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NEWTON B MATUPI

Prediction of Manufacturing Flexibility by the Use of Simulation Modelling

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ABSTRACT

Flexibility is seen as a desirable attribute of a manufacturing system. Virtually every manufacturing organisation wants it, but find it difficult to define, predict or measure. Most researchers look inwards to try to obtain measures. This research defines a framework that provides a structured methodology for developing flexibility requirements. The framework ensures that the flexibility requirements are derived from manufacturing objectives that relate to business strategy. This way flexibility becomes an issue that is driven by the business needs and not just by the advances in technology. Through the framework all the important factors of the business as a whole are considered in the design of the manufacturing system. The research examines the tactical level of decision making in detail. A simulation model was developed to predict the performance of a manufacturing system faced with various types of flexibility requirements. The model was used to convert potential flexibility to demonstrated flexibility, thereby predicting the manner in which the manufacturing system might perform. The results from the model showed the performance of the whole system and these were related to the contribution that flexibility makes to the overall manufacturing objectives. However, it was also observed that different types of models may be required depending on the nature of the decisions. Through the development of the mechanism for evaluating flexibility requirements, it was observed that much time was invested in the definition of flexibility requirements and how these contributed to the manufacturing strategy. This shows that much time needs to be spent on the definition of flexibility requirements before evaluation can take place.

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CHAPTER 1

BACKGROUND

This chapter provides the background information on which this thesis is based. It highlights the problems which manufacturers have to overcome in order to compete in today's environment and the reason for them believing that manufacturing flexibility offers the competitive advantage that is so much needed. This chapter will also provide some information, specifically, in relation to the changes facing manufacturers of packaged consumer goods, generally referred to as fast moving consumer goods (FMCG).

During the past decade the business environment has become more volatile and unpredictable for all types of manufacturers, and the competition is worldwide. This was confirmed by Collins and Schmenner (1993) who said that in recent years, consolidation of the retail trade has created hypermarkets and chains that frequently dominate retail distribution. Their size, market share, and high-volume-low-price strategies force manufacturers to trim margins and lower costs. "As a result, retailers demand from consumer packaged goods manufacturers, rapid, frequent delivery of fast moving items and extensive, ever changing product diversity.", (Collins and Schmenner 1993). Customers are demanding a higher level of service, quality, dependability and lower prices from the suppliers. The pressure on manufacturers is set to intensify more than it has ever done at any time in the past. Introduction of new products has become more frequent and order quantities have reduced significantly as retailers are striving to reduce operating costs and maximise use of the limited shelf space.

For manufacturers to achieve low cost, rapid and frequent deliveries, and fast introduction of new products, as demanded by the customer, flexibility in manufacturing systems is seen as the answer. This was confirmed by Stalk (1988) who said a flexible factory enjoys more variety with lower total costs than traditional factories.

Thilander (1992) wrote regarding the changes in the international competitive climate of the chemicals industry which has been caused by over capacity and scale related effects among other things. This resulted in the industry attempting to produce in small batch sizes more frequently. Most manufacturers including those in the fast moving consumer goods industry had for many years made products in large batch quantities and the products had a long life cycle. The products were mostly made using dedicated equipment. The length of the product life cycle and the high demand volumes justified having dedicated production equipment since the product life cycle spanned a long period of time. There was less risk of not achieving the desired return on the investment made in the equipment.

As was observed by De Meyers (1989), since the 1970s manufacturing has been used as a competitive weapon. This was not only in the metal industry, the fast moving consumer goods industry also saw in the 1970s the beginning of increased competition between manufacturers of fast moving consumer goods. This has affected the chemicals industry as well, as shown by Thilander (1992). In recent years there have been numerous mergers and acquisitions as companies establish themselves in the international market. Large companies seek to establish critical mass and strengthen their presence in the enlarged marketplace but at the same time they have to meet the requirements of the local needs. The food industry provides a good example of meeting local needs because of different tastes and preferences in types of food and drink. Manufacturing companies are having to become more adaptive to meet the increasingly changing market requirements to meet the global nature of the competition.

Product safety and quality have always been taken as minimum qualifying requirements for consumer products. Manufacturing companies do still regard quality as a major competitive advantage but the competition has reached different levels. It is not only product safety and quality that the companies have to be good at, but a host of other competitive requirements. This was confirmed in the survey of competitive priorities by De Meyers (1992) which showed the competitive priorities being set by

manufacturing organisations. As most fast moving consumer products have, in the past, been produced on mass, the production cost per unit has been very low but now companies have to achieve low costs while making smaller batch quantities.

Stalk (1988) said that like competition itself, competitive advantage is a constant moving target. For any company in any industry the key is not to get stuck with a single simple notion of source of advantage. Flexibility of manufacturing systems is the requirement. De Meyers (1989) observed that since the 1970s, interest in the use of manufacturing and manufacturing strategy as a competitive weapon has gradually been increasing. Therefore, if manufacturing and manufacturing strategy are to be used as a competitive advantage, they have to constantly keep improving. This can only be achieved if manufacturing systems are flexible. Jordan and Graves (1996) also said increasing manufacturing flexibility is a key strategy for efficiently improving market responsiveness in the face of uncertain future product demand.

Companies faced with these new challenging competitive pressures have responded in a number of ways. Hill and Chambers (1991) said that in recent years many manufacturing companies have responded to the competitive pressures by investing in new production technologies and advanced inventory control systems. The new technologies are purchased because they are perceived as offering increased flexibility. Flexibility of manufacturing systems is seen as a way to provide the means by which manufacturing can move closely with the changing market requirements. Fast moving consumer goods manufacturers have not escaped these competitive pressures.

Flexibility is seen to have the capability to offer highly desirable attributes which are seen as providing a number of inherent competitive advantages. The capability of a flexible manufacturing system needs to be defined adequately in order to specify the system with the right attributes. However, this does not seem to have been achieved, as can be seen from a statement made by Hill and Chambers (1991) who said, *"However, appropriate measures for flexibility have not been developed but they are essential if adequate and relevant analysis is to be undertaken when evaluating*

significant capital investments". Gupta (1994) said that despite recognition of manufacturing flexibility as a formidable competitive weapon, measurement of it has remained difficult. Sarker et al. (1994) also concluded that further work is required to enable the definition and the measurement of manufacturing flexibility.

This chapter has introduced the problem with which manufacturers of fast moving consumer goods are faced. Most manufacturers see flexibility of manufacturing systems as the solution to most problems in the ever-changing manufacturing environment. The key driving forces for flexibility are as follows:

1. Customers demand small order sizes and frequent deliveries.
2. Market competition, which has resulted in companies using manufacturing strategy as a source of competitive advantage.
3. Technology advances are being exploited to provide manufacturing flexibility.

However, measures for evaluation and implementation of the flexibility of manufacturing systems have yet to be developed.

CHAPTER 2

MANUFACTURING FLEXIBILITY

2.1 INTRODUCTION

This chapter reviews the appropriate literature which covers definition and assessment of the flexibility of manufacturing systems covering the relevant topics which refer to general flexibility rather than machine specific issues. The gaps in the current research will be identified, hence the need for further research. In recent years there has been a steady growth of literature in the areas of manufacturing strategy and manufacturing flexibility. Increasingly manufacturing companies are formalising their strategy. This provides the opportunity to formalise the methods used for selecting the required manufacturing technologies.

The main sections of the literature review are:

1. The meaning of manufacturing flexibility;
2. The importance of manufacturing flexibility;
3. The analysis of manufacturing flexibility;
4. Quantitative measures for manufacturing flexibility;
5. Manufacturing flexibility and automation;
6. Dynamic simulation models for flexibility;
7. The need for further research.

2.2 THE DEFINITION OF MANUFACTURING FLEXIBILITY

This part of the chapter examines views from different authors about the meaning of manufacturing flexibility. The way in which flexibility is perceived may influence the methods used to analyse it.

