material flow charts' (Section 7.2.2).

Model execution
As comparative tests between the execution speeds of models are not to be carried out, it is unnecessary to apply controls that are specific to model execution.

Model verification and validation
To complement the model building procedure the facilitators will require training on model validation and verification as described in Section 7.2.2. As the effects of the strategic scenarios anticipated by strategy formulators cannot be disclosed, the researcher will assist in this activity.

9.2.3 Selecting an industrial test-bed

The guidelines developed in Section 7.1 have been adopted and the resulting activity follows a similar sequence to that described in Section 7.2.3. The participating company chosen for this study is DORMAN DIESELS LIMITED, Staffordshire, England. This company manufactures large diesel engines for the marine and electricity generation markets. This is a relatively large company and typical of a multi-product batch manufacturing environment. This company is described in more detail in Appendix E.

9.2.4 Selecting suitable modelling tools

To apply the modelling principles in practice, a modelling tool is required. This presents a dilemma; it is intended that the modelling principles are applied as a tailored modelling tool, yet investment in a purpose built software package is dependent on the results of this study. Therefore, integration is required between the modelling techniques at a minimum cost. One solution is to coarsely integrate the modelling tools previously applied in experimentation (Section 7.2.4) through computer file handling capabilities. Unfortunately, this is made particularly difficult because of the different hardware platforms used by each modelling tool, namely, STELLA[1] (SD) on MacIntosh whereas BPS-ABCM (ABC) and ABP (BP) use a IBM compatible Personal Computer (PC). The alternative solution, which has been selected, is to manually integrate the computer tools by instructing the facilitators to apply the information flows illustrated in Figure 8.7.

9.3. EXECUTION OF EXPERIMENTATION PROGRAMME

A summary of the experimentation programme for this stage is given in Figure 9.3. The application of this experimentation programme, and the subsequent results, are presented in this section.

9.3.1 Experimentation

The first activity was to identify a group of practising managers who were willing to adopt the role of strategy formulators. Through discussions, five personnel became involved in this study. These will be subsequently termed the strategy formulators. These personnel were used to establish a coarse set of strategic scenarios. These scenarios were to be subsequently refined but were required at this point to allow the general physical boundaries of the manufacturing system, with which the study was concerned, to be determined.

The facilitators were then introduced to the study. This introduction commenced with dividing the group into three teams of what was felt to be equal ability. Two individuals applied ABC, two individuals applied BP, and three individuals addressed SD. Training was then given on the modelling tools, data collection, model verification and validation methods. Likewise, access was given to the appropriate computer hardware and software. Finally, the teams were instructed to define the necessary data to construct a model of the manufacturing system at the industrial test-bed, and a mechanism to provide the information flows between models was set up. Throughout the study, the researcher orchestrated the adoption by each group of common assumptions, product families, etc. The researcher also policed the model building process by requiring the facilitators to

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[1] At the time of this study only MacIntosh versions were available. More recently a PC version has been introduced.

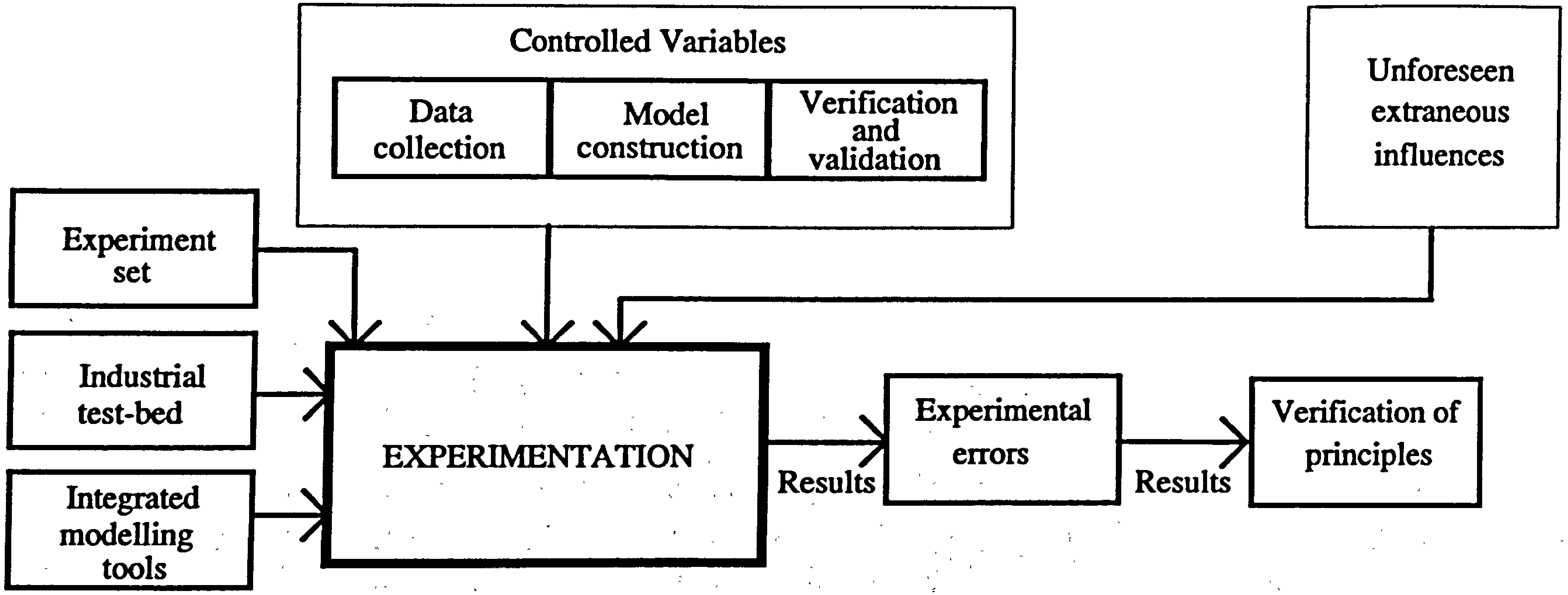

Figure 9.3: Overview of second experimentation programme

give formal weekly presentations of their progress. At each weekly meeting, and generally when necessary, the researcher offered guidance on the modelling tools, thus synthesising access to a supplier company.

A formal introduction of the strategy formulators to the facilitators, and vice versa, was then performed at the company. This introduction was carried out over one day and included a presentation about the company, a presentation by the researcher on the study, and guided tours given around the company's manufacturing facility. On conclusion of the visit, formal arrangements had been made for direct contacts between the company personnel and the facilitators for data collection purposes.

The facilitators commenced construction of models of the company's existing manufacturing system. The researcher focused their activities generally in the areas covered by the scenarios. Specific details of the strategic development scenarios were not released until the models of the existing manufacturing system had been validated. This approach was necessary to prevent the models becoming narrowly focused at an early stage in the study.

During the period of model construction, interviews were undertaken with strategy formulators to refine the strategic development scenarios. Once a common set of nine scenarios had been developed the strategy formulators were asked to judge the effect of these changes in terms of manufacturing system performance. First this was done on a one-to-one interview basis to capture each individual's judgement. These interviews themselves revealed that the strategy formulators were unwilling to give precise numerical estimates of the effect of each development. Hence, the process had to be simplified by requesting only the direction and order of magnitude of change. The strategy formulators were then brought together as a group, the collated opinions presented, and the group questioned as to whether any amendments were necessary. This was carried out to encourage bargaining between individuals. The outcome of this process was a set of scenarios and anticipated effects from the strategy formulators, as given in Table 9.2.

At the fifth week the teams of facilitators were given the nine manufacturing scenarios to evaluate. Again, the researcher only intervened to ensure that all assumptions were, as far as possible, common and to police the transfer of information between the teams of facilitators.

Decision category represented	Manufacturing development to be evaluated	Required structural change to models	Main anticipated effects to model performance
Facilities	Storage of components on assembly line.	Reduction in storage area and associated stock by 40%. Reduction in time between component arrival and assembly.	Reduction in lead time Reduction in product cost Improvement in cash flow
Capacity	A linear increase in sales volume over 2 years, so that after this period overall production has increased by 40%. This increase is measured in terms of cylinder sets.	Steps of 5% increases in the volume of materials delivered to the factory, measured against the initial delivery volume, at each of eight three monthly periods. Product mix kept constant.	Increase in product volume and lead time. Reduction in product cost. Reduction in cash flow
Span of process	Subcontracting cylinder head sub-assembly operation so that components arrive ready for assembly onto engine.	Removal of cylinder head manufacturing and assembly operations from model. Introduction of product assembly cost.	Reduction in lead time Reduction in product cost Improvement in cash flow
Processes	Integrating sub-assembly operations into main assembly. Effectively setting up subassembly cells which are spurs off the main assembly line.	Contain sub-assembly cells within main assembly line.	Reduction in lead time. Reduction in product cost. Improvement in ROI.
Human resources	Double day shift in assembly and test areas.	Changes in manning levels and times in assembly and test areas.	Reduction in product lead time. Increase in product cost. Improvement in cash flow.

Table 9.2: Strategic manufacturing development scenarios

Decision category represented	Manufacturing development to be evaluated	Required structural change to models	Main anticipated effects to model performance
Quality	Full inspection of crankcases when delivered to ensure acceptable quality.	Establish additional inspection activity when crankcases arrive. Removal of disturbances in machining and assembly of inferior quality crankcases.	Increase in product lead time. Increase in product cost. Reduction in ROI.
Control policy	Shop floor scheduling programme for cylinder head manufacture.	Change from make-to-stock to make-to-order on cylinder heads.	Reduction in product lead time. Reduction in product cost. Improvement in ROI.
Suppliers	All supplied crankcases 'right first time'.	Removal of disturbances in machining and assembly of inferior quality crankcases.	Reduction in product lead time. Reduction in product cost. Improvement in cash flow.
New products	Product mix changing over 1 year so that marine engines account for 40% of volume	Blocks of 10% increases in the volume of materials delivered for marine engines, with a corresponding decrease in other products.	Reduction in lead time, change in activity utilisation. Reduction in cost of marine engines. Improvement in ROI.

Table 9.2 (cont'd): Strategic manufacturing development scenarios

On the tenth week of experimentation the work was drawn to a conclusion. A presentation was given to the strategy formulators, by the facilitators, on the models constructed and the model based predictions about the effects of the strategic scenarios on manufacturing system performance. On conclusion of the presentation the researcher gave the predictions made by the strategy formulators on the effects of the strategic scenarios. A debate was then encouraged between the two groups in order to ensure completeness and validity of results, then each team of facilitators were interviewed by the researcher and their opinions sought on problems encountered in the study. A similar meeting was then held with the strategy formulators and their opinions sought as to the usefulness of the models constructed. The opinions received in each case were then documented.

9.3.2 Experimental errors

The main experimental concern was that at one point the facilitators who were applying the SD modelling technique introduced discrete elements into their model. This occurred because the researcher had not cautioned the group about following this approach. The consequence was that the model behaved in an unreliable fashion, as discussed in Section 9.4.1, and initially caused some lack of confidence and criticism of the technique by the students concerned.

Data collection at the test-bed company was fraught with difficulties because information held on formal data bases within the company was frequently inaccurate and misleading, as discussed in Section 9.4.1. This did limit how comprehensive the models constructed by the facilitators became. However, the models were sufficiently complete for meaningful results to be gained from the study.

9.4 DISCUSSION OF RESULTS

This section first expands upon the experiences of the facilitators, and then the strategy formulators. The third part of this section then draws together these opinions to form a statement on the verification of the modelling tool principles.

9.4.1 View of facilitators

The views of the facilitators were mainly concerned with problems that arose when applying the modelling tools. Three major concerns were encountered by the students in the role of facilitators.

The main problem that the facilitators encountered was in carrying out data collection. An initial problem occurred because the evaluation teams were unsure of the data requirements of each modelling technique. This was felt to be exaggerated by the researcher not divulging the scenarios to be modelled until half way into the study, as explained in Section 9.3.1 this approach was necessary to prevent the models becoming narrowly focused at an early stage in the study. As a consequence, strategy evaluators initially felt that their models lacked purpose. Second, even when the necessary information had been defined, it was either difficult to find, often in an inappropriate form, or totally inaccurate. For example, accounts information was not in a form that suited the models, or even suited the management of manufacture. Likewise, the standard times for component manufacture were both inaccurate and inconsistent. Indeed, much information on the company's manufacturing planning and control system was inaccurate and misleading. To overcome this particular problem the facilitators had to resort to gathering the opinions of employees directly involved in product manufacture.

The second concern that arose was with training. Whilst basic training on each of the modelling techniques and modelling tools had been conducted the researcher purposely did not influence the form of the actual models constructed. This was thought to best synthesise the situation faced by strategy formulators. However, the result was that the facilitators complained that their progress was hampered by the lack of previous modelling experience. This was particularly the case with SD, as detailed information about applying this technique to manufacturing system modelling is scarce. Nevertheless, model build times were reasonable, as shown in Table 9.3. This was felt to provide a case for some form of education and training guide for personnel faced with manufacturing system modelling in the context of strategy evaluation.

The third concern also arose as a consequence of the limited focused training given on the modelling tools. The issue is the use of discrete elements in the SD model. The use of such elements was avoided in the experimental work in Chapter 7 so as to reinforce a SD philosophy (Section 7.4.1). However, when the facilitators became aware of this functionality they applied it to model some machining processes. As a consequence, problems were encountered first with the level of detail the model contained, and second with obtaining precise performance measurement values.

Modelling technique	Recorded model build time for fully validated models
System Dynamics	240 man hours
Activity Based Costing	160 man hours
Business Planning	80 man hours

Table 9.3: Recorded model build times

In the first case, because a discrete time value could be assigned to an activity, instead of a rate, the amount of detail in the model quickly multiplied. For example, a machining cell was modelled as individual machines, materials handling was modelled as an individual activity, etc. In this particular example it would have been adequate to consider the whole machining cell as a production rate. It appeared that once the principle of being concerned with an aggregate flow was discounted, the amount of detail quickly increased.