One of the most comprehensive definitions of manufacturing flexibility so far is that by Upton (1994). Manufacturing flexibility was defined as the ability to change or react

with little penalty in time, effort, cost or performance. Other authors have defined flexibility in a slightly different way but in most cases they are subsets of the above definition. Buzacott & Mandelbaum (1985), Gupta & Goyal (1991) and Tincknell & Radcliffe (1996) defined manufacturing flexibility as the ability of a manufacturing system to cope with changing circumstances. Cox (1989) defined manufacturing flexibility as the quickness and the ease with which the plant can respond to changes in the market conditions. Mascarenhas (1981) defined manufacturing flexibility as the ability of a firm to cope with instability caused by the environment. Zelenovic (1982) defined the flexibility of a production system as a measure of its capacity to adapt to changing environmental conditions and process requirements.

The number of ways in which manufacturing flexibility is perceived by different people demonstrates the complexity of the subject. All these definitions which refer to coping with changing circumstances, quickness and ease of response to change and the capability to adapt are correct in their own right. This shows that there are many types of issues for which flexibility may be required. Some definitions have only considered an aspect of this multi-dimensional attribute of manufacturing.

This section has examined the meaning of manufacturing flexibility from the literature. It may be concluded that a manufacturing system may use its flexibility to introduce change to enable the organisation to enhance its competitiveness or to respond to competitive pressures. For example, a manufacturing system might use its flexibility to enable it to introduce new products, processes or services to the market quickly. Here, flexibility is shown in the ability of a system to instigate change for competitive advantage. The system must also be able to ensure that stability concerning the system's ability to produce or supply is maintained when disturbances occur. For example, a manufacturing system has to maintain its customer service level at a minimum cost in spite of fluctuating demand and equipment breakdown.

In summary, manufacturing flexibility can be defined as the ability of a manufacturing system to accommodate changing requirements and to cope with uncertainty within the

environment in which it operates, with little time or financial penalty. Penalty in time may reflect the effort or the ease with which the change is made, and these together with performance may contribute to the cost penalty.

2.3 THE IMPORTANCE OF FLEXIBILITY

This section examines the perceived importance of manufacturing flexibility. The perceived importance of the flexibility of a manufacturing system may influence the amount of effort invested in its analysis and the support provided by senior management.

Stecke and Raman (1995) said "While global competition has clearly underlined the need for enhanced productivity, shorter product life cycles and greater product proliferation and market fragmentation indicate that manufacturing flexibility is essential for the long-term viability of many firms".

Hill and Chambers (1991) said that the concept of flexibility of manufacturing systems has received unprecedented attention from equipment suppliers, specifiers and users alike. There are many reasons why manufacturing flexibility is regarded as an important attribute of a manufacturing system. Flexibility along with cost, quality and dependability is considered as an important dimension of manufacturing strategy, Hayes and Wheelwright (1984). Chen and Chung (1996) also confirmed that manufacturing flexibility is becoming a key dimension for the competitiveness of a manufacturing organisation. The correlation between manufacturing performance and flexibility has been considered as an important decision variable in formulation of manufacturing strategy in recent years. Tombak (1988_1), through a study of 1455 business units found that the performance of a manufacturing organisation is correlated with manufacturing flexibility. It was also found that flexibility had a more significant effect in the growth phase of the product life cycle than in the mature phase. This indicates the importance of recognising that as strategy changes in the life of a product, so will the required flexibility of the manufacturing system.

Tombak (1988_2) mainly discusses automated Flexible Manufacturing Systems, but also mentions the importance of long range planning and that flexibility is an integral element of such strategic thinking. He also observed that the firms that survive in the long run are those that are able to adapt to the changing market environment because they have been flexible in their manufacturing. These are the firms that build flexibility into their manufacturing systems as they decide future manufacturing strategy.

De Meyers (1989) said that for four years previous to 1985 research teams at INSEAD (Fontainebleau, France), Boston University (Boston, USA) and Waseda University (Tokyo, Japan) carried out a yearly survey on large manufacturers about their manufacturing future. The object of the research has been to understand the competitive environment within which the large manufacturers have to operate and the type of manufacturing strategies and policies they develop in order to provide a response to this environment. De Meyers, et al. (1989) compiled data to assess the priorities which a number of manufacturing companies pursue in order to meet the concerns of today's manufacturing environment as shown in Table 2.1.

Table 2.1: Manufacturing priorities survey: from De Meyer et al. (1989).

Europe	North America	Japan
1. Consistent quality (1)(1)(1)	1. Consistent quality (1)(1)(1)	1. Low prices (1)(1)(1)
2. High performance products (3)(2)(2)	2. High performance products (2)(2)(3)	2. Rapid design changes (2)(2)(2)
3. Dependable deliveries (2)(3)(3)	3. Dependable deliveries (3)(3)(2)	3. Consistent quality (3)(3)(2)
4. Fast delivery (6)(6)(5)	4. Low prices (6)(5)(5)	4. Dependable deliveries (4)(4)(5)
5. Low prices (5)(5)(6)	5. Fast delivery (4)(4)(4)	4. Rapid volume changes (6)(6)(6)
6. Rapid design changes (5)(5)(6)	6. Rapid design changes (7)(5)(7)	6. High performance products (4)(4)(4)
7. After-sales service (8)(8)(7)	7. After-sales service (5)(7)(6)	7. Fast delivery (8)(7)(7)
8. Rapid volume changes (7)(7)(8)	8. Rapid volume changes (8)(8)(8)	8. After-sales service (7)(8)(8)

Note: The priorities are listed according to their importance as ranked in the 1986 survey. Numbers within parentheses indicate the ranking of the competitive priorities in the surveys of 1983, 1984, 1985 respectively.

The main findings in the analysis were:

a) There was a remarkable stability in the pattern of competitive priorities in manufacturing over the years the data were collected. Therefore, manufacturing strategies that consider fundamental manufacturing issues do not need to come and go like fashionable ideas.

b) There was a strong similarity between North America and Europe in the issues that were seen as priorities. Both had the same top three priorities: the ability to provide consistent quality, the ability to deliver high-performance products and the ability to be a dependable supplier. Flexibility can contribute to the improvement of most of the top 12 priorities such as, production and inventory policies, dependability, low price, lead time reduction, introduction of new products and new processes, reduction of set up time, giving workers a broader range of tasks and making manufacturing strategy clearer.

In North America, Europe and Japan, providing low price, which could imply low production costs, is seen as of great importance but it is dealt with in different ways by these countries. At times low prices were achieved by taking advantage of the exchange rates. In most cases low costs, which may consequently lead to low prices, are achieved by the use of sensible manufacturing strategy. The survey showed that America and Europe are still trying to overcome the trade off between flexibility and cost efficiency. However, these priorities are not seen as a reflection of existing strengths or capabilities.

It was reported in this survey that the Japanese research team defined competitive priorities in manufacturing by the use of four dimensions: quality, dependability, cost-efficiency and flexibility. To offer dependability a company needs, at least, to qualify for a minimum level of quality. To be cost-efficient it has to qualify for a minimum level of quality and dependability. To become flexible it has to have a minimum level of quality, dependability and cost-efficiency. These issues of quality, dependability, cost and flexibility are not dealt with as alternative points of emphasis but rather they are addressed sequentially over time. The analysis suggests that the Japanese had at this point reached an appropriate level of quality, dependability and cost-efficiency to start pursuing flexibility as a competitive priority while maintaining the level of the other priorities.

Roller and Tombak (1988), analysed the strategic implications of production technology choice in a game theoretic setting. In the game, two firms were simultaneously committed to a selected production technology. There were two differentiated products, each characterised by a linear function, with a positive cross-price effect. If a manufacturing organisation chose to invest in flexible manufacturing technology, it could produce both products, whereas dedicated technology could only produce one of the two products. The model also took into account quantity competition.

This research concluded that when consumers perceived the markets for different products being more related, the industry was driven to adopt flexible technologies. As the market became more profitable and as the distinction between the fixed technologies diminished, there was increased incentive to adopt flexible manufacturing systems. In general, the same market forces that would push firms towards adoption of flexible systems will tend to ensure that total welfare is maximised, which means that the consumer, the worker and the company all benefit from the use of flexible systems. When flexible technology is for purely strategic purposes it yields a transfer of welfare from producers to consumers.

2.4 ANALYSIS OF TYPES OF FLEXIBILITY

This section of the chapter examines the literature about the methods used to analyse the flexibility of a manufacturing system.

Researchers such as Buzacott (1982) and Browne (1984) have used taxonomies of aspects of manufacturing flexibility while Slack (1987) and Upton (1994) have defined multi-dimensional frameworks to analyse various types of flexibility. In most cases these have been presented in the form of a taxonomy. The contents of the taxonomies are very much influenced by the authors' backgrounds or the specific area in which research is involved. This part of the chapter reviews the way in which literature has defined and analysed manufacturing flexibility.

2.4.1 INTERNAL AND EXTERNAL CHANGES FRAMEWORK

Buzacott (1982) suggested that the flexibility of a manufacturing system can be evaluated by considering the nature of changes or disturbances which affect the operation of the system. He suggested that the changes and disturbances should be classified as internal and external. Using this approach evaluation of manufacturing systems starts with defining the elements that compose the system, thus defining the scope of the system. Once the boundaries of the system have been defined, the nature of the changes that are to be encountered by the system are defined and grouped according to the two classes.

Changes are external if they include factors such as product mix, processing requirements, number of jobs assigned to the system, skills of the operators assigned to the system. Changes are internal if they are disturbances caused within the system, for example, machine and materials handling systems breakdown, variability in processing time, quality problems and operator absence. An important point to note is that the boundaries of a system may include sub-systems, thus external changes in one system could become internal in another.

2.4.2 ACTION AND STATE FLEXIBILITY FRAMEWORK

Mandelbaum and Brill (1989) said that action flexibility relates to situations such as high level planning, plant expansion, engineering economics and introduction of new products. The system has action flexibility if it requires intervention from outside to cope with the changes. The external intervention normally comes from senior management on medium and long term issues. This type of flexibility could be defined as the capacity for taking new action to meet new circumstances. A well designed manufacturing system will require little external intervention regarding short term problems.

A system has state flexibility if its capacity to respond to changes is contained within the system. The system has the capability to absorb the changes, thus making the system self sufficient in dealing with the changes. Therefore, a system could be said to have state flexibility if it has the capability to continue functioning effectively despite the changes in circumstances in the short term, Mandelbaum and Brill (1989). Gupta and Goyal (1989) in their review of literature on flexibility referred to the same issue and emphasised that a system is more effective if change can be contained within the system.

2.4.3 JOB FLEXIBILITY AND PROCESS FLEXIBILITY FRAMEWORK

Buzacott (1982) defined job flexibility as the ability of a manufacturing system to cope with changes in the job to be processed by the system.

One of the ways to increase flexibility is by increasing the capability of the machines to adapt to changes in the job. The system is made more versatile, therefore more complex, and also the system will need to be provided with quick change mechanisms.

At the system level job flexibility can be achieved by distributing the required capability among a wide range of machines or production lines, each would be specialised to do certain tasks. This then introduces the need to move jobs between machines or work stations in order for different tasks to be completed.

Machine flexibility is defined as the ability of a system to cope with changes and disturbances at the machine and the work station. This type of machine flexibility can be achieved by quick changeover, fast repairs after breakdown and providing a carefully planned machine maintenance schedule.

Buzacott (1982) said that at the system level machine flexibility can be achieved by providing a wide range of machines or production lines that have similar capabilities. This shows that there may be different considerations at different levels of the system.

2.4.4 EIGHT TYPES OF FLEXIBILITY FRAMEWORK

Browne, et al (1984) defined eight types of manufacturing flexibility to clarify the condition under which a manufacturing system may be termed 'flexible' in relation to Flexible Manufacturing Systems (FMS). Although the emphasis was put on describing flexibility in integrated and automated computer controlled manufacturing systems, the principles of flexibility are of interest. The types of flexibility were as listed below.

a) Machine flexibility

Machine flexibility was defined as the ease of making the machine changes required to produce a given set of part types. Machine flexibility would take into consideration, for example, the time to replace worn-out or broken cutting tools, the time to change tools in the tool magazine to produce a different subset of the given part types and the time to assemble and mount new fixtures required. Machine flexibility also takes into consideration the set-up time required for the machine tool to switch from making one part type to another including: cutting tool preparation time, part positioning and release time, and NC program changeover time.

b) Process flexibility

Process flexibility was defined as the ability to produce a given set of part types, each possibly using different materials, in different ways. Process flexibility enables each part to be machined individually, and not necessarily in batches.

c) Product flexibility

Product flexibility was defined as the ability to changeover to produce a new product economically and quickly. The flexibility takes into account the time required to switch from making one part type to another, not necessarily of the same part type.

d) Routeing flexibility

Routeing flexibility was defined as the ability to handle breakdowns and to continue to produce the given set of parts. The flexibility exists if a part type can be processed using several routes, or equivalently, if each operation can be performed on more than one machine. Benjaafar et al. (1995) also investigated the effects of routeing flexibility on the performance of a manufacturing system.

e) Volume flexibility

Volume flexibility was defined as the ability of a manufacturing system to produce products economically at different production volumes. This is achieve mainly by low machine set-up time and low variable costs such as direct labour. Highly automated systems have a greater capability of attaining volume flexibility. The flexibility could be measured by how small the volume can be for all product types with the system still being run profitably. However customer service is an important issue to consider as well as profitability.

f) Expansion flexibility

Expansion flexibility was defined as the capability of a manufacturing system to expand easily and modularly. The ability of one machine or a group of machines to increase their volume capability and increasing the range of products that can be processed by installing more machines in a modular manner.

g) Operational flexibility

Operational flexibility was defined as the ability to interchange the ordering of several operations for each product type. There is usually a predetermined order in which operations should be carried out, but with operational flexibility it is possible not to predetermine the next operation or machine.

h) Production flexibility

Production flexibility was defined as the universe of product types that a manufacturing system can produce. To attain this flexibility the other seven types of flexibility are required. None of these types of flexibility are independent. Some types of flexibility would require a more complex planning system than others.

The types of flexibility may not all be required at the same time. The list of flexibility types shown above is comprehensive but it requires a framework under which the flexibility required for a particular system may be determined.

2.4.5 A FLEXIBILITY FRAMEWORK BASED ON TYPES OF CHANGE

Hill and Chambers (1990) observed the changes that forced manufacturing companies to adopt manufacturing systems that were flexible. The observations showed that most companies were taken by surprise by the changes that took place in the 1980s. Many reacted by down-sizing their operations and postponing investment, which did not in itself restore competitiveness - it was a "minimising harm" strategy. For some companies the results went unnoticed as they were in the form of incremental change.

Hill and Chambers (1990) also noted that other businesses responded to the loss of total volume by offering a wider product range and more customisation. The orders received reflected the market proposals based on offering a wider range of products. This led to many smaller orders. Therefore, the manufacturing companies had to start

manufacturing in smaller batches. The advantage of flexible equipment was beginning to be seen.