Discrete elements also presented problems by causing the model to behave in an inadequate manner. A concern about containing such elements has previously been highlighted in Section 7.4.1, namely, that the state of an element can only change at whole values of the time increment 'DT' chosen. It can be appreciated therefore that for a manufacturing system model containing many discrete elements, each with a different value for time duration, choosing an appropriate value for DT is difficult. One approach is to choose DT to be equivalent to the smallest time duration. However, as the quantity of discrete elements tends to proliferate readily as model detail increases, the required value of DT will need to become smaller and smaller. The result is likely to be a very inefficient, pseudo-discrete event, simulation model.

The reason the facilitators had chosen to apply discrete elements appeared to be because they found this approach easier to associate with, rather than the concept of rates. This was compound by the modelling tool STELLA containing an element called 'oven', the characteristics of which provide an appealing surrogate for a machining operation. There are distinct benefits of working at an aggregate level for strategy evaluation (Section 8.3), however the modelling tool should support this focus. One method of achieving this was felt to be a modelling tool that was characterised, both terminological and graphically, to this task. For example, terms such as 'production rates' should be used along with graphical icons that can be clearly associated with manufacturing facilities.

The final concern of the facilitators was with integration of the modelling tools. No attempt was made to integrate the three modelling tools at a computer level, rather formal communications were set up between the student groups (Section 9.2.4). In practice it was found that in spite of these communications being very formal and policed by the researcher, there were occasions where inconsistencies arose in the three models constructed. In one example, the ABC model contained departments within the factory that the SD model did not consider. In a second instance, the BP model included some financial information for a second manufacturing site that was outside the scope of the study. It can be argued that in many cases the inconsistencies between the models may not have occurred if the company's own personnel, with their inherent knowledge of the manufacturing system, had been used. However, as the facilitators demonstrated, the models need to be consistent to a low level of detail that is impractical to ensure manually. Furthermore, manual integration effectively triplicates the data entry requirements. In conclusion, a strong case was observed to exist for automated integration of the modelling tool.

9.4.2 View of strategy formulators

Generally the strategy formulators felt that the modelling tool offered a greater insight into the behaviour of their company's manufacturing system. Two issues in particular were raised during execution of the experimentation programme.

First, the strategy formulators felt that the models enhanced their understanding of their company's manufacturing system because a holistic view of developments could be seen. Furthermore, the models were observed to stimulate debate and discussion between the strategy formulators. However, they also felt that this understanding would have been enhanced if they themselves had constructed the models.

Second, the strategy formulators did appreciate the predictive capabilities of the models, and although the numerical values provided by the models were often treated with some scepticism, a major advance was considered to be made by such values existing. As Section 9.3.1 states, the strategy formulators were unwilling to make such numerical predictions themselves. Again, the strategy formulators felt that the predictive power of the models would have improved if they had been directly responsible for model construction. For example, on one particular occasion the BP model predicted a considerable financial loss during one month of the company's operation. It transpired during the final presentation that the model did not account for a factory 'shut down' period. This validation error would probably have been avoided if the strategy formulators had been more closely involved in model building.

9.4.3 Verification of the modelling solution

A number of issues have been raised by both the facilitators and formulators. It is now appropriate to consider the verification of the modelling tool.

Firstly, it has been demonstrated that the modelling solution satisfies all the factors in the requirement set. This occurred even though the industrial test-bed and the model builders were different from those used in Chapter 7. There were no challenges made by either the strategy formulators or facilitators against the content of the requirement set. The modelling tool could provide the necessary performance measures, the flexibility to address the strategic scenarios, and could provide the system transition capabilities. No anomalies were recorded with issues of credibility, build time or accuracy, each technique performing in a comparable manner to the results previously obtained. Therefore, the foundation on which much of the preceding research has been conducted is upheld.

Secondly, the strategy formulators at the test-bed company felt that the models constructed were an enhancement to understanding and prediction about the company's manufacturing system. Furthermore, debate and communication amongst personnel was stimulated. Indeed, through the application of modelling, managers were prepared to discuss the effect of strategic developments quantitatively. Therefore, the modelling tool has demonstrated utility to practising managers.

The modelling tool has demonstrated to be correct and useful in each of the tasks of concern. On this basis it can be concluded that the principles of the modelling tool have been primarily verified and are worthy of further development. Finally, a number of issues have been raised concerning further work, these are discussed further in the conclusion of this thesis.

9.5 CONCLUSION

In conclusion, the research presented in this chapter has sought to primarily verify the principles of the modelling tool for manufacturing strategy evaluation. Such verification has been gained by executing an experiment programme at an industrial test-bed company. As a consequence of this work, the modelling tool is considered worthy of further development. However, three important issues have been highlighted that must be considered for future work, namely:

- That there is a strong case for strategy formulators to apply the modelling tools directly. This should be reflected in the design of modelling tools and creation of a supporting methodology.

- There is a need to provide a unified and integrated computer tool on the basis of the principles established in this thesis.
- There is a need for an education guide on how to approach data collection and model building for manufacturing system modelling when addressing strategy evaluation.

These issues are considered further in the conclusion of this thesis.

Finally, thorough the verification work described in this chapter, an observation about model detail has been made that, on the basis of the reasoning given in Section 8.3, is pertinent to discuss further. There is a high risk of a model builder becoming overwhelmed in model detail. This situation appears to exist for a number of reasons, such as, an expectation of company personnel for a life like emulation of the real system under study, and a tendency for the model builder to include detail because the modelling tool has a facility to do so. As a consequence, the model builders may be unable to deliver an effective decision support aid to strategy formulation. This was demonstrated in this study when one student group introduced a large amount of detail into the System Dynamics model. On the basis of this study, the researcher considers that a model that is purposely lean on detail, if supported by a set of assumptions agreed amongst participating personnel, is more useful to strategy formulators in practice than a complex model that is an exhaustive attempt to capture all aspects of a manufacturing system design. Therefore, the reasoning given earlier for choosing a modelling technique that forces a rationalisation of model detail, has been upheld in this particular study.

CHAPTER 10

CONCLUSIONS

The aim of this research has been to form and verify the principles of a modelling tool that will enable a practical analytical evaluation of a manufacturing system performance, as a strategy is applied. In doing so, it should directly support judgement and bargaining in strategy evaluation as a procedure in formal planning processes. A five stage research programme has been executed, and has resulted in these principles being established and primarily verified. Therefore, it can be concluded that the aim of this research has been successfully realised.

This section summarises the research findings, the limitations and concerns of the work that has been conducted, and issues for future research to address. At the end of each individual chapter of this thesis, specific conclusions relating to that chapter have been detailed. Therefore, this chapter draws general conclusions on this body of research as a whole.

10.1 SUMMARY OF RESEARCH CONTRIBUTION

The research presented in this thesis makes two principal contributions to knowledge about the subject of manufacturing strategy evaluation. Furthermore, in executing the research programme, a number of advances have been made that are themselves important contributions to knowledge and deserve highlighting. This section summarises both the primary and secondary contributions of this research.

10.1.1 Primary research contributions

The novel contribution to knowledge that this research programme has provided is twofold. Firstly, comprehensive and in-depth knowledge has been gained about the capabilities of existing modelling techniques in the role of manufacturing strategy evaluation. Secondly, the principles of a modelling tool that is tailored to the task of manufacturing strategy evaluation have been formed and verified. Within each of these categories a number of findings have been made that can be summarised as follows.

Comprehensive and in-depth knowledge of modelling techniques in manufacturing strategy evaluation

Initially in this research physical models have been considered for the task of manufacturing strategy evaluation (Section 6.6), and for these models the following conclusions were drawn.

1. Physical models have distinct limitations. A physical replica requires excessive resources to apply, and can also be expensive to modify once constructed. Non-functional replica, non-functional scale, and 2D non-functional scale models are limited because, by definition, no numerical capabilities are available. Scale models are restricted because, although they contain functionality, it is not possible to directly model human resources. Also, embedding functionality into such a model is likely to be expensive. Finally, analog computer models have a limited flexibility.

Symbolic modelling techniques are more suited to the task of manufacturing strategy evaluation, and though limitations do exist, the following capabilities have been established empirically (Section 7.4) for the representative modelling techniques of Discrete Event Simulation, System Dynamics, Queuing Theory, Activity Based Costing, Business Planning, $IDEF_0$ and Integrated Enterprise Modelling.

2. Discrete Event Simulation can evaluate a wide variety of issues, to a low level of detail, with relatively high model accuracy, and good model credibility. However, the technique has a slower model build rate than System Dynamics, and the resulting model will take longer to execute.
3. System Dynamics has the flexibility to address a wide variety of issues, it exhibits a relatively rapid model build rate and model execution time. However, because of the inherent approximation of treating a product as a flow, the depth of model detail, credibility, and absolute level of accuracy are less than for Discrete Event Simulation.
4. Queuing Theory enables a reasonably accurate model to be constructed relatively quickly. The predominant concerns are that performance measures are given for conditions of steady state system behaviour, and that the inherent approximations restrict the depth and breadth to which a manufacturing system can be modelled. Credibility is weak because graphical animation cannot be provided.
5. Activity Based Costing is focused at providing product cost, and has the flexibility to assess a range of strategic developments in terms of this measure. Contrary to some evidence in the literature, see for example Cooper (1990), this modelling technique can be applied in a reasonably short amount of time if restricted to addressing strategic issues within a manufacturing company.

6. Business Planning provides a business perspective of manufacturing developments. The predominant weaknesses are that valid flexibility and credibility are limited because the manufacturing system characteristics are only superficially considered.
7. $IDEF_0$ is a strong mechanism for illustrating the activities in a system, and their interactions, at an instance in time. The principal limitations observed were based on an integration with mathematical modelling within the tool DESIGN/IDEF (Section 7.2.4). Experimentation revealed distinct limitations with the mathematical, and hence predictive, capabilities of this modelling approach.
8. Integrated Enterprise Modelling provides a model that is less abstract than $IDEF_0$, as the modelling syntax was more easily related to the real system. As a consequence, models are better understood, accepted, and model building is faster. However, this relaxation in syntax does mean that a $IDEF_0$ model provides a system description that is richer in information.

In summary, these findings provide a valuable foundation to knowledge, across different types of models, adding order to the existing views in the literature. For example, the findings on Queuing Theory concur with the view of authors such as Suri (1985) (Section 3.5), in that Queuing Theory is in practice a feasible modelling tool in the early stages of manufacturing system design. Conversely, the opinions of authors such as Buchanan and Scott (1992) (Section 3.5) have been found to be, at best, dated. Likewise, though Love and Barton (1993) may be cautious about System Dynamics (Section 2.4.4), however this modelling technique does provide reasonably accurate results that have utility to practising managers (Section 9.4). Therefore, on the basis of the contributions described above, progress should be possible on modelling in the evaluation of a manufacturing strategy.

Formation of a modelling solution to manufacturing strategy evaluation

The principles of a modelling tool have been established (Chapter 8) using the knowledge gained of modelling techniques. This modelling tool is based on an integration of System Dynamics, Activity Based Costing and Business Planning (Section 8.4). These principles have been tested in a second industrial study in order to gain preliminary verification. The results gained from experimentation (Section 9.4) demonstrated that:

1. The principles of the modelling tool enable an evaluation of a manufacturing system's performance, as strategic manufacturing developments are applied. This evaluation capability is sufficient flexibility to assess a breadth of manufacturing system developments that are generally

associated with the content of a manufacturing strategy. Likewise, this evaluation is given in terms of performance measures that allow the assessment of the consistence between the manufacturing, financial and marketing strategies of a company.

2. In practice the principles of the modelling tool were found to be useful, stimulating debate and communication between practising managers. Furthermore, the modelling approach supported, and to some extent enticed, managers to make quantitative predictions about the effects of strategic developments to the performance of a manufacturing system.

On this basis, the modelling tool principles are considered to be worthy of further development into a unified modelling tool.

10.1.2 Secondary research contributions

In the process of executing the research programme a number of advances have been made that are themselves important contributions to knowledge. This section highlights these.

1. Model taxonomy: To reveal the forms of models that may be considered for manufacturing strategy evaluation, a taxonomy of models was sought from the literature (Chapter 3). However, existing taxonomies were either incomplete or out of date with current terminology. Therefore, a contemporary and comprehensive taxonomy was developed specifically for this research programme. This may now be of further assistance to other researchers who are also considering a fundamental appraisal of modelling approaches.

2. Requirements of a modelling technique in manufacturing strategy evaluation: To assess the capabilities of modelling techniques a measurement system was required against which the performance of comparable modelling techniques could be plotted. Such a measurement system was developed and termed the 'requirement set' (Chapter 5), and consists of a set of criteria that are perceived to be what practising managers desire of a modelling approach. This requirement set provides an important foundation for future work addressing manufacturing strategy evaluation.

3. Assessing product features, design flexibility and quality: Explicit in the manufacturing objectives (Section 2.1.2) are measures of quality, product features and design flexibility. This research has considered at some length how such manufacturing objectives can be assessed by a model (Section 5.4.3). While the approach developed has not been exhaustively tested (Section 10.2.2), important groundwork has been carried on which future work can build.

10.2 LIMITATIONS AND CONCERNS OF THE RESEARCH

Although this work supports the concept of manufacturing strategy, it is considered to be at the earlier stages of the research helix discussed in Section 4.2. A foundation has been provided on which future research can proceed, though in doing so, the work here must inevitably receive objective criticism before progression in this subject can take place. Therefore, this section indicates weaknesses within both the research programme and the findings presented in this thesis.

10.2.1 Limitations of research programme

The research activities have followed the cycle shown in Figure 10.1. Preceding this cycle a literature review provided knowledge of strategy formulation processes and generic modelling techniques. The research then followed a complete sequence of conjecture, deduction and verification, to arrive at the formerly presented findings. There are however two prominent issues that need to be highlighted about the manner in which this research has been conducted.

First, it is important to relinquish any claim that the modelling solution formed has been proven to be ever more suited, or always the best solution, to manufacturing strategy evaluation. The research process undertaken has not attempted such a proof, rather, the modelling tool principles have been verified as contributing to manufacturing strategy formulation, and are worthy of further development.

Second, only two sets of industrial case studies have been executed in this study. Fortunately, these have been sufficiently thorough to expose the limitations of individual modelling techniques. Furthermore, extensive use has been made of personnel from modelling companies to ensure validity and generality of results. In the case of the modelling solution formed, the nature of the coarse prototype meant that extensive verification at several companies was not feasible. Hence, sufficient testing was conducted to gain confidence to develop a robust prototype with which more extensive testing can take place.

10.2.2 Limitations of research findings

This section identifies prominent concerns that have arisen about the findings gained from executing the research programme.

First, the research activity has made extensive use of generic modelling techniques to represent the wide variety of models available. During

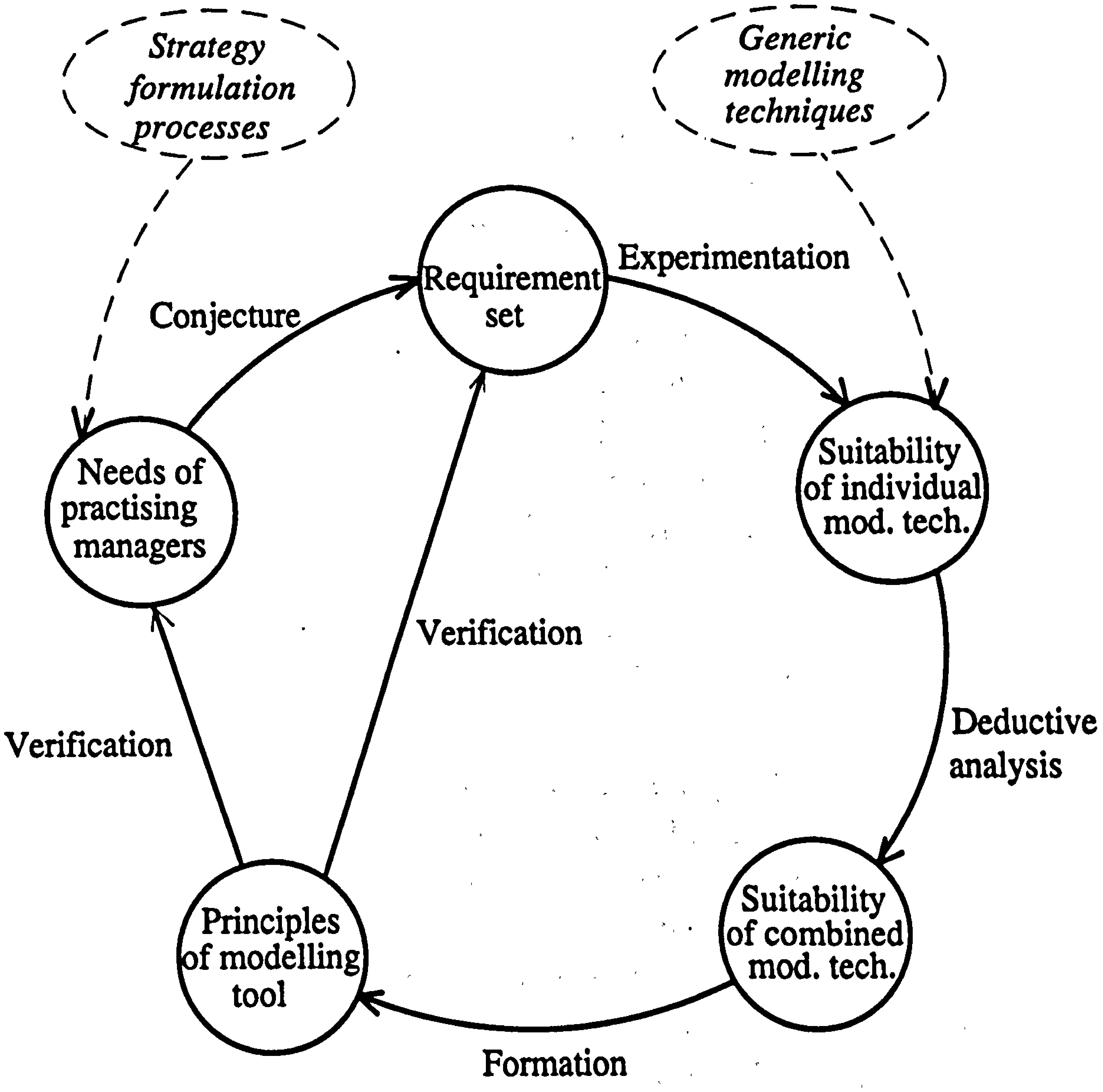

Figure 10.1: The completed research cycle of this thesis

experimentation questions have been asked continuously about whether each modelling technique is indeed representative, or could another modelling technique from the same category have performed better. Further reassurance has been gained from personnel with modelling expertise. On this basis a claim is confidently made that no individual modelling techniques are fully suitable to the manufacturing strategy evaluation task. However, this research does acknowledge in making this claim, that there is a risk that the modelling techniques and tools chosen are not fully representative.

Second, there is a concern that the strategic development scenarios chosen may not be of sufficient breadth to fully represent the structural and infrastructural jurisdiction of a manufacturing strategy. This is felt to be particularly the case with facility decisions where there is an opportunity to address the geographic location of a company (Figure 5.1). This study has focused at the development of an existing manufacturing facility and hence relocation issues have been neglected. Whilst this approach is felt to be justified because it reflects the situation of many manufacturing companies, this is an issue that should be addressed by future research.

Third, modelling was generally perceived to be weak where infrastructural issues, such as human resources, were considered. Indeed, during discussions some practitioners revealed a dismissive attitude towards the usefulness of modelling. On completion of this work the reason for this perception became apparent. Fundamentally, modelling requires cause and effect relationships to be embodied within a model. For example, to evaluate the effect of a change in cycle times on machine utilisation, the relationship between cycle time and utilisation must be known. This relationship may be implicitly defined, not all values may be precisely known, and can be complicated by taking into account variables such as products, labour, materials handling, etc. However, without such a relationship existing within a model no evaluation can be conducted. Frequently, the concerned practitioners could not define the form of the cause and effect relationship that they desired a model to contain. This was especially the case where cultural or social issues were being considered. Therefore, this criticism of modelling is more a reflection of current knowledge about the interdependencies and relationships that occur within manufacturing systems, and future work should attempt to expand this knowledge.

Finally, it is important to caution that this body of research has not been an attempt to replace the practising manager with a computer tool. Rather, the intention is to assist such personnel in addressing the strategic development of a manufacturing company.

10.3 FUTURE RESEARCH

As discussed above this research is considered to be an essential preliminary stage in the research helix, and a significant foundation and progression has been made in the analytical evaluation of a manufacturing strategy. This section identifies the direction that future work should take to support the progress of research in this area.

First, during the second experimental programme it was observed that it is inefficient and difficult to manually integrate three individual modelling techniques to form one modelling tool. To promote the practical application of this tool a computer software package should be developed that unifies System Dynamics, Activity Based Costing and Business Planning into a modelling tool. This modelling tool should be integrated as illustrated in Figure 8.3, and operate as specified in Section 8.4. Once this has been achieved, testing of the modelling tool should be carried out across a wide range of industrial situations.

Second, it is recognised that a strategy formulator will want to assess product features, design flexibility, and quality (Chapter 5). A method of accommodating these factors has been developed and briefly tested (Section 7.5). Future work should however integrate this mechanism explicitly into a computer tool. This will enable a debate about the suitability of this method, and may stimulate the development of other approaches to addressing this issue.

Third, this research can be viewed as a critical and objective investigation about how well modelling techniques can be moulded to formal strategy planning processes. On completion of this work, and along side the further development of a modelling tool, it is appropriate that the design of such processes should be revisited and amendments made to complement the known capabilities of modelling. In the design of such a methodology, it is particularly important to recognise the contribution that modelling can make to developing a holistic understanding of the behaviour of a manufacturing system (Section 9.4.2). Therefore, it is proposed that modelling is introduced early in a strategy formulation process, as illustrated in Figure 10.2.

Fourth, to guide the practising manager in the activity of modelling for manufacturing strategy evaluation, some form of education and training tool is required (Section 9.4.1). Such a tool should complement work such as DTI

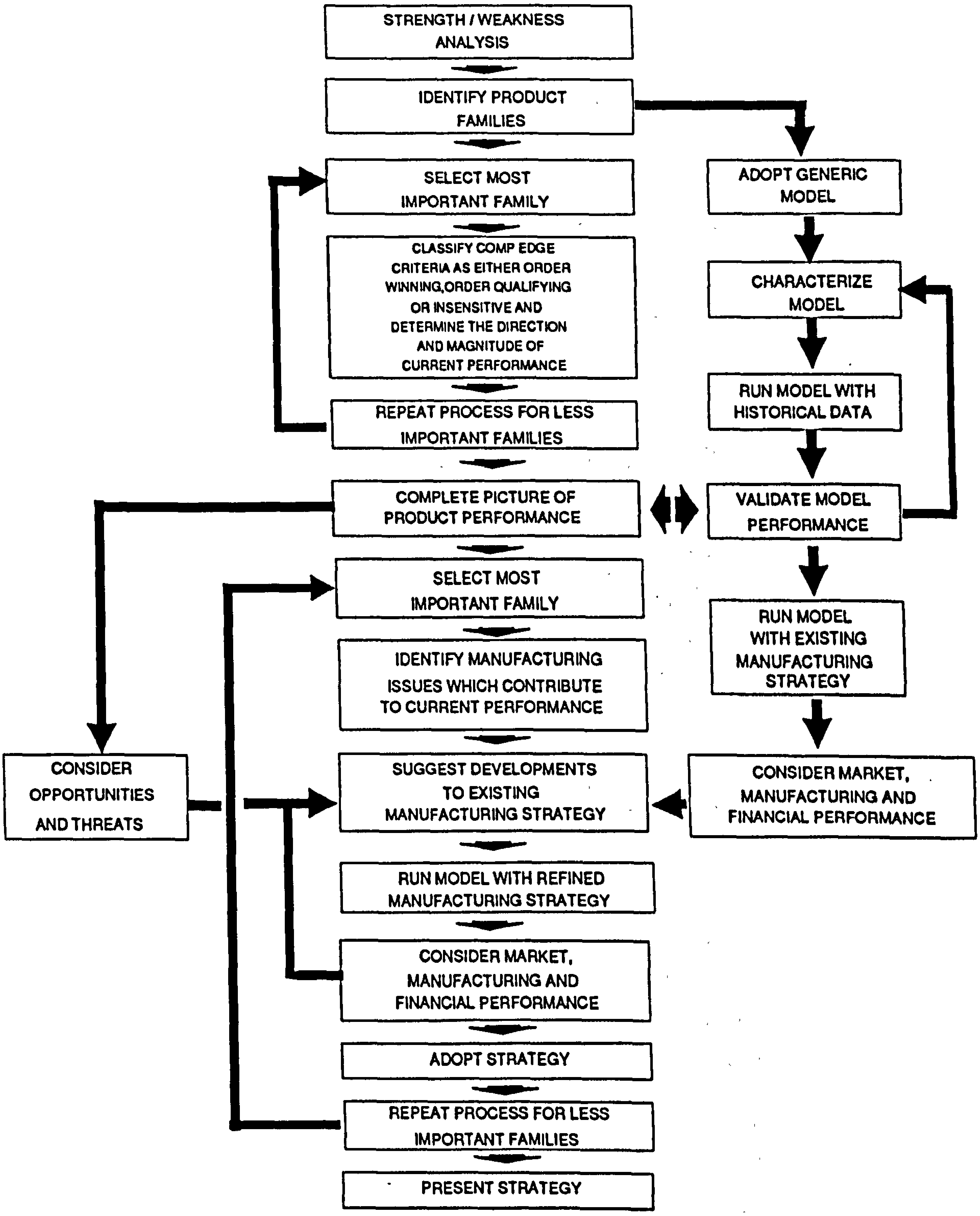

Figure 10.2: Proposed integration of modelling in a manufacturing strategy formulation process

(1988) by assisting a practising manager in the evaluation of a manufacturing strategy. Traditional strategy tools (Section 2.4.4) could be included, but a focus should be made on supporting modelling of a manufacturing system from a strategic perspective. Hence, content should include data collection, validation, verification and model building procedures. The medium for such a tool could be a booklet, as with DTI (1988), however application of recent advances in multimedia should be carefully considered.

Fifth, whilst developing the requirement set in Chapter 5 it became apparent that formal linking between manufacturing and financial strategy is weak compared with the linking between marketing and manufacturing strategy (Section 5.3.2) Future work should address this discrepancy.

Finally, Mintzberg (1978) suggests that, perhaps there is no process in organisations that is more demanding of human cognition than strategy formation. The research in this thesis is one endeavour, amongst a number, that have the intention of assisting practising managers in this process. However, there is still considerable work to be done in this field, with many opportunities for researchers to make valuable contributions to managers faced with the task of manufacturing strategy formulation.