The changes which necessitated the need for flexible manufacturing systems, as observed by Hill and Chambers (1990), are shown below.

a) Capital-Related Change

A decision to offer a wider range of products was followed by a recognition that competitors gained advantage by replacing products more frequently. This resulted in shortening of product life cycles. The total output of a product during its life was reduced, making investment in equipment more expensive per unit. To increase the total volume output over the life of the machine, more flexible machines were preferred over dedicated ones.

b) Change Induced by Customers

As customer orders reduced in size because of changing customer order practices, companies providing subcontract capability also experienced the effect of the decline. This lead to the development of "Just-in-Time" systems so that inventory levels could be reduced.

c) Change in Equipment

Makers of manufacturing equipment started to appreciate the need for increased flexibility and greater attention was being given to reduction of set up time. This was achieved by improved design of machines, standardisation of equipment and application of computerisation.

The types of changes listed above show the reason why flexibility may be required. These changes may have influenced the decision taken by firms in relation to the choice

of systems that have been adopted. However, a framework is required to analyse the type of flexibility that may be required for each type of change that has been described above.

2.4.6 PRODUCT DESIGN, PRODUCTION, LAYOUT AND FLEXIBILITY

Andreasen and Ahm (1986) examined the relationship between product design, production, layout and flexibility in an assembly system. In Table 2.2, market trends are listed along side the production implications that are as a result of the trends.

Table 2.2: Actions and their causes: from Andreasen and Ahm (1986)

MARKET TRENDS	PRODUCTION IMPLICATION
- Short market life cycles; - Increased competition; - Increased technical development rate; - Smaller market margins; - Increased quality demands on products.	- Developing new products more frequently; - Offering a higher number of variants; - Aiming at short times of delivery; - Reducing the production costs; - Ensuring a higher product quality.

Six types of flexibility required to meet the changes in a product's life cycle were identified as shown below.

a) Planning flexibility

This was described as the suitability of the assembly system to be structured at the planning stage according to the actual tasks spectrum for a given product range.

b) Running-in Flexibility

This was described as the ability of the assembly system to be built up and run-in easily and in a controlled manner, for the given task. New changes in the process will require a renewed running-in process.

c) Insensitivity

This was described as the ability of the assembly system to accept variation in the assembly sequence. Uniform components and a few conversions of the assembly system reduce the demand on insensitivity.

d) Versatility

This was described as the ability of the system to be changed over easily to another foreseen assembly task. The products affect versatility by acting uniformly to the assembly system.

e) Adaptability

This was described as the ability of the assembly system to accept in the new and unforeseen products. It is, therefore, possible to affect the design of these products in favour of the assembly system.

f) Reusability

This was described as the ability of a system to accept rebuilding for other tasks. At this stage, entirely new products with new variance are designed. The products are subject to tight restrictions in design if they should be assembled by a new assembly system.

The conclusion from the study, firstly, showed that the need for flexibility in an assembly system could be reduced by the use of flexible product design. Secondly, the flexibility of an assembly system is established when the layout is designed and to a lesser degree as a result of the subsystems such as robots.

2.4.7 A MULTI-DIMENSIONAL FRAMEWORK

As it has been shown in the above literature, flexibility can take on many dimensions. Gerwin (1993) said that most treatments of flexibility assume it is multi-dimensional but provide no theoretical basis for finding its relevant dimensions and so he defined dimensions as shown in Table 2.3. Dixon (1992) defined mix and modification flexibilities but also added the new-product dimension.

Table 2.3: Dimensions of flexibility: from Gerwin (1993)

Type of Uncertainty	Strategic Objective	Flexibility Dimension
Market acceptance of kinds of product	Diverse product line	Mix
Length of product life cycles	Product innovation	Changeover
Specific product characteristic	Responsiveness to customers' specification	Modification
Aggregate product demand	Market share	Volume
Machine down time	Customers' due dates	Re-routeing
Characteristics of materials	Product quality	Material
Changes in the above uncertainties	Strategic adaptability	Flexibility responsiveness

Slack (1983) suggested that a system's flexibility could be considered as the sum of more than one type of flexibility. A three dimensional approach was used, where the three dimensions are the range of states which a system can possess; the cost of moving from one state to another; and the time that it takes to move from one state to another. This forms a framework from which traditional production management task areas can be examined as shown in Table 2.4.

Table 2.4: The dimensions of flexibility: from Slack 1983

	THE DIMENSIONS OF FLEXIBILITY	
TYPES OF FLEXIBILITY	The RANGE of feasible change	The COST of making a change The TIME necessary for a change
The ability to make something novel	Process technology Labour skills	Product design Process technology Job design Material management Organisational design
The ability to make a product mix	Process technology Facility layout and job design Capacity management	Product design Production planning and control Materials management Process technology
The ability to change quality level	Process technology Labour skills	Labour and management attitudes Payment system
The ability to change the volume of output	Capacity management	Manpower policies Material management
The ability to change delivery times	Production planning and control Capacity management	Production planning and control Materials management

Slack and Correa (1992) defined three levels of analysis to deal with flexibility research. By defining these levels it showed the importance of the infrastructural flexibility. Most of the literature dwells much on the resource flexibility and ignored the infrastructure. The three levels are as shown below.

1) The level of the firm, where flexibility issues concern the ability of the whole organisation to change its strategic position while keeping its functional strategies coherent.

2) The level of the function, where flexibility issues concern the ability of the operations function to change the nature, volume or timing of its outputs.

3) The level of the resources of the operation, where flexibility issues concern, for example, the variety of tasks which individual people, machines, or control systems can perform, and the time, cost or difficulty of changing between tasks.

The study concentrated on the functional level but using eight classifications of manufacturing flexibility similar to those listed in Table 2.4.

A framework used as a basis for field research was developed by Upton (1994) in an attempt to characterise flexibility without the use of taxonomies of types of flexibility. The framework uses dimensions, time horizon and elements to define the concerned flexibility as shown in Figure 2.1.

The dimension describes what needs to be changed or be adopted. This defines the flexibility that is required without imposing predetermined categories. The dimension may be continuous, such as output rate or discrete such as number of products. The dimension may at times be abstract but the aim is to define the dimension of change as precisely as possible.

The time horizon describes the general period over which changes will occur, minute by minute, days, weeks or years. Operational flexibility is associated with the day to day changes. Tactical flexibility is associated with the occasional change or adaptation. The longer term changes are usually associated with a larger degree of commitment and with strategic flexibility.

Elements define most important aspects of flexibility that are to be managed. These are in the form of range, uniformity of performance across the range and mobility. Flexibility is concerned with one or more of these elements.