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APPENDIX A: DESCRIPTION OF GENERIC MODELLING TECHNIQUES

Commonly used abbreviations in appendices

1. ABC: Activity Based Costing
2. BP: Business Planning
3. DES: Discrete Event Simulation
4. IEM: Integrated Enterprise Modelling
5. QT: Queuing Theory
6. SD: System Dynamics

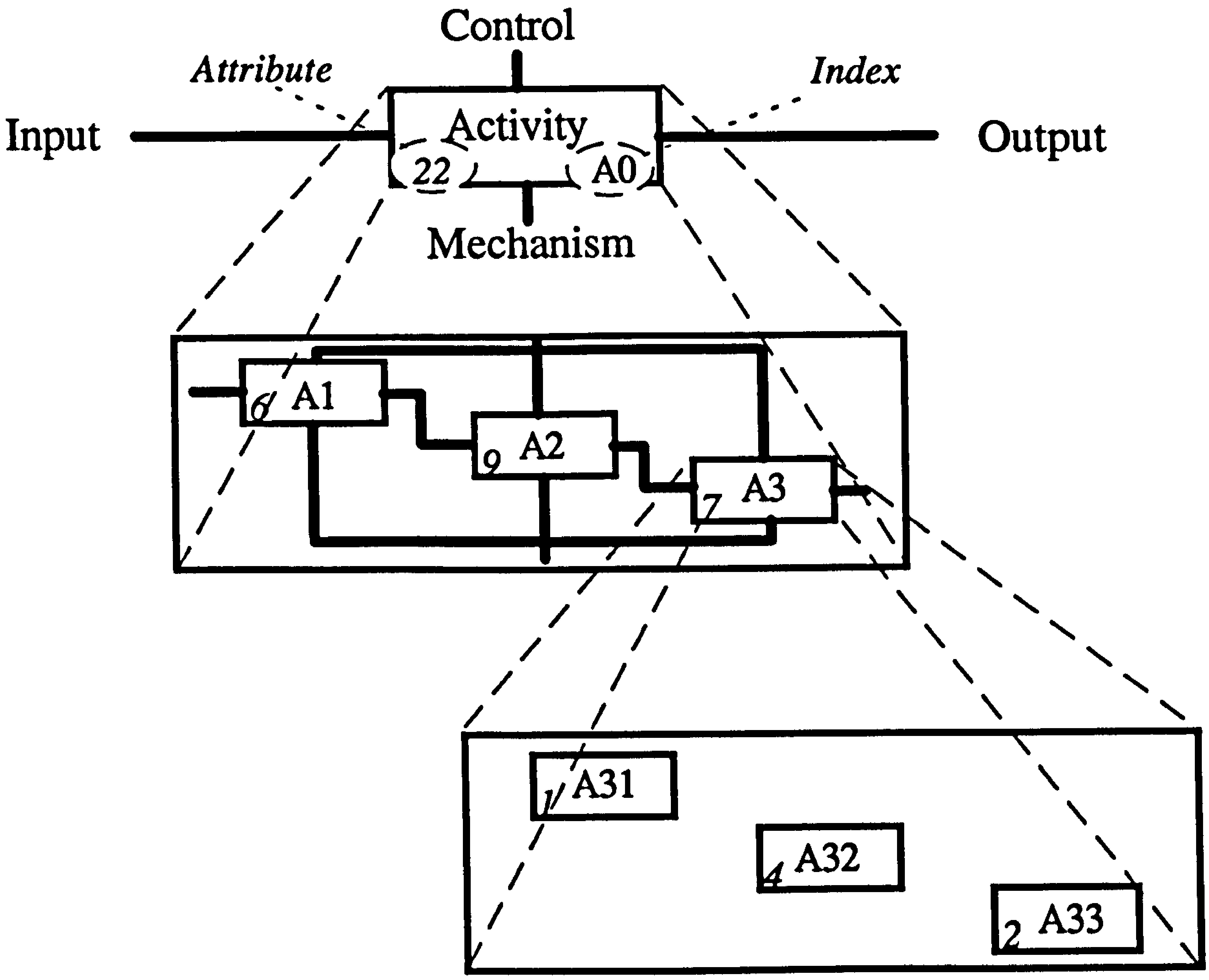
A.1 IDEF$_0$

A description of this technique has been compiled through general reference to Johannson et al (1993), LUCAS (1989), Bravoco and Yadav (1985), Marca and McGowan (1986), and Williams and Pontin (1989). These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description.

IDEF$_0$ diagrams follow a specific syntax and decomposition as shown in Figure A.1. Modelling commences by defining the purpose, boundaries and viewpoint of the model. A typical purpose of a model could be to provide an activity oriented description of a manufacturing system. Similarly, an appropriate view point in this case could be that of the manufacturing manager. The boundary is an imaginary line within which activities will be considered in detail, no activities outside of this boundary will be considered. The initial modelling activity is to draw a single rectangular box that represents this boundary and to highlight against this box, using arrows, the inputs, outputs, mechanisms, and controls.

The inputs, outputs, mechanisms and controls are a set of criteria that are fundamental to IDEF$_0$ modelling. An input is either material or data that is transformed to an output by the activity contained within the IDEF$_0$ box. The activity itself must be described by a verb. For example, metal bar (input) may be sawn (activity) to produce billets (output). A control is any constraint that may act on an activity. For example, information describing billet length could be a control on the sawing activity in the previous case as without this information the activity cannot commence. Some activities may have no significant input, data or material to be transformed, but a control must always be present. Finally, the mechanism is the person, system or device that performs the activity. Again in the example, the mechanism would be a sawing process. Every activity box in a model interacts with other activities though inputs, outputs, mechanisms or controls.

A major characteristic of IDEF$_0$ is that of system decomposition. A maximum of six activities are normally allowed to be described at any one level in a model. If further detail is required to describe an activity then that activity must be decomposed into a second set of activity diagrams. The inputs, outputs, controls and mechanisms that are available to the activity box prior to decomposition are made available to the new decomposed level. The modeller can think of the situation as if the contents of a box are being exposed for further analysis. To



Note: The *attribute* feature is specific to the modelling tool DESIGN/IDEF and allows a set of numerical values to be assigned to each activity within a model (Section 7.2.4). This facility is provided by combining IDEF$_0$ and mathematical modelling techniques.

Figure A.1: Manufacturing system modelling using IDEF$_0$

trace the decomposition's that take place in a model a unique numbering system is used, where A0 refers to the highest level of activity diagram, this numbering is then expanded as a model is developed giving such codes as A123.

A.2 Integrative Enterprise Modelling (IEM)

A description of this technique has been compiled through general reference to Mertins et al (1991) and Heslop (1991).

Enterprise modelling adopts the less abstract characteristics of Materials Flow Charts, relaxes the strict rules associated with $IDEF_0$ but maintains a decomposition approach. A model consists of instances of a number of generic entity classes, and each entity class has a set of predefined attributes that record information about the instance, and inter-relationships with other instances of the same and other entity classes. These entity classes are as follows:

Activity : An action or process which takes place in a system or organisation. An activity converts or transforms materials and / or data during its execution.

Data : Information or data used in a system.

Material : A physical object transformed during the operation of an organisation.

Store : A place where data and / or materials are held for a period of time.

Flow : The movement of data and / or materials between activities or a store and an activity. A flow is analogous to a pipe through which data and / or materials flow.

Resource : Physical objects and people required to perform activities and flows.

Product group : A product of an organisation or a natural grouping of a number of products.

A.3 Discrete Event Simulation (DES)

A detailed description of DES is provided by Pidd (1988), Carrie (1988), Law and Kelton (1991), ElMaghraby and Ravi (1992), Roth (1987), and Thesen and Travis (1989). These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description.

A DES model operates through emulating the time dependent behaviour of activities within a real system, by acting through equivalent activities in the model. The number of activities in a DES model are usually less than within the real system so as to improve modelling efficiency. Likewise these activities will be considered to behave in a discrete manner, meaning that activities will start and stop instantaneously even though in reality they may take a short period of time so to do. Model execution time is reduced relative to the real system through considering activities in terms of the events that take place at the start and finish of an activity. When a DES model is first executed, events that can be scheduled are placed in to an event list, in order of the time at which they will occur. Time is then advanced to the first event, the event is executed, and then removed from the event list. When an event has been executed this may cause more events added to the list, then once again time is advanced forward and the cycle repeated. A detailed description of this mechanism is given by Law and Kelton (1991).

Other terms associated with DES are entities, sets, attributes, and states. Entities are mobile components upon which transactions take place, for example, products flowing through a manufacturing system. Sets are mechanisms used to group entities in any convenient way, for example, a queue or machine. Attributes are parcels of information attached to entities. Finally, states refer to the condition of elements, such as entities, in a model.

A.4 System Dynamics (SD)

Authors that describe the concept of SD include, Pidd (1988), Towill (1993a), Roberts (1964), Coyle (1977), and Kumar and Vrat (1989). Considerable reference has been given to the work of Wolstenholme and Towill in this section. These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description. A SD model consists of the following elements:

Resources : Resources are usually material assets on which a system operates. A relevant resource example to manufacturing is 'Products'. However, resources can be non-physical, for example the flow of knowledge, motivation, etc.

States (levels or stocks) : A system often transforms resources through a series of states, in this case a 'Product' may be associated with states of store, transport, machine, etc. A state of a resource can also be defined as any accumulation of resources which is relevant to the concern. The states are alternatively known as system levels or stocks, depending on the researcher being referenced.

Rate variables : The rate at which resources are converted between states is represented in SD by rate variables. Rate variables are control variables which directly increase or deplete resource levels and their dimensions are usually in units per period of time. That is, they control flows into and out of stocks. Two pieces of knowledge are required before rates can be specified. The first is a need to know if any system states effect a rate variable. Note that rates can be considered as being dependent on either exogenous or endogenous, and this in turn depends on the model boundaries. Rates can only depend on levels since these are often the only measurable variables of a system. The second piece of information is the need to know the type of effect a state has on a rate variable, for example, a depletion in stock may be compensated by an increase in a rate variable.

Organisational boundaries : The main purpose of marking such boundaries on the diagrams is to try to clarify which organisations or people control each rate variable in the process.

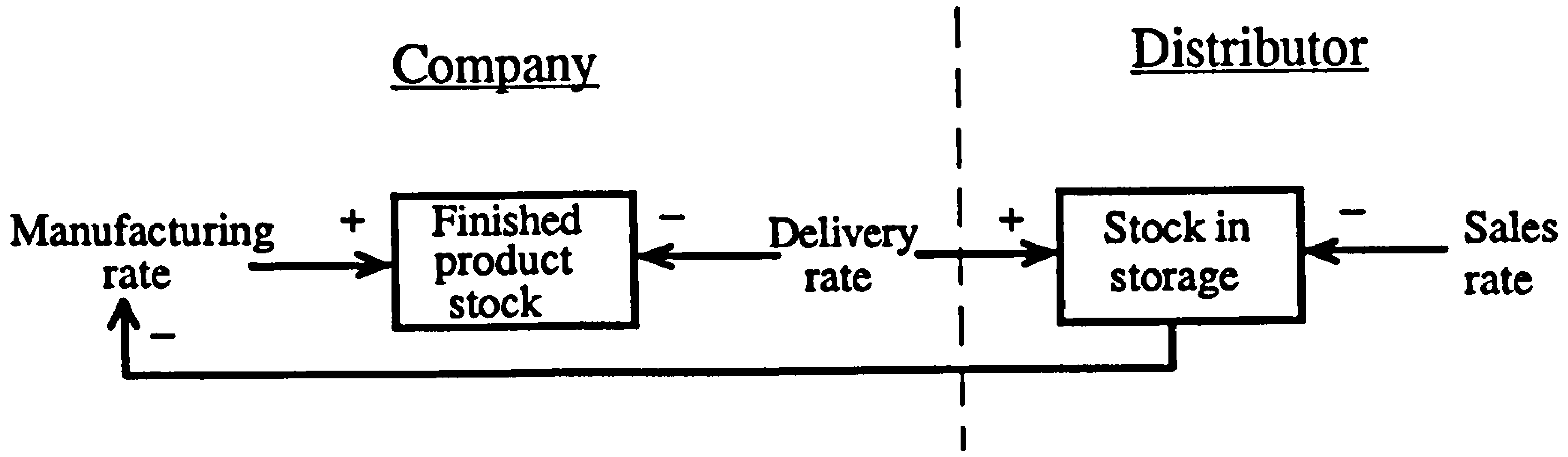
Structure : A SD model can be considered in terms of both information and process structure. Process structure is focused at the direct transformation of resources to states. Whereas the information structure illustrates how levels and rates are connected. For example an increase in the level of 'stock in storage' can be used to effect a reduction in 'manufacturing rate'. In a more complex system the feedback may be based on several states, and this information may be sequentially merged using *Auxiliary rate variables.* These variables are purely steps leading from levels to rates, with the aim of fleshing out the reality of the information flows.

A SD model can be represented as a map using an Influence (or casual loop) or Pipe diagram syntax. Figure A.2 gives a simple illustration of the different approaches. Influence diagrams are usually associated with the construction of qualitative models, as illustrated by Tsalgatidou and Loucopoulos (1991).

In the Pipe diagram representation the resource flow is depicted by a thick or double line connecting a source to a sink, both of these elements being represented by a 'cloud' symbol indicating an infinite availability of the resource outside the boundary of the model. The rate variables can be thought of as control valves which allow the resource to flow from the source into the state and out of the state into the sink.

Quantitative SD introduces mathematical sophistication to, what would otherwise be, a purely qualitative model showing levels and rates. Such numerical functionality is achieved in a model by first identifying what levels effect which rates, and then forming the appropriate mathematical expression in each case. Levels should depend on rates, never auxiliaries or other levels, and rates should depend only on information from auxiliaries and other levels, never on other rates. Definition of all the appropriate relationships in a model effectively means that a complete mathematical expression has been formed that determines the behaviour of the model. SD then employs numerical simulation methods based on difference equations.