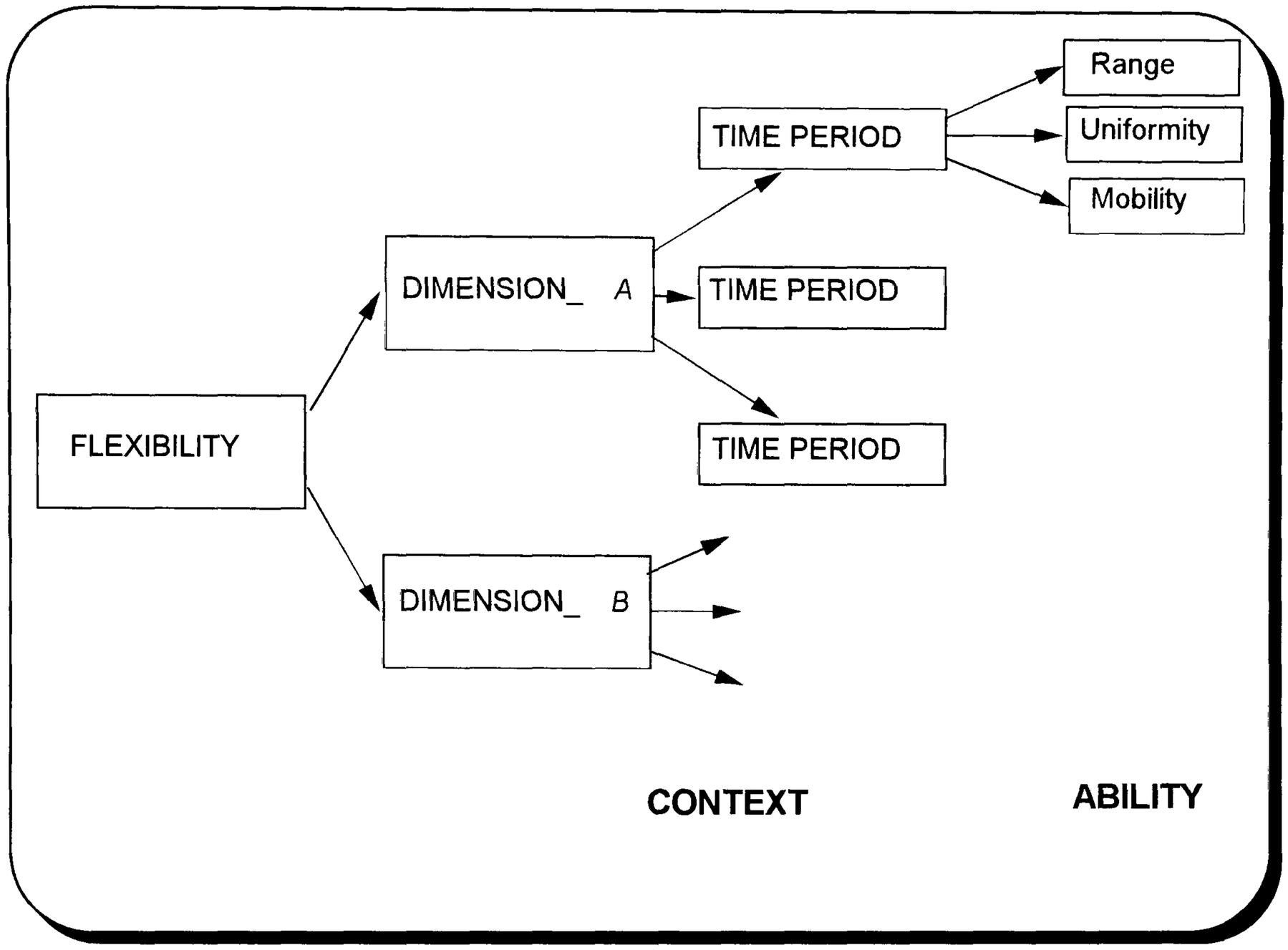

Figure 2.1: The flexibility framework: Upton (1994)

Range defines the limits within the identified dimension of change across which variation may be made or tolerated. Increased range is seen as providing more flexibility.

Within the identified range the system will have differential performance. Performance may be defined as appropriate for a particular application. Uniform performance across a range is seen as being more flexible.

Mobility concerns the ability to move from point to point within the range. A low value of transition costs imply mobility in the space. Mobility may be measured in time or cost change or both.

Gustavsson (1984) recognised that a concept such as flexibility could not fall nicely into a simple standard pattern. However, a classification was made to assist with the clarity of types of flexibility as shown in Table 2.5.

Table 2.5: Classification of types of flexibility: from Gustavsson (1984)

ASPECT	MODE OF FLEXIBILITY
Capacity	Change of volume
Product	Design, models, generations
Steering system	Structural programmes, raw materials/primary products
Production	Direction, flow
Machinery	Machines, tool, fixtures
Personnel	Competence, structure

Some indicative approaches to solving these problems were discussed by Gustavsson (1984) as shown below.

a) Demand flexibility

If there is little risk that the demand will change significantly, investment in fixed capacity may be the ideal solution. However, if there is a risk that the demand may vary significantly, investment could be made in small parallel steps.

b) Product flexibility

If there is a likelihood that there will be frequent product and model changes, then the product should be designed in such a way that changes can be carried out step by step without major changes to the product structure.

c) Flexibility of machinery

Gustavsson (1984) suggested that if it is very likely that there will be a technological change from, for example, steel to plastic, then it is advisable to employ subcontractors who have several other customers with other products which facilitate the technological transfer.

The principle of parallel product lines and parallel production machines is very plausible but the idea of the use of subcontractors begs the question whether the company has become more flexible by doing so.

Eppink (1978) defined three types of change which could be related to unforeseen changes. These changes were classed as operational, competitive or strategic. These changes may also be classed as reversible or irreversible, the terms used by Rhenman (1973) in Eppink (1978).

Reversible changes are define as random or cyclic variations around a stable mean. The example of this are seasonal purchasing patterns or periodic inflow of orders for a manufacturing firm. Irreversible changes are defined as the variations that build up to a permanent change in the mean. Example of these are emergence of new technology or growing concerns about pollution. The author draws a resemblance between operational changes and reversible changes. Irreversible change falls in either the competitive or strategic range.

Types of changes and the time scale over which they take place are the issues presented in this situation. However, according to Upton (1994), this is only one level of consideration in the framework for determining the flexibility of a manufacturing system.

Mandelbaum and Buzacott (1986) suggested that the need for flexibility could be eliminated if precise estimates about future events could be obtained because the

system could be designed to cope with these events. As it was realised that it is difficult to obtain precise estimates for future events, a decision theoretic approach was proposed according to which, flexibility is an objective and its desirability is dependent on the decision-maker's uncertainty about the future. It has been shown however, that this leads to a multiple criteria decision problem.

2.5 FLEXIBILITY - A MEANS TO OTHER ENDS

From the literature reviewed in the previous sections, it can be seen that flexibility, as a concept, has enjoyed unprecedented support from all quarters of the manufacturing industry including marketeers, equipment suppliers, academics, operations managers and customers. However, each one of these perceives flexibility in a very different way. Flexibility can only be justified on the basis of it being able to enhance the competitiveness of the manufacturing firm. For flexibility to be successful, one must be able to quantify the contribution it makes to the whole system. This, therefore, means that flexibility should be included in the development of a manufacturing strategy. From these facts it can be deduced that flexibility is an attribute of manufacturing strategy used to meet an objective or a set of objectives. This was illustrated by Slack (1987) in the manufacturing flexibility hierarchy shown in Figure 2.2.

In established markets, quality, product availability, delivery reliability and value for money are expected by all customers. This makes flexibility indispensable as it is the way through which these prerequisites can be achieved.

Flexibility in a manufacturing system can be realised through the inherent characteristics of the systems, processes, equipment and people, and through organisational procedures and control. The inherent characteristics of the system are dependent upon the way in which systems, equipment, processes and products are designed, and the way in which the operators are trained. The control activities are to

do with the infrastructure, these include the capability to plan and schedule production for effective response and to cover a range of product mixes.

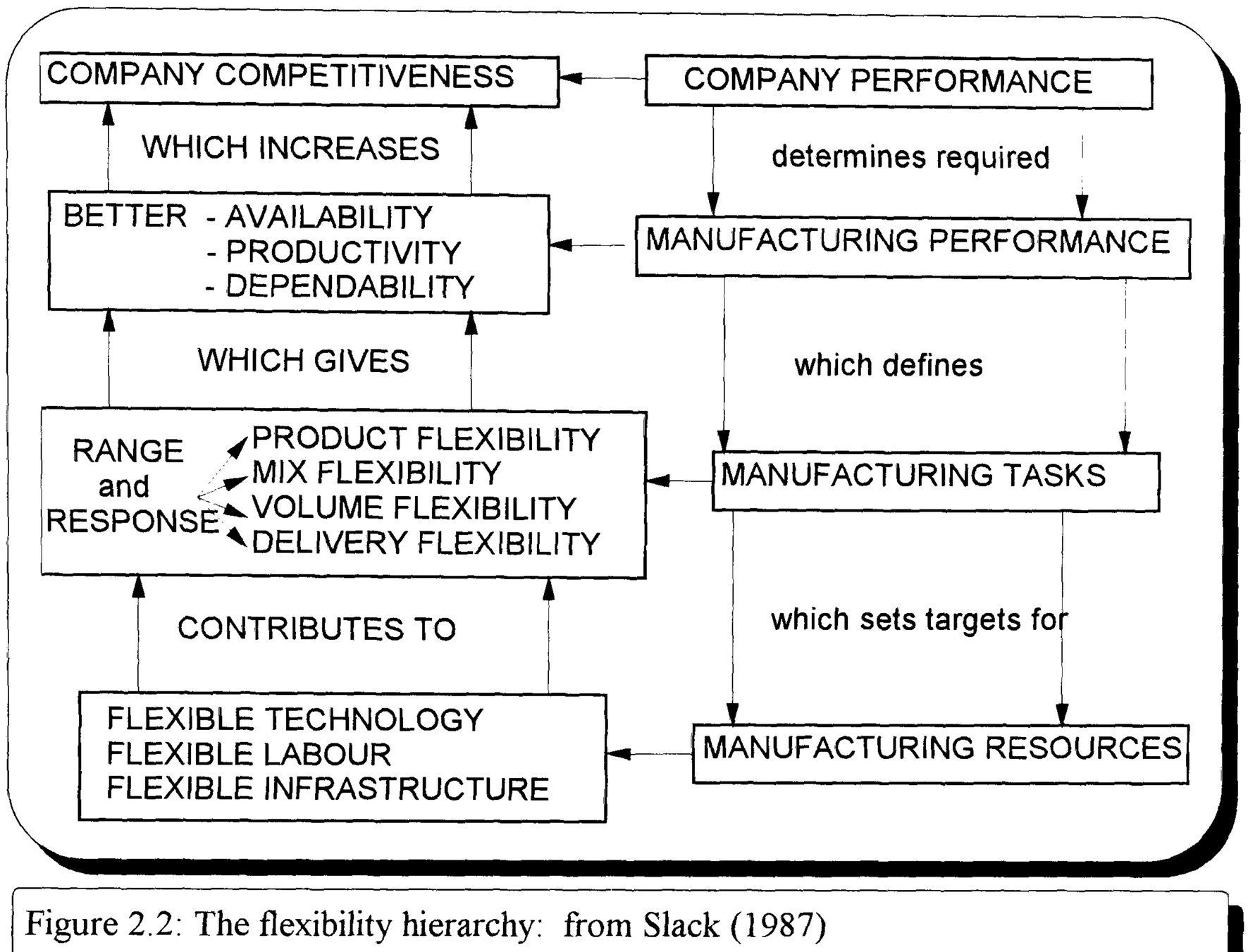

Figure 2.2: The flexibility hierarchy: from Slack (1987)

Often flexibility is seen as expensive because of its association with automated production machines which were at times implemented without careful consideration of the business objectives. If it were to be analysed to see what flexibility as an attribute to a manufacturing strategy actually does, it will be found that flexibility enhances competitiveness when delivered within reasonable costs.

Slack (1983) suggested that manufacturing objectives must encompass as wide a range of operating attributes as the corporate strategy dictates. Slack (1983) has also shown that in addition to efficiency measures which were suggested by Skinner (1978), quality, customer lead time, reliability of promised dates given, return on investment, flexibility to introduce new products, flexibility to handle substantial volume changes, product mix changes and appropriate social criteria must be included.

Wild (1980) suggested that objectives fall in two groups: those related to customer service and those that related to resource productivity. The former includes specification of product, its cost to the customer and its timing (delivery delay for manufacturing systems). The latter includes the productivity of physical facilities, labour and materials. A further customer service objective, reliability, exists as a qualification to be applied to the other customer service objectives.

Slack (1983) suggested that in addition to achieving particular levels of performance, a system will want to achieve levels of dependability and flexibility for each of them. Table 2.6 shows how the two aspects of customer service objectives interact to give five types of system flexibility. These types of flexibility apply to a complete manufacturing system, for a smaller manufacturing unit or a department a different list might be appropriate.

Table 2.6: Types of system flexibility: from Slack (1983)

	LEVEL (What you want to achieve)	DEPENDABILITY (How reliable you want to achieve it)	FLEXIBILITY (How far and how easily you could change what you want to achieve)
PRODUCT SPECIFICATION	The ability to manufacture products a) of a particular design or performance b) in a particular mix	The ability to consistently achieve promised product performance or mix of products	The ability to a) make something or b) to change to a different product mix
QUALITY	The ability to achieve a particular level of quality	The ability to consistently achieve the desired quality level	The ability to change quality level
VOLUME OF OUTPUT	The ability to manufacture at a particular rate	The ability to meet particular targets consistently	The ability to change the volume of outputs
DELIVERY	The ability to deliver within a particular period from customer order	The ability to meet delivery promises consistently	The ability to change delivery times

There are several types of flexibility which could result from applying the concept to other customer service objectives that describe output. This section of the chapter has demonstrated that flexibility does not stand in isolation. It is a means of increasing the performance of the manufacturing firm. Remembering also, that the performance of the firm is measured by the achievement of its business objectives.

2.6 QUANTITATIVE MEASURES

This part of the chapter discusses the methods that have been used to quantify flexibility. Some measures are illustrated by the use of examples.

Slack (1983) observed that the ability of a system to change the way in which it operates is determined exclusively by its production management and the decisions they take in task areas such as those listed in Figure 2.3 The ability of a production manager to recognise the need to change is more difficult than these task areas in the way they affect flexibility. The factors which determine the system's ability to change can be ranked in order of how readily their contribution to its flexibility can be described.