Influence diagram



Pipe diagram

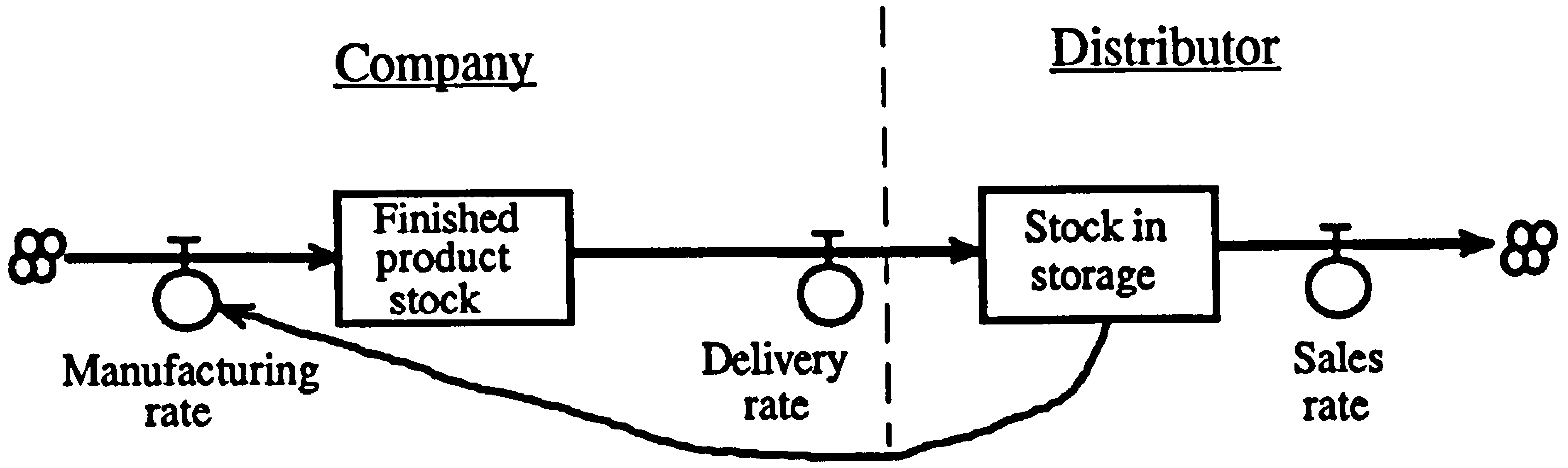


Figure A.2: Influence and Pipe diagrams in System Dynamics

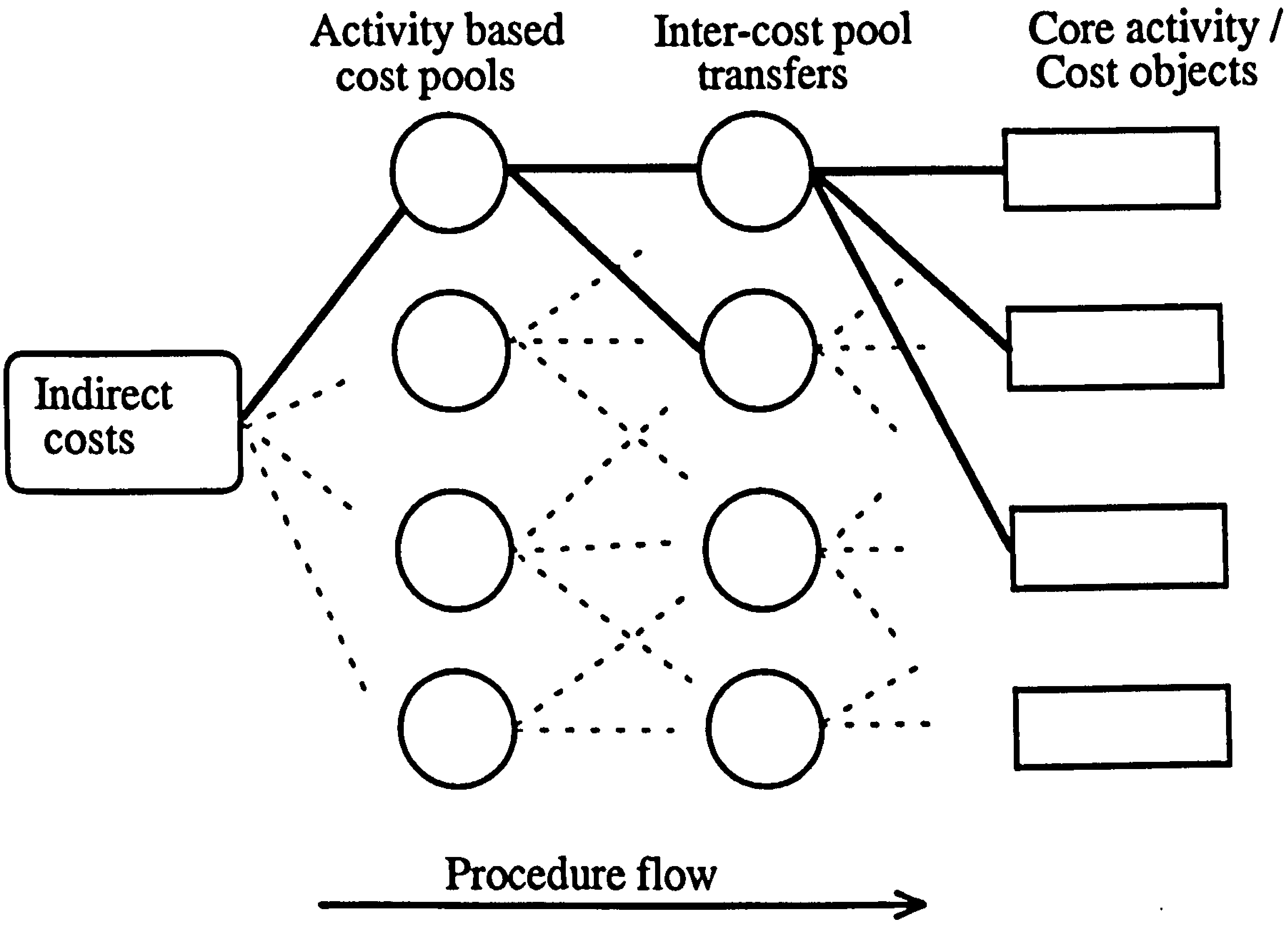


Figure A.3: Manufacturing system modelling using Activity Based Costing

A view of the simulation mechanism is given by Roberts (1964) as follows. Once a model's equations have been written, simulation calculations of the model can be made over any desired time period into the future. At each point in time the status of the system (i.e. the values of its levels) is determined based on the known prior status and the changes (i.e. the values of the rates) that had taken place during the prior time interval. With this updated status, the new set of changes can be calculated that will take place during the next time interval (by calculating the values of the auxiliary and then the rate equations). The newly calculated changes permit the next updating of the system's status (i.e. its levels), and the simulation calculation can thus carry forward indefinitely.

A.5 Queuing Theory (QT)

A description of this technique has been compiled through general reference to Snowdon and Ammons (1988), Hiezer and Render (1988) and ElMaghraby and Ravi (1992). These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description.

Queuing theory based modelling techniques provide a set of mathematical equations that describe the behaviour of a system under specific conditions. Models are either modelled as an Open Queuing Network (OQN) or a Closed Queuing Network (CQN). In open queuing networks the parts arrive according to a Poisson process and leave the system when completed. In CQN a fixed number of parts is maintained in the system at all times with no arrivals or departures.

To construct a model workstations and material handling devices are modelled as servers. The storage areas, namely, the input and output buffers, are modelled as queues. The part types are modelled as entities or customers with given routings and processing time distributions. Inputs to the model include the average time a part spends at a particular server (workstation), the average inter-arrival time of the various part types and the average frequency of visits to a particular station. The model provides outputs such as the average values of the expected production rate, mean queue lengths and machine utilisation's.

There are four basic sets of queuing theory based expressions. The simplest system that these equations consider is a 'single-channel, single-phase system'. and represents such situations as one machine performing operations on one type of part. More complex systems are expressed using similar, but more complex, mathematical expressions. The three other categories of expressions that exist, in order of complexity, are: 'single-channel, multi-phase', 'multi-channel, single-phase', and 'multi-channel, multi-phase'.

A.6 Activity Based Costing (ABC)

A description of this technique has been compiled through general reference to Innes and Mitchell (1989), Steeple and Winters (1993), Wizdo (1993) and Barbee (1993). These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description.

The principle of activity based costing is to precisely apportion the costs of an organisation to the products produced or services provided. The approach taken with ABC is to divide overheads, into activity based *cost pools*, and to assign these to products on the basis of consumption of there resources using *cost drivers*. The process is described in more detail as follows with reference to Figure A.3.

First, it is necessary to identify the significant cost elements in the organisation. This requires a reasonably accurate assessment of the major pools of cost. Cost pools need not be by product or organisation, but rather, they must be definitive elements or categories such as material handling costs, energy, or maintenance.

The next step is to identify cost drivers of the most significant costs or those that merit direct control and product cost identity. Examples of cost drivers are machine or kilowatt hours for the energy cost pool; material moves or stationary truck hours for the material handling cost pool; and machine operation hours or production throughput for the maintenance cost pool.

The rate that each activity contributes to a cost pool can then be calculated by determining the use of the cost driver. At this point, the opportunity exists to determine two costs for each product. Expected cost is calculated by determining the expected usage of each driver/activity in the production of each product. Actual cost can be determined, but this requires a procedure for collecting actual usage of activities by product.

In many ways ABC is often seen as a successor to absorption costing techniques. A simplified absorption costing procedure typically uses the following approach to product cost determination. Initially, the overheads of an organisation are listed and then either, directly allocated to a cost centre for which the overheads exist, or an attempt is made to fairly apportion cost to a cost centre on the basis of benefit received. The costs attributed to a cost centre are then considered to be absorbed by the products that pass through that cost centre. ABC differs to absorption costing in the mechanism used to determine the benefits received by a cost centre.

The weakness with absorption costing is that although direct labour and materials are accurately determined, the rules used for apportioning overheads may be arbitrary and inappropriate. For example, consider a manufacturing system which processes two families of products. One product regularly repeats while the other is irregular, requires design modifications, and considerable effort to control, yet both products require the same amount of direct labour, materials, and capacity. In this situation conventional techniques would cost each product family similarly. However, with ABC an attempt is made to consider the disruptive nature of the second product when assigning cost.

A.7 Business Planning (BP)

Description of this technique has been compiled through general reference to Gray (1984), Asch (1991) and West (1988). These authors have been generally referenced in the construction of this summary, and should be referred to for a further more detailed description.

A financial business planning model is a series of projected financial statements about anticipated company financial performance. A typical financial business planning model is based on information about the performance of a business at the start of the time period under consideration. This information is obtained from standard company accounting records such as the balance sheet, profit and loss account, and the overhead analysis. The model is then augmented with sales forecasts and predictions about the financial environment for the period under consideration. Based on these inputs a model would provide, for example, statements of profit and loss accounts, cash flow forecasts and balance sheets. More complex models may provide additional performance information such as financial performance ratios.

The information structure of business planning models is determined by financial conventions. If two modelling techniques were to be compared, assuming identical data inputs and no computational errors, then the techniques would provide the same results.

APPENDIX B: INTRODUCTION TO AUTOPRESS Ltd.

AUTOPRESS is an operating company within the Compounds and Mouldings Group of DSM Resins. This group of companies form one division of DSM IV chemical corporation based in the Netherlands. AUTOPRESS were formally ERF Plastics Ltd, an operating company of ERF Trucks Ltd, Sandbach, Cheshire, England. AUTOPRESS was acquired by DSM IV in 1990. AUTOPRESS itself consists of two manufacturing sites. The larger site is at Winsford, Cheshire, England, and is dedicated to the production of automotive products. The second site is several miles from the first, being at Biddulph Moor, Staffordshire. This second site is focused at the manufacture of products for a range of markets including Construction, Public Utilities, Domestic Appliances, and Automotive. It is this second site which was chosen as a test-bed for modelling techniques, and all future reference to AUTOPRESS will specifically imply this Biddulph site only.

AUTOPRESS manufactures products from thermo-setting plastic. The plastic materials processed by AUTOPRESS are either Sheet Moulding Compound (SMC) or Dough Moulding Compound (DMC). Both materials are glass fibre reinforced thermo-setting compounds that cure under heat and pressure to form tough, lightweight composite parts. SMC produces stronger components and is more suited to large products, for example ERF truck cabs. DMC is more suited to smaller more intricate products such as small handles for domestic appliances. The heat and pressure required to produce these components is applied by an one of sixteen large presses ranging in size from 150 - 2000 Tonnes.

A typical manufacturing cycle for a product at AUTOPRESS starts with a customer order which is typically for a batch of 1000 items. The customer will also probably provide the necessary press tooling. On receiving an order the required material is either purchased or produced in-house and a press is scheduled to produce the product. When a press becomes available the appropriate tooling is loaded into the press and raw DMC or SMC is delivered to the press. Material is fed into the press in quantities equal to that required for one component. Each press stroke compresses the raw material into the required shape and heat is applied, the press will remained closed typically for five minutes while the material is thoroughly heated and cured. When the press opens the finished component is removed, material for the next component is loaded, and whilst the next product is being produced the press operator may perform some simple deburring to the last component produced. Quite often some secondary operations are performed, typically the component may be assembled or receive a small amount of routing. Finished components are loaded onto pallets, shrink wrapping is often applied, and then the product may be delivered or stored awaiting collection by the customer. A more detailed account of this process is given in the data collection section of this report.

The AUTOPRESS manufacturing facility covers an area of 2,800 m^2, there are approximately 110 people working full-time at the site, and the annual turnover is in the region of £8 million.

APPENDIX C: LETTER FROM RAJAN SURI OF NETWORK DYNAMICS Inc.

Manufacturing
Systems Engineering

University of Wisconsin-Madison
College of Engineering

Professor Rajan Suri
Director

253 Mechanical Engineering Bldg
1513 University Avenue
Madison, WI 53706-1572
Phone: 608-262-0921
FAX: 608-265-4017
Email: suri@engr.wisc.edu

February 24, 1994

Mr. Tim Baines
Senior Lecturer, School of Engineering
Staffordshire University
Beaconside, Stafford ST18 0AD
UNITED KINGDOM

Dear Mr. Baines,

Thank you for sending me both your papers and for giving me the opportunity to comment on them. Please accept my apologies for taking so long to read them. There were too many urgent matters requiring my attention! I did however, finally read them during an airplane ride last week.

Regarding the papers themselves, I really do not have any substantial comments. The project that you undertook seemed very well thought out (and quite ambitious!) and you have done a nice job on it. The comments and observations that you made about queueing/MPX were reasonable and fair. So I do not have any concerns about your paper at all.

I do, however, have some answers to the specific questions in your letter:

1. Manufacturing control rules are hard to model. While there has been some progress on this in the literature, the mathematics that exist are for special configurations. Our aim in developing MPX was to allow a lot of flexibility in the system that can be modeled. At the present time I do not know of any math that will work for control rules in general system configurations.

   On the other hand, it is arguable whether the control rules alone influence the performance. While they do to a small extent, it is more so that the improvements which result from the control rules then improve the performance. For example, a pull system forces problem resolution, which then improves throughput. (See the discussion in the attached paper by Suri and deTreville.) So, while I agree that modeling the rules is important, this broader aspect should not be forgotten.

2. System history is likewise very hard to model. Transient analysis of queueing systems is notoriously hard, even for the M/M/1 queue. Good approximations have not yet been developed. I am thinking about this problem though, so maybe in a few years...

   In the meantime, multiple independent runs for each time period is the only way to go for now.

3. I completely agree with your comment about graphical iconic representation. In fact, we are beginning to think about this ourselves and have some ideas. We would definitely welcome your input in this matter.

4. I am happy to hear that you were impressed with the modeling tool, and am also pleased that you would like to construct a prototype which integrates it with several other tools. I have already discussed this with Mr. Michael Tomsicek at Network Dynamics (Madison office) and he is willing to support you on this matter. Please contact him directly at 608-273-4949 (fax 608-273-4922) and he will continue the dialog. If you so desire, I will be happy to remain involved in terms of advising you and Mike on overall concepts and strategy, but it would be best if you discussed operational details directly with Mike.

Thanks again for sending me the papers and for all your comments and feedback on the modeling tool and approach. I wish you the best in your future work on this topic.

Sincerely,

Rajan

Rajan Suri

cc: Mike Tomsicek
Greg Diehl

APPENDIX D: EXPERIMENTAL RESULTS

Note: $IDEF_0$ and IEM were observed to have similar performance, therefore for presentation purposes, these results are grouped together with indications made were any pertinent distinctions exist.

Policy area	IDEF0 / IEM	DES	SD	QT	ABC	BP
(1) **Facilities.** (Factories, number, size, location and focus) Representative issue: Purchase of a dedicated warehouse for storage of finished product stock.	Model modification: Warehouse defined, products shown as routed to warehouse, overall time delay for materials handling introduced. 1. (x) A reduction in product lead times was measured. 2. (o) 3. (o) No structure to consider materials handling utilisation. Noted that materials handling re-assigned and a change in delay introduced though this is a contribution measure. 3. (o) No structure to consider ROI. Conclusion drawn: Financial structure weakness when considering facility decisions.	Model modification: Warehouse defined, products re-routed, materials handling routine and times changed. 1. (x) A reduction in product lead times was measured as a consequence of improved customer service time. This service time improvement was a result of reduced materials handling. 2. (x) A reduction was recorded in the utilisation of materials handling equipment. 3. (o) No structure to consider ROI. Conclusion drawn: Financial structure weakness when considering facility decisions.	Model modification: Warehouse defined, flow of products re-routed. 1. (x) A reduction in product lead times was measured as a consequence of improved customer service time. This service time improvement was a result of reduced materials handling. 2. (x) A reduction was recorded in the utilisation of materials handling equipment. 3. (o) No structure to consider ROI. Conclusion drawn: Financial structure weakness when considering facility decisions.	Model modification: Warehouse defined, products re-routed, estimation of materials handling reduction made for each product. 1. (x) A reduction in product lead times was measured as a consequence of improved customer service time. This service time improvement was a result of reduced materials handling. 2. (x) A reduction was recorded in the utilisation of materials handling equipment. 3. (o) No structure to consider ROI. Conclusion drawn: Financial structure weaknesss.	Model modification: Warehouse investment converted into depreciation rate and allocated to products based on anticipated stock levels within warehouse. 1. (o) No structure to consider product lead time. However, an effect on product cost could seen. 2. (o) No structure to consider materials handling utilisation.. 3. (o) No structure to consider ROI. Conclusion drawn: General structure weakness when considering facility decisions.	Model modification: Warehouse investment introduced into model for specific accounting period. 1. (o) No structure to consider product lead time. However, an effect on product cost could seen. 2. (o) No structure to consider materials handling utilisation 3. (x) The effect of the facility purchase could be expressed in terms of a reduction in ROI. Conclusion drawn: Manufacturing and market structure weakness when considering facility decisions.
(2) **Capacity.** (policy for dealing with output demands) Representative issue: Increase capacity of high volume product manufacture to deal with fluctuations in product demand. Production capacity increased by reorganising machine availability.	Model modification: Additional machine made available for high volume products, products shown as re-routed. 1. (o) No structure to consider the effect of production control rules on lead time. 2. (o) No structure to consider machine utilisation. 3. (o) No structure to consider cash flow. Conclusion drawn: General structure weakness when considering capacity decisions.	Model modification: Additional machine made available for high volume products, control rules at machines modified. 1. (x) A reduction in lead time was recorded for high volume products. 2. (x) A change in machine tool utilisation's resulted from the dedication of machines to a specific product family. 3. (o) No structure to consider cash flow. A reduction in finished goods stock was recorded. This, however, could not be equated to a financial benefit. Conclusion drawn: Financial structure weakness when considering capacity decisions.	Model modification: Additional machine made available for high volume products, adjustment of product flow route. 1. (x) A reduction in lead time was recorded for high volume products. 2. (x) A change in machine tool utilisation's resulted from the dedication of machines to a specific product family. 3. (o) No structure to consider cash flow. A reduction in finished goods stock was recorded. This, however, could not be equated to a financial benefit. Conclusion drawn: Financial structure weakness when considering capacity decisions.	Model modification: Additional machine made available for high volume products, products re-routed on percentage basis. 1. (o) No structure to consider the effect of production control rules on lead time. 2. (x) A change in machine tool utilisation's resulted from the dedication of machines to a specific product family. 3. (o) No structure to consider cash flow. A reduction in finished goods stock was recorded. This, however, could not be equated to a financial benefit. Conclusion drawn: Financial and flow control structure weakness when considering capacity decisions.	Model modification: Model could not be modified to incorporate scenario. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine utilisation. 3. (o) No structure to consider cash flow. Conclusion drawn: General structure weakness when considering capacity decisions.	Model modification: Model modified illustrate an anticipated reduction in stock. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine utilisation. 3. (x) An increase in cash flow could be calculated from reduced stock. Conclusion drawn: Market and manufacturing structure weakness when considering capacity decisions.

Table D.1: Review of the flexibility of modelling techniques

Policy area	IDEF0 / IEM	DES	SD	QT	ABC	BP
(3) Span of process. (Definition of the organisations position in the logistics chain.) Representative issue: Separation of primary product processing from the main manufacturing facility.	Model modification: Illustration of factory division, communication and material flow links. 1. (o) No structure to consider lead time. The effect of batching material could not be considered. 2. (o) No structure to consider machine utilisation. 3. (o) No structure to consider change in profit. Conclusion drawn: General structure weakness when considering span of process decisions.	Model modification: Facility displayed as separate, products transferred in batches between facility and factory, introduction of external orders to the facility. 1. (x) An increase in lead time was measured as a product of increasing the batch quantity and reducing the order frequency. 2. (x) An increase in machinery utilisation was measured at the autonomous facility. This was caused by an introduction. 3. (o) No structure to consider change in profit. Conclusion drawn: Financial structure weaknesss.	Model modification: Facility displayed as separate, products flow between facility and factory modulated by orders arriving to the facility. 1. (0) Effect of batch quantity not considered. 2. (x) An increase in machinery utilisation was measured at the autonomous facility. This was caused by an introduction. 3. (o) No structure to consider change in profit. Conclusion drawn: Financial structure weakness when considering span of process decisions.	Model modification: Facility displayed as separate, products transferred in batches between facility and factory, introduction of external orders to the facility. 1. (x) An increase in lead time was measured as a product of increasing the batch quantity and reducing the order frequency. 2. (x) An increase in machinery utilisation was measured at the autonomous facility. This was caused by an introduction. 3. (o) No structure to consider change in profit. Conclusion drawn: Financial structure weakness.	Model modification: Establishment of transfer product cost, increase in volume of external orders. 1. (o) No structure to consider lead time. The effect of batching material could not be considered. 2. (o) No structure to consider machine utilisation. 3. (x) An increase in profit could be seen from the increase in products processed. Conclusion drawn: Market and manufacturing structure weakness when considering span of process decisions.	Model modification: Establishment of transfer product cost, increase in volume of external orders. 1. (o) No structure to consider lead time. The effect of batching material could not be considered. 2. (o) No structure to consider machine utilisation. 3. (x) An increase in profit could be seen from the increase in products processed. Conclusion drawn: Market and manufacturing structure weakness when considering span of process decisions.
(4) Processes. (Transformation processes and the way in which they are organised) Representative issue: Automation of high volume product manufacture.	Model modification: Change in activity duration time. 1. (o) No structure to consider product cost. A reduction in manpower could not be transposed to a change in product cost. 2. (o) No structure to consider machinery utilisation. 3. (o) No structure to consider ROI. Conclusion drawn: General structure weakness when considering process and technology decisions.	Model modification: Change in process and set-up times of a machinery, reduction in assigned manpower. 1. (o) No structure to consider product cost. A reduction in manpower could not be transposed to a change in product cost. 2. (x) An increase in the utilisation of specific machinery was recorded. 3. (o) No structure to consider ROI. The financial effects of machine modification could not be considered. Conclusion drawn: Financial structure weakness when considering process and technology decisions.	Model modification: Change product flow rate to represent changes in process and set-up times of a machinery, reduction in assigned manpower. 1. (o) No structure to consider product cost. 2. (x) An increase in the utilisation of specific machinery was recorded. 3. (o) No structure to consider ROI. The financial effects of machine modification could not be considered. Conclusion drawn: Financial structure weakness when considering process and technology decisions.	Model modification: Change in process and set-up times of a machinery, reduction in assigned manpower. 1. (o) No structure to consider product cost. A reduction in manpower could not be transposed to a change in product cost. 2. (x) An increase in the utilisation of specific machinery was recorded. 3. (o) No structure to consider ROI. The financial effects of machine modification purchase could not be considered. Conclusion drawn: Financial structure weakness.	Model modification: Change in the content and balance of direct and indirect costs 1. (x) A reduction in product cost was seen. 2. (o) No structure to consider machinery utilisation. 3. (o) No structure to consider ROI. Conclusion drawn: Manufacturing and some financial structure weakness when considering process and technology decisions.	Model modification: Machinery modification costs, estimation of change in product costs. 1. (o) No structure to generate product cost. A reduction in manpower could not be transposed to a change in product cost. 2. (o) No structure to consider machinery utilisation. 3. (x) The financial effects of machine purchase could be seen in terms of ROI. Conclusion drawn: Market and manufacturing structure weakness when considering process and technology decisions.