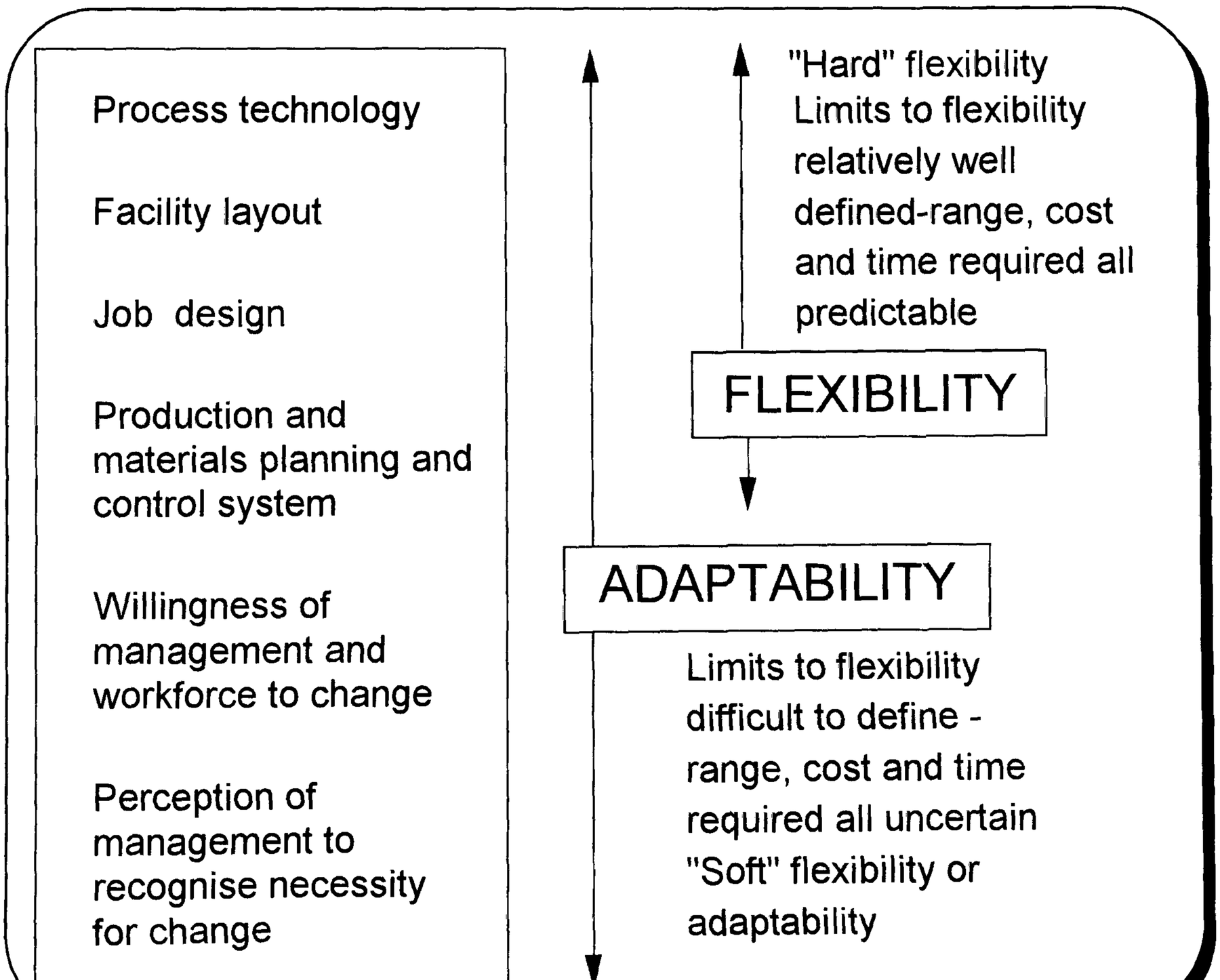

Figure 2.3: Flexibility factors: from Slack (1983)

The factors which will ultimately determine how far and how easily a system can change are ranked in Figure 2.3. At the top are factors which are termed as factors of "hard flexibility", whose flexibility might be directly measurable. At the bottom of the list are the "soft flexibility" factors which although having a considerable influence over how the system actually behaves, are far less readily accessed. The distinction between these factors is that some give potential to change the system's way of operating and others contribute to its adaptability.

This distinction is likened to the one used by Zelenovic (1982), who defined the effectiveness of a production system as a function of:

a) Its operational readiness, measured in the time taken to make a change, what Slack (1983) has called adaptability and Upton (1994) has called mobility.

b) Its design adequacy, measured as the system's ability to change to what the environment demands at a particular cost, what Slack (1983) has called hard flexibility.

c) Its reliability, a measure of the probability of the system's ability to adapt.

Here flexibility is said to be different from other manufacturing objectives because it is a measure of potential of certain behaviour. The operating behaviour does not have to be demonstrated for the system to be attributed with the ability to change. It is also recognised that there can be no single measure for flexibility.

Slack (1983) noted that the difficulty in measuring the flexibility of a system as a whole seems to be due to three factors:

a) It is a measure of potential rather than performance.

b) It is not a single concept, but needs to be applied to the other production objectives of product specification, quality, volume and delivery.

c) It has three dimensions, range (which may itself consist of several elements), cost and time.

For these reasons, the flexibility of a production system may not always be measured in a straight-forward sense.

The difficulty that arises in measuring flexibility was shown by Tombak (1988_2) who wrote that "While the profit impact of production costs is direct and clear, the effects of factors such as quality, dependability and flexibility are more indirect, as they depend on such extraneous factors as buyer behaviour and costs involved in creating the system".

2.6.1 FLEXIBILITY AND ADAPTIVITY

Zelenovic (1982) stated that a measure of the flexibility of production systems can be observed as the value of design adequacy for it to be able to adapt itself to environmental conditions and to the process requirements within the limits of the given design parameters. He then continued to provide a measure which had previously been used by Scimigalla (1977) and was called "The flexibility of system spaced structure". This measure attempts to evaluate the time needed for the system adaptation from one task to another. The measure used was named degree of co-operation (k) in the form of:

$$k = \frac{2(\bar{i}-1)\,\bar{K}_{ei}\,\eta_i}{\bar{q}_j \bar{t}_{ii} \alpha}$$

where:

$\bar{i}$	average number of operations
$\bar{K}_{ei}$	the effective capacity of machine i.
$\bar{q}_j$	average quality over a given period of time.
$\bar{t}_{ii}$	average operation time.
α	degree of similarity of parts in materials flow.
η_i	degree of utilisation (load).

Cox (1989) identified the key dimensions for product-mix flexibility and volume flexibility in order to quantify the flexibility of a production system. Against each key dimension, a measure of flexibility is applied as shown in Table 2.7.

Table 2.7: Flexibility elements and their measures: from Cox (1989)
Notes: 1. (-) indicates an inverse relationship between this item and flexibility.
2. Measures for all entries except Element 2 should be percentages.

PRODUCT FLEXIBILITY	
Element	**Measure(s)**
Vendor Network: 1. Lead time on orders(-)	 % inputs which can be obtained in X days or less
Labour: 2. Number of job classifications(-) 3. Extent of worker cross-training 4. Extent of worker "doing" multiple jobs	 100 minus number of job classifications % of work force cross trained to do two or more jobs % of work force doing more than production job in a given month
Facility/Equipment 5. Set-up time(-) 6. Production cycle time(-) 7. Extent to which equipment is programmable 8. Extent to which equipment is special purpose(-)	 % of equipment changeover in X minutes or less Make time/total time in system % of equipment programmable % equipment with multiple versus single product design
Production Control Processes: 9. Lot size(-) 10. Extent to which a strict "pull" system is used 11. WIP inventory(-)	 % of products for which economic lot size is smaller than X % of products made under kanban or similar system Work-on-station/total work on floor
VOLUME FLEXIBILITY	
Vendor Network: 1. Lead time for orders(-) 2. Volume range for orders obtainable within lead time	 % inputs which can be obtained in X days or less % increase of normal previous order quantities within the lead time specified in 1.
Labour: 3. Work-time slack	 % slack time
Facility/Equipment: 4. Production cycle time excluding queue time(-) 5. Production capacity slack	 100 minus number of days required to make a product % slack time
Production Control: 6. Scheduling slack	 % of slack time

Muramatsu et al. (1985) listed similar factors but only for the production system. Unlike Cox (1989) who examined a wider range of issues, here only those issues which are necessary for increasing flexibility of the actual production system were examined. However, they went further and examined factors for a single stage and a multi-stage production system.

Mandelbaum and Brill (1989) developed quantitative measures to determine flexibility and adaptivity for machines and groups of machines within a manufacturing system. The measure of flexibility takes into account the ability of a machine or group of machines to perform relative to a background set of tasks. The measure of adaptivity is considered as the difference of weighted flexibility in two situations, usually taken at different points in time, and the measure may also be used to determine how the flexibility of a machine changes in continuous time. The example shown below illustrates the flexibility and the adaptivity measures. The example considers a finite discrete set of tasks that can be undertaken by a number of production machines.