Table D.1 (cont'd): Review of the flexibility of modelling techniques

Policy area	IDEF0 / IEM	DES	SD	QT	ABC	BP
(5) Human resources. (People related factors, including the workforce, supervisory structure, reward system and workshift design) Representative issue: Setting up quality circles to address issues of machine tool reliability.	Model modification: Model modification: Model could not be modified to incorporate scenario. 1. (o) No structure to consider lead time as queuing could not be considered. 2. (o) No structure to consider machine tool utilisation. 3. (o) No structure to consider overtime costs. Conclusion drawn: General structure weakness when considering human resource decisions.	Model modification: Reduce breakdown probability. 1. (x) A reduction in lead time could be seen from an improvement in machine availability. 2. (x) An improvement in machine utilisation was recorded. 3. (o) No structure to consider overtime costs. Conclusion drawn: Financial structure weakness when considering human resource decisions.	Model modification: Reduce breakdown probability. 1. (x) A reduction in lead time could be seen from an improvement in product flow.. 2. (x) An improvement in machine utilisation was recorded. 3. (o) No structure to consider overtime costs. Conclusion drawn: Financial structure weakness when considering human resource decisions.	Model modification: Reduce breakdown probability. 1. (x) A reduction in lead time could be seen from an improvement in machine availability. 2. (x) An improvement in machine utilisation was recorded. 3. (o) No structure to consider overtime costs. Conclusion drawn: Financial structure weakness when considering human resource decisions.	Model modification: Costpool created for non-productive direct labour costs, allocated to products on the ratio of product volumes. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine tool utilisation. 3. (x) Increase in Overtime costs could be equated to a reduction in profit. Conclusion drawn: Market and manufacturing structure weakness when considering human resource decisions.	Model modification: Direct labour costs increased. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine tool utilisation. 3. (x) Increase in Overtime costs could be equated to a reduction in profit. Conclusion drawn: Market and manufacturing structure weakness when considering human resource decisions.
(6) Quality. (means of ensuring that products, processes and people operate to specification) Representative issue: Introduction of final colour inspection activity on all products.	Model modification: Definition of inspection facility, re-routing of parts, assignment of manpower, facility for scraping sub-standard parts. 1. (x) An increase in lead time was recorded because of the additional inspection activity. 2. (o) No structure to consider machine utilisation. 3. (o) No structure to consider ROI. Conclusion drawn: Financial and manufacturing structure weakness when considering quality systems and procedure decisions.	Model modification: Definition of inspection facility, re-routing of parts, assignment of manpower, detailing materials handling, facility for scraping sub- standard parts, introduction of scrap probability. 1. (x) An increase in lead time was recorded because of the additional inspection activity. 2. (x) The utilisation of the inspection activity was measured. 3. (o) No structure to consider ROI. Equipment purchase could not be introduced. Conclusion drawn: Financial structure weakness when considering quality systems and procedure decisions.	Model modification: Definition of inspection facility, re-routing of product flow, assignment of manpower, facility for rerouting sub-standard parts, introduction of scrap probability. 1. (x) An increase in lead time was recorded because of the additional inspection activity. 2. (x) The utilisation of the inspection activity was measured. 3. (o) No structure to consider ROI. Equipment purchase could not be introduced. Conclusion drawn: Financial structure weakness when considering quality systems and procedure decisions.	Model modification: Definition of inspection facility, re-routing of parts, assignment of manpower, general detailing of materials handling, facility for scraping sub-standard parts, introduction of percentage scrap. 1. (x) An increase in lead time was recorded because of the additional inspection activity. 2. (x) The utilisation of the inspection activity was measured. 3. (o) No structure to consider ROI. Equipment purchase could not be introduced. Conclusion drawn: Financial structure weakness when considering quality systems and procedure decisions.	Model modification: Costpool set-up for inspection facility, costs directly allocated to all products on basis of volumes. This approach adopted as costs were directly assigned to products and not cost centres.. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine utilisation. 3. (o) No structure to consider ROI. Conclusion drawn: General structure weakness when considering quality systems and procedure decisions.	Model modification: Introduction of equipment purchase, estimation of change in product costs. 1. (o) No structure to consider lead time. 2. (o) No structure to consider machine utilisation. 3. (x) The effect of the facility purchase could be expressed in terms of a reduction in ROI. Conclusion drawn: Manufacturing and market structure weakness when considering quality systems and procedure decisions.

Table D.1 (cont'd): Review of the flexibility of modelling techniques

Policy area	IDEF0 / IEM	DES	SD	QT	ABC	BP
(7) Control policy. (Organisational infrastructure which concerns planning and control systems, operating policies, and lines of authority and responsibility) Representative issue: Introduction of MRP II manufacturing planning and control system.	Model modification: Identification of planning and control activities effected by computer system, estimation of in change of activity duration, identification of activities receiving additional information and estimation of impact. 1. (o) No structure to consider lead time. Control rule situation too complex. 2. (x) A reduction in scheduling activity was recorded. This was achieved because service activities could be easily considered. Not strictly utilisation but significant benefit in this situation. 3. (o) No structure to consider cash flow. Conclusion drawn: Market and financial structure weakness when considering control system decisions.	Model modification: Input of raw materials based on stock re-order levels and not production schedule, introduction of push control rules. 1. (x) A reduction in lead time was achieved because of greater availability of component stock. 2. (x) A reduction in scheduling activity was recorded. 3. (o) No structure to consider cash flow. An increase in wip was recorded because of the stocking policy and push system. The conventional manual system had promoted particularly lean manufacture. Conclusion drawn: Financial and structure weakness when considering control system decisions. Also, difficult to address service activities because of focus of tool specifically and technique generally.	Model modification: Input of raw materials based on stock re-order levels and not production schedule. 1. (x) A reduction in lead time was achieved because of greater availability of component stock. 2. (x) A reduction in scheduling activity was recorded. 3. (o) No structure to consider cash flow. An increase in wip was recorded because of the stocking policy and push system. The conventional manual system had promoted particularly lean manufacture. Conclusion drawn: Financial and structure weakness when considering control system decisions. Also, difficult to address service activities because of focus of tool specifically and technique generally.	Model modification: Manufacturing procedure reduced to consider only manufacture and no delivery of products. 1. (x) A reduction in lead time was achieved. However, confidence limited because of an inability to consider stock conditions and push rules. 2. (o) No structure to consider a reduction management utilisation. 3. (o) No structure to consider cash flow. Conclusion drawn: General structure weakness when considering control system decisions.	Model modification: Model modification: Model could not be modified to incorporate scenario. 1. (o) No structure to consider lead time. 2. (o) No structure to consider a reduction management utilisation. 3. (o) No structure to consider cash flow. Conclusion drawn: General structure weakness when considering control system decisions.	Model modification: Investment in computer system incorporate. 1. (o) No structure to consider lead time. 2. (o) No structure to consider a reduction management utilisation. 3. (o) No structure to consider cash flow because control rules can not be considered by this technique. Conclusion drawn: General structure weakness when considering control system decisions.

Table D.1 (cont'd): Review of the flexibility of modelling techniques

Policy area	IDEF0 / IEM	DES	SD	QT	ABC	BP
(8) Suppliers. (The level of materials control between suppliers and manufacturers) Representative issue: Purchase of all raw materials from external suppliers on a lowest cost basis.	Model modification: Removal of surplice machinery, re-routing of products, setting up a material acquisition facility to trigger material delivery. 1. (o) No structure to consider delivery performance. 2. (x) The material acquisition service could be clearly illustrated. Although strictly no utilisation could be measured, it is significant that the activity was modelled. 3. (o) No structure to consider profit. No financial implications could be recorded for selling off of old equipment. Conclusion drawn: General structure weakness. However, significant capability to model service activities .	Model modification: Removal of surplice machinery, re-routing of products, setting up a material acquisition facility to trigger material delivery. 1. (x) A degradation of delivery performance resulted from poorer raw material delivery performance. 2. (x) A utilisation was measured for the new material acquisition facility. This however, required considerable effort to model. 3. (o) No structure to consider profit. No financial implications could be recorded for selling off of old equipment. Conclusion drawn: Financial structure weakness when considering supplier decisions.	Model modification: Removal of surplice machinery, re-routing of products flow, setting up a material acquisition facility to trigger material delivery. 1. (x) A degradation of delivery performance resulted from poorer raw material delivery performance. 2. (x) A utilisation was measured for the new material acquisition facility. This however, required considerable effort to model. 3. (o) No structure to consider profit. No financial implications could be recorded for selling off of old equipment. Conclusion drawn: Financial structure weakness.	Model modification: Removal of surplice machinery, re-routing of products. 1. (o) No structure to consider delivery performance. 2. (o) The material acquisition service could not be adequately modelled. 3. (o) No structure to consider profit. No financial implications could be recorded for selling off of old equipment. Conclusion drawn: General structure weakness when considering supplier decisions. Particularly difficult to model the effect of the service facility.	Model modification: Removal of surplice machinery from Costpool, reallocation of costs, increase in direct material costs. 1. (o) No structure to consider delivery performance. 2. (o) The material acquisition service could not be adequately modelled. 3. (x) An increase in profit was recorded. Conclusion drawn: Manufacturing and market structure weakness when considering supplier decisions.	Model modification: Removal of surplice machinery from capital, increase in direct material costs. 1. (o) No structure to consider delivery performance. 2. (o) The material acquisition service could not be adequately modelled. 3. (x) An increase in profit was recorded. Conclusion drawn: Manufacturing and market structure weakness when considering supplier decisions.
(9) New products. (Mechanisms for coping with new product introduction, including the communication infrastructure between design, the factory floor and marketing) Representative issue: Modification of new product introduction procedure.	Model modification: New product introduction modelled, re- routing of products, assignment of additional personnel. 1. (o) No structure to model lead time. 2. (o) No structure to model manpower utilisation. 3. (o) No structure to consider profit. Conclusion drawn: General structure weakness when considering new product introduction decisions.	Model modification: New product introduction modelled as a direct manufacturing activity, re- routing of products, assignment of additional personnel. 1. (x) A reduction in lead time was recorded from the improved procedure. 2. (x) A change in manpower utilisation was recorded. 3. (o) No structure to consider profit. Conclusion drawn: Financial structure weakness when considering new product introduction decisions.	Model modification: New product introduction modelled as a direct manufacturing activity, re- routing of products, assignment of additional personnel. 1. (x) A reduction in lead time was recorded from the improved procedure. 2. (x) A change in manpower utilisation was recorded. 3. (o) No structure to consider profit. Conclusion drawn: Financial structure weakness when considering new product introduction decisions.	Model modification: New product introduction modelled as a direct manufacturing activity, re- routing of products, assignment of additional personnel. 1. (x) A reduction in lead time was recorded from the improved procedure. 2. (x) A change in manpower utilisation was recorded. 3. (o) No structure to consider profit. Conclusion drawn: Financial structure weakness when considering new product introduction decisions.	Model modification: Additional indirect personnel costs. 1. (o) No structure to model lead time. 2. (o) No structure to model manpower utilisation. 3. (x) An increase in profit was recorded. Conclusion drawn: Manufacturing and market structure weakness when considering new product introduction decisions.	Model modification: Additional indirect personnel costs. 1. (o) No structure to model lead time. 2. (o) No structure to model manpower utilisation. 3. (x) An increase in profit was recorded. Conclusion drawn: Manufacturing and market structure weakness when considering new product introduction decisions.

Table D.1 (cont'd): Review of the flexibility of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(1) Lead time Time from receiving an order to despatching the product.	1. An overall value for Lead time is given. However, the output is of a coarse, static, nature. 2. Techniques act as a mechanism to capture and refine, through decomposition, the model builders estimation of a system's Lead time. Values of Lead time at subsystem levels have to be input, these are then aggregated by the technique to provide an overall value for Lead time. 3. The techniques contains no mathematical functionality to provide generation of Lead time based on a precise calculation of the content, characteristics and interactions of the elements present in a system.	1. Lead time provided either as an average value or a time dependent profile. 2. Because of flat nature of models, Lead time contribution from support activities can be overlooked. 3. WITNESS currently introduces the user in at man, machine level.	1. Product flow can be 'time stamped' to allow Lead time to be measured. 2. Lead time can still be measured even after a number of flows have combined.	1. An average value of Lead time provided. 2. Again, because of flat nature of models, Lead time contribution from support activities can be overlooked. 3. MPX currently introduces the user at man, machine level. 4. MPX tool gives graphical output of composition of Lead time, includes for example, time a part spent waiting for a machine.	1. No capability.	1. No capability. 2. Lead time is actually required as an INPUT into models. 3. There is no mechanism to check that the Lead time input is actually achievable

Table D.2: Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(2) Delivery (1) Make to order How well quoted Lead time is maintained. Measured in terms of Percentage of products overdue. or (2)Make to stock. Is sufficient stock available to satisfy customer orders. Measured in terms of average amount of time customer waits for products.	1. No capability. 2. Models contained anticipation of Lead time, which is equivalent to the 'quoted' value of Lead time. No mechanism for calculation of actual Lead time is present. 3. Due to static nature of the techniques, the models constructed could not generate information about the average time that a customer waits.	1. Model generated Lead time can be compared to an anticipated Lead time and, if appropriate, a overdue time can be presented. 2. The amount of time that a customer has to wait for a product can be recorded. 3. The second case was modelled in WITNESS by setting a machine to remove stock from a 'finished stock' buffer. The cycle time of the machine represented the frequency between customer calls, and the process batch quantity represented the order quantity. If the machine had to wait for products this time was taken as a measure of delivery performance.	1. In principle model generated Lead time can be compared to an anticipated Lead time and, if appropriate, a overdue time can be presented. 2. The amount of time that a customer has to wait for a product can be determined.	1. No capability. 2. There is no mechanism to compare model generated Lead time to anticipated Lead time. This, however, can be argued to be a software issue as the basic Lead time information is provided by the technique. 3. For make to stock the customer delivery profile is required by the model (this is considered to be an acceptable input). This profile must consist of product delivery quantities and frequency. Both of these can be statistical expressions. An average batch size can be included into the model but not the delivery frequency. Hence, this performance measure can not be generated.	1. No capability.	1. No capability.

Table D.2(cont'd): Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(3) **Volume** Quantity of products produced.	1. As with Lead time, volume is an 'INPUT' into the models provided by these techniques. 2. A value for volume can be provided by the model builder by introducing a value for volume into a model as an attribute of one activity. Realistically this activity would be the perceived *capacity constraint* in a system. This value is then automatically displayed at the highest level of the model. 3. Values of volume could be attached to several activities. These would then be aggregated as a sum to one value at the highest level of the model. Such an approach can be dangerously inaccurate. 4. The value for volume is again the model builders estimation of a systems performance. No measure of the true capabilities of a system is made.	1. Volume of products produced can be generated. 2. Fluctuations in volume can be measured using time-series. 3. Summary of volume can be given using histograms.	1. Volume of products produced can be generated. 2. Fluctuations in volume can be measured using time-series. 3. Summary of volume can be given using histograms.	1. Volume is an INPUT as well as an OUTPUT. The quantity of products required per time period must be defined during model building. 2. Model execution is based on fulfilling the volume required, in the time specified, using the manufacturing capacity of the model. 3. If the volume cannot be achieved by the manufacturing system, the model execution terminates. The user is requested to alter the model configuration until execution is achievable.	1. No capability. 2. Volume is required as an INPUT to generate actual product costs.	1. No capability. 2. Volume is required as an INPUT to generate product sales turnover, overall material costs, etc.,

Table D.2(cont'd): Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(4) **Cost** Establishing individual product cost.	1. No capability. 2. Product cost could not be provided as the relationship between 'activity and service activities' could not be specified. 3. DESIGN/IDEF alleges to offer an ABC capability. However, when this technique is considered in detail it is actually a mechanism for storing a cost attribute at an activity and lacks the essential cost driver structure. 4. Furthermore, if an attribute is assigned to activity there is only a mechanism to allocate cost in the simplest cases. Differing product families and time spent at an activity can not be considered.	1. No capability. 2. Product cost could not be provided as the relationship between 'activity and service activities' could not be specified. 3. Such a relationship can be specified using the tool, however this is a reflection on the programing power of the tool being able to encapsulate a financial model. 4. If an overhead rate is independently established, the technique can be used to update a 'cost' attribute of a product. This is a case of cost allocation and not generation.	1. No capability. 2. Product cost could not be provided as the relationship between 'activity and service activities' could not be specified. 3. Such a relationship can be specified using the tool, however this is a reflection on the programing power of the tool being able to encapsulate a financial model. 4. If an overhead rate is independently established, the technique can be used to update a 'cost' attribute of a product. This is a case of cost allocation and not generation.	1. No capability. 2. Product cost could not be provided as the relationship between 'activity and service activities' could not be specified. 3. No capability to allocate cost to product attributes.	1. A capability exists to generate product cost information. 2. Cost drivers act as a mechanism for distributing overhead costs to core activities or products. 3. Model output has to be augmented with an estimation of product sales volumes to establish individual product costs. However, there is no functionality that checks that such product volumes can be produced by the manufacturing system. 4. Stock holding costs are not considered in calculation of product costs. 5. The mechanism is flexible and can be can figured to reflect absorption costing system. 6. Product cost is taken from a static, historical, perspective.	1. No capability. 2. Product costs are required as an INPUT into the model.

Table D.2(cont'd): Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(5) **Contribution** The contribution of an activity or series of activities to market and financial performance measures.	1. Lead time: values for Lead time can be inspected at each point in the hierarchy of a model. However, these are coarse values with no distinction between products. 2. Delivery: no capability. 3. Volume: input at perceived capacity constraint - coarse and dangerously open to misrepresentation. 4. Cost: no capability.	1. Lead time: time taken between any two points can be measured. 2. Delivery: both forms of delivery can be considered within a manufacturing system. 3. Volume: volume of products at any point can be measured. 4. Cost: no capability.	1. Lead time: time taken between any two points can be measured. 2. Delivery: in principle both forms of delivery can be considered within a manufacturing system. 3. Volume: volume of products at any point can be measured. 4. Cost: no capability.	1. Lead time: comprehensive profile of contributing activities to Lead time is given. 2. Delivery: no capability. 3. Volume: input for whole model, volume through sub-sets of activities is not given but can be calculated. 4. Cost: no capability.	1. Lead time: no capability. 2. Delivery: no capability. 3. Volume: no capability. 4. Cost: overall product cost or the cost of core activities (hence machine hour rates) can be provided. Also supports identification of where costs exist in support functions of an organisation.	1. Lead time: no capability. 2. Delivery: no capability. 3. Volume: no capability. 4. Cost: no capability.
(6) **Utilisation** A measure of business at an activity. Measured as a percentage of time available.	1. No capability.	1. The level of activity utilisation can be measured. 2. Utilisation can be measured in terms of total time available or on-shift time. 3. This measure can be monitored as the system evolves.	1. A value for utilisation can be determined by comparing the maximum flow rate through a resource with the actual flow rate	1. The average level of activity utilisation can be measured.	1. No capability.	1. No capability.
(7) **Profit** Profit or loss before tax and interest. Based on a financial period being the year prior to the month being considered	1. No capability - due to the inability of the technique to generate product cost.	1. No capability - due to the inability of the technique to generate product cost.	1. No capability - due to the inability of the technique to generate product cost.	1. No capability - due to the inability of the technique to generate product cost.	1. Based on an estimation of product volumes, and product selling price, the profit of the manufacturing activity can be estimated.	1. Calculation of profit based on product cost, sales, volume, information, etc., which have been input into the model.

Table D.2(cont'd): Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(8) **Cash flow** Accumulated difference between receipts and payments.	1. No capability.	1. No capability.	1. No capability.	1. No capability.	1. No capability.	1. Calculation of cash flow based on product cost, sales, volume, information, etc., which have been input into the model.
(9) **Turnover** Total product sales based on a user input of selling price.	1. No capability.	1. No capability. 2. Technique can provide an prediction of the quantity of products a system is capable of providing. However, no mechanism exists to consider this volume with the product selling price. Can be argued to be a software issue as the basic volume information is provided by the technique. However, strictly speaking the calculation is a simple financial model. Using the capabilities of the tool to perform this calculation is effectively combining two techniques.	1. No capability. 2. Technique can provide an prediction of the quantity of products a system is capable of providing. However, no mechanism exists to consider this volume with the product selling price. Again, Can be argued to be a software issue as the basic volume information is provided by the technique. However, strictly speaking the calculation is a simple financial model. Using the capabilities of the tool to perform this calculation is effectively combining two techniques.	1. No capability. 2. Technique can provide an prediction of the quantity of products a system is capable of providing. However, no mechanism exists to consider this volume with the product selling price. Again, Can be argued to be a software issue as the basic volume information is provided by the technique. However, strictly speaking the calculation is a simple financial model. Using the capabilities of the tool to perform this calculation is effectively combining two techniques.	1. No capability. 2. Total sales turnover is required as an INPUT for each product family.	1. Calculation of turnover based on product sales volume information, etc., which have been input into the model.
(10) **ROI** Return on Investment. Based on a financial period being the year prior to the month being considered	1. No capability.	1. No capability.	1. No capability.	1. No capability.	1. No capability.	1. Calculation of ROI based on product cost, sales, volume, information, etc., which have been input into the model.

Table D.2(cont'd): Review of the performance measurement capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(1) Time transition behaviour. Support of time dependent model behaviour.	1. No capability. 2. Only a static snap shot of a systems behaviour provided.	1. Time dependent behaviour exhibited. 2. Model behaviour against time can be recorded using 'Time series graphs'. 3. Time/behaviour characteristic of each activity approximated to discrete event.	1. Time dependent behaviour exhibited. 2. Time increments determined by user input. Can be changed to favour precision or model execution speed 3. Essential that appropriate value of time is chosen if elements are defined has having discrete behaviour.	1. Considers average behaviour of a manufacturing system over a defined time period. 2. Behaviour variance during the time period not provided.	1. No capability. 2. Strictly, only a static snap shot of a systems behaviour provided. 3. Pseudo-dynamic behaviour can be provided if time averaged values are input.	1. Provides time slices of a systems behaviour. 2. Time slices linked to take account of system history. For example, the calculation of Cashflow. 3. Standard time slice time period of one month used in model. Typical time horizon of model is 3 years.
(2) Dynamic content change. Support of model reconfiguration at a pre-defined instance in time	1. No capability.	1. Model can be constructed to effectively change content at a specified instance in time. 2. Example of content change. At time=100 days, stop routing parts to old machine and start routing parts to new machine.	1. Pulsation in flow can be used to represent influx of products or other resources. Such resources could be machines, manpower, etc,.	1. Modelling tools do not support dynamic content change. 2. Content change can be modelled coarsely by using 'time slices'. First time slice considers time period up to model reconfiguration. Second time slice considers re configured model. 4. Time slicing limited as models do not consider system history. For example, the stock built up at the end of one time slice is not considered in the subsequent time slice.	1. No capability.	1. Change in system content can be specified to take place at an instance in time. 2. A change in content, such as an investment in a machine tool, would be introduced as a change in the company's fixed assets.

Table D.3: Review of the time transition capabilities of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(1) Stage 1 ***Build time.***	1. Build time of 40 hours for IDEF0 and 35 hours for EM. 2. Construction of coarse top level model. 3. Estimates included for delays before activities	1. Build time of 68 hours. 2. Basic model constructed to include machines, parts, and basic manufacturing control rules.	1. Build time of 30 hours. 2. Basic model constructed to include rates for machines, part flows, and basic interactions between flows.	1. Build time of 24 hours. 2. Preparation of data into appropriate form. Construction of basic model to include machines and parts.	1. Build time of 42 hours.	1. Build time of 22 hours.
Accuracy.	1.Accuracy recorded to be 80%.	1.Accuracy recorded to be 63%.	1.Accuracy recorded to be 60%.	1.Accuracy recorded to be 64%.	1. Inappropriate to consider model accuracy as model structure based on accounting convention. (see above).	1. Inappropriate to consider model accuracy as model structure based on accounting convention. (see above).
(2) Stage 2 ***Build time.***	1. Build time up to 68 hours for IDEF0 and 59 hours for EM. 2. Construction of model to three levels of decomposition.	1. Build time up to 116 hours. 2. Model modified to include labour and more comprehensive manufacturing control rules.	1. Build time up to 50 hours. 2. Model modified to include labour and more comprehensive manufacturing control rules.	1. Build time up to 32 hours. 2. Model modified to include labour and coarse labour availability to reflect shift restrictions.	1. Measurement not appropriate.	1. Measurement not appropriate.
Accuracy.	1.Accuracy recorded to be 80%	1.Accuracy recorded to be 92%	1.Accuracy recorded to be 72%	1.Accuracy recorded to be 75%	1. Measurement not appropriate.	1. Measurement not appropriate.
(3) Stage 3 ***Build time.***	1. Total build time up to 90 hours for IDEF0 and 79 hours for EM. 2. Detailed model with six levels of decomposition.	1. Total build time 156 hours.. 2. Final model development including materials handling and order scheduling and customer collection activities.	1. Total build time 64 hours.. 2. Final model development to include complex manufacturing control logic.	1. Total build time 42 hours. 2. Final model development including assignment of manpower to set-ups and materials movement. 3. Detailed materials handling not considered as complexity would be significantly increased.	1. Measurement not appropriate.	1. Measurement not appropriate.
Accuracy.	1.Accuracy recorded to be 80%	1.Accuracy recorded to be 94%	1.Accuracy recorded to be 88%	1.Accuracy recorded to be 86%	1. Measurement not appropriate.	1. Measurement not appropriate.

Table D.4: Review of model build time, accuracy and credibility of modelling techniques

Issue	IDEF0 / IEM	DES	SD	QT	ABC	BP
(4) Experimentation time. Time taken for the completed model to execute. Computer hardware consistent	1. Model execution time effectively zero.	1. Time for one model execution is 21 min for a simulated run time of 11 weeks. 2. This time recorded on a 33MHz computer in BATCH mode. 3. Good practice would require several independent runs to be performed, each run would contain different random number streams.	1. Time for model execution depends on time increment chosen.	1. Time for one model execution is less than 1 min for a simulated run time of 1 year.	1. Model execution time effectively zero.	1. Model execution time effectively zero.
(5) Credibility. How believable is the modelling mechanism. Workshop of various personnel at company. (last presentation). Score of 10 means that the individuals involved would invest their money on the basis of the models predictions. Score of 1 means that the individuals have no confidence in the model.	1. Credibility score of 5, 6. 2. Decomposed structure can be confusing, and difficult to trace links between some activities. Generally overcome by triangular presentation approach. 3. EM has a relaxed syntax which promotes better credibility. 4. IDEF0 gives richer model description because a distinction between controls and inputs is given. However, EM has a relaxed syntax which promotes better credibility and reduced model building time.	1. Credibility score of 9. 2. Credibility achieved by computer animation of manufacturing system operation.	1. Credibility score of 7. 2. Credibility assisted by animation of manufacturing system operation. 3. Some scepticism shown be personnel in relating flow nomenclature to discrete product manufacture.	1. Credibility score of 3. 2. Credibility constrained by lack of graphical representation of system. 3. Static, but iconic, representation of system suggested.	1. Credibility score of 3. 2. Lack of graphical expression about underlying mechanism meant that structure was difficult to communicate.	1. Credibility score of 2. 2. Serious concern about the ability of manufacturing to behave as suggested by the technique. 3. Technique contained considerable features that were redundant in this instance. These caused some confusion which subsequently threatened credibility.

Table D.4: (cont'd) Review of model build time, accuracy and credibility of modelling techniques

APPENDIX E: INTRODUCTION TO DORMANS DIESELS Ltd

Dorman Diesels was established in 1897, for the purpose of the design and manufacture of diesel and gas fuelled engines. It was later bought by GEC, and as such, became part of GEC Diesels Ltd. Today, it continues to be involved in the same business. Its current owners are Broadcrown Ltd., who are based in nearby Stone, Staffordshire. They purchased the company from GEC in 1987.

As it exists today, Dorman Diesels employs over 550 people, and is split between two sites, Stafford and Lincoln. The Lincoln site is primarily a warehouse operation, and it is here that the responsibility lies for the storage and supply of spare parts. However, it is also responsible for the machining of the crank cases. The Stafford site is the main one, and it is the location at which the experimentation was carried out. All the other operations are carried out here, from the initial design of component, jigs and fixtures, through to their manufacture and final testing. Virtually every operation is carried out 'in-house', although the exception to this is the production of the raw material castings, which are currently contracted out.

The company has an international dealer network, spanning 120 countries. Hence, offering a comprehensive sales and service network. Dorman Diesels manufacture and supply a range of gas and diesel engines for the purpose of power generation. The engines are designed to a number of criteria, of which, the principle ones are long term reliability with constant power output, and a start-up time of under 10 seconds, to provide an operational speed of either 1500 RPM or 1800 RPM. New engine designs are under development, but the current engine production is centred around the SE range, which has been around since 1982.

The SE, range consists of four basic models, each having a number of different options available. The main option is whether the engine is to be powered by gas or diesel fuel. Other options are available to cater for marine applications, and various other upgrades on the basic models. In addition to this current range, orders are still accepted for all the earlier engine ranges. Although few of these are now built, there are still quite a number of these in use, and so spares requests are still fairly common.