Example: A task set consisting of six tasks is to be performed, and eight different machine are being considered to do them (see Table 2.8). To each machine task pair corresponds a number between 0 and 1 which indicates how effective the machine is in doing the task. An effective rating of one indicates that the machine can perform the task most effectively, while the rating of 0 indicates that the machine cannot do the task at all. Also, to each task corresponds a non-negative weight of importance such that the total weight for the whole set of tasks is 1. Deciding the weight of importance is based on knowledge of the plant and experience. Intuitively, a machine is more flexible than another if its weighted effectiveness in performing the tasks in the task set is greater. Thus, a measure of flexibility for a machine is its weighted effectiveness over all the tasks in the set. For example, the measure of flexibility of mc_2 is given by:

$$F_{mc2} = 0.1 \times 0.7 + 0.1 \times 0.6 + 0.2 \times 0.5 + 0.2 \times 0.3 = 0.29.$$

Table 2.8: Machine flexibility

Tasks	1	2	3	4	5	6	
Weight of importance	0.1	0.1	0.2	0.2	0.4	0	Machine Flexibility F_{mci}
Group 1 machines							
mc_1	0.9	0.9	0	0	0	0	0.18
mc_2	0.7	0.6	0.5	0.3	0	0	0.29
mc_3	0	0	0.9	0.8	0.6	0	0.58
mc_4	0	0	0	0	1	0	0.4
Group 2 machines							
mc_5	1	1	1	1	1	1	1
Group 3 machines							
mc_6	0.5	0.5	0.4	0.7	0.8	0.9	0.62
mc_7	0	0	0.2	0.3	0.3	0	0.22
mc_8	0	0	0	0	0	0.9	0

Where only a subset of the tasks is relevant, flexibility of a machine relevant to the subset can be computed. For example, if 2, 3, and 4 are the only relevant tasks forming subset T, then flexibility of machine mc_2 is given by:

$$F_{mc_2,\ T} = \frac{(0.1\times0.6+0.2\times0.5+0.2\times0.3)}{(0.1+0.2+0.2)} = 0.44$$

Where a group of machines is of interest rather than the individual machines, there are various ways of defining flexibility. An optimistic measure would select the best machine for each task, similarly, for a pessimistic measure the worst machine is selected for each task in the set. For example, the optimistic flexibility for Group 1 is given by:

$$F^{(1)}_{G_1,\ T} = 0.1\times0.9+0.1\times0.9+0.2\times0.9+0.2\times0.8+0.4\times1.0 = 0.92$$

The measure given by the method described above can be a reasonable basis for selecting the best available machine to do a specified task at a particular moment in

time. It must be noted that this measure does not necessarily show the capability of the machine or machines. Therefore it cannot be used for determining the strategic potential capability of a machine. The measure also disregards other aspects of flexibility, for example, although mc_4 can do only one task, in the example above it is seen to be more flexible than mc_2 which can do four different tasks. Furthermore, selection of weights requires a consistent methodology.

Ma and Kochhar (1988) developed measures for assessing the design of a flexible assembly system (FAS) and the effect of its flexibility on the whole system. The key flexibility parameters considered in the study were batch size and set-up time. The flexibility ratio (R) was expressed as:

$$R = \frac{\bar{S}}{\bar{B}}$$

Where $\bar{S}$ is the mean set-up time and $\bar{B}$ is the mean batch size. The higher the ratio the lower the flexibility of the particular system. This implies that if the average changeover time is low a wider range of product mix can be produced.

When a set-up time is dependent on different product types as well as assembly stations the flexibility ratio at the station was defined as:

$$R_i = \frac{\bar{S}_i}{\bar{B}}, \; for \; i = 1, 2, ..., N$$

If the economic batch quantity calculation is used to calculate the batch size $\bar{B}$, this measure would be an indicator of the response of the production system. However, this ratio does not take into account the service level that is provided by the system. The ratio only looks at the machines but not the other systems around it.

Hutchinson and Sinha (1989) suggested a way of quantifying the value of flexibility by using a method that maximised the net present value of a production system over the

life cycle of a product. The life cycle of a product could be defined as having three phases as shown in Figure 2.4 where the demand is assumed to be linear with time in each stage.

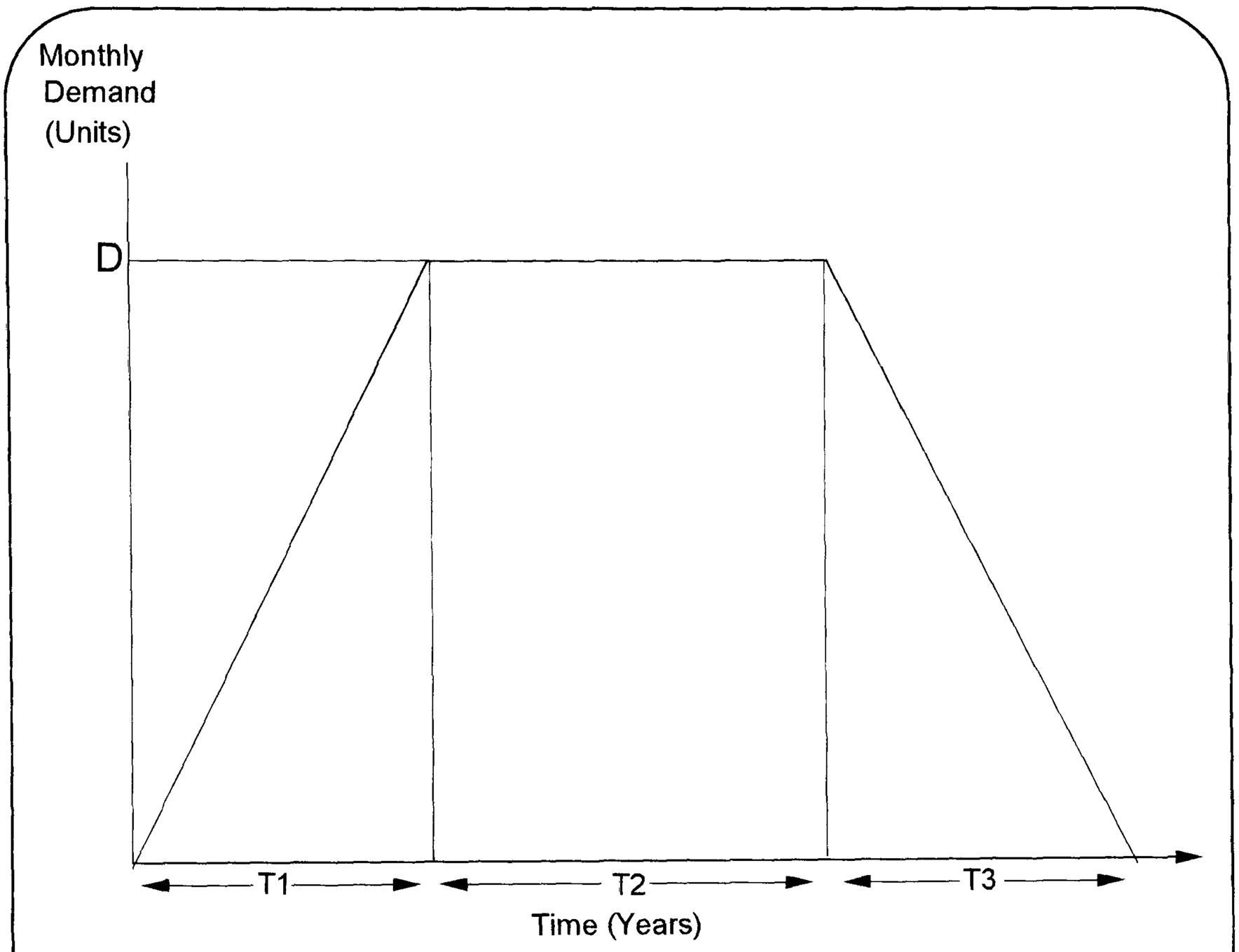

Figure 2.4: Product life cycle : Hutchinson and Sinha (1989)

The time for each phase is represented by:

T_1 = growth phase

T_2 = maturity phase

T_3 = decline phase

D = maturity demand

The maturity demand (D) was assumed to be normally distributed. An example of the distribution for monthly demand is shown in Figure 2.5.

The value of flexibility was examined as a function of the uncertainty faced by the investor, as measured by θ_D. Values of θ_D were increased in equal steps. The results showed that the net present value for a flexible system decreased with increased θ_D, but at a lower rate than the dedicated line.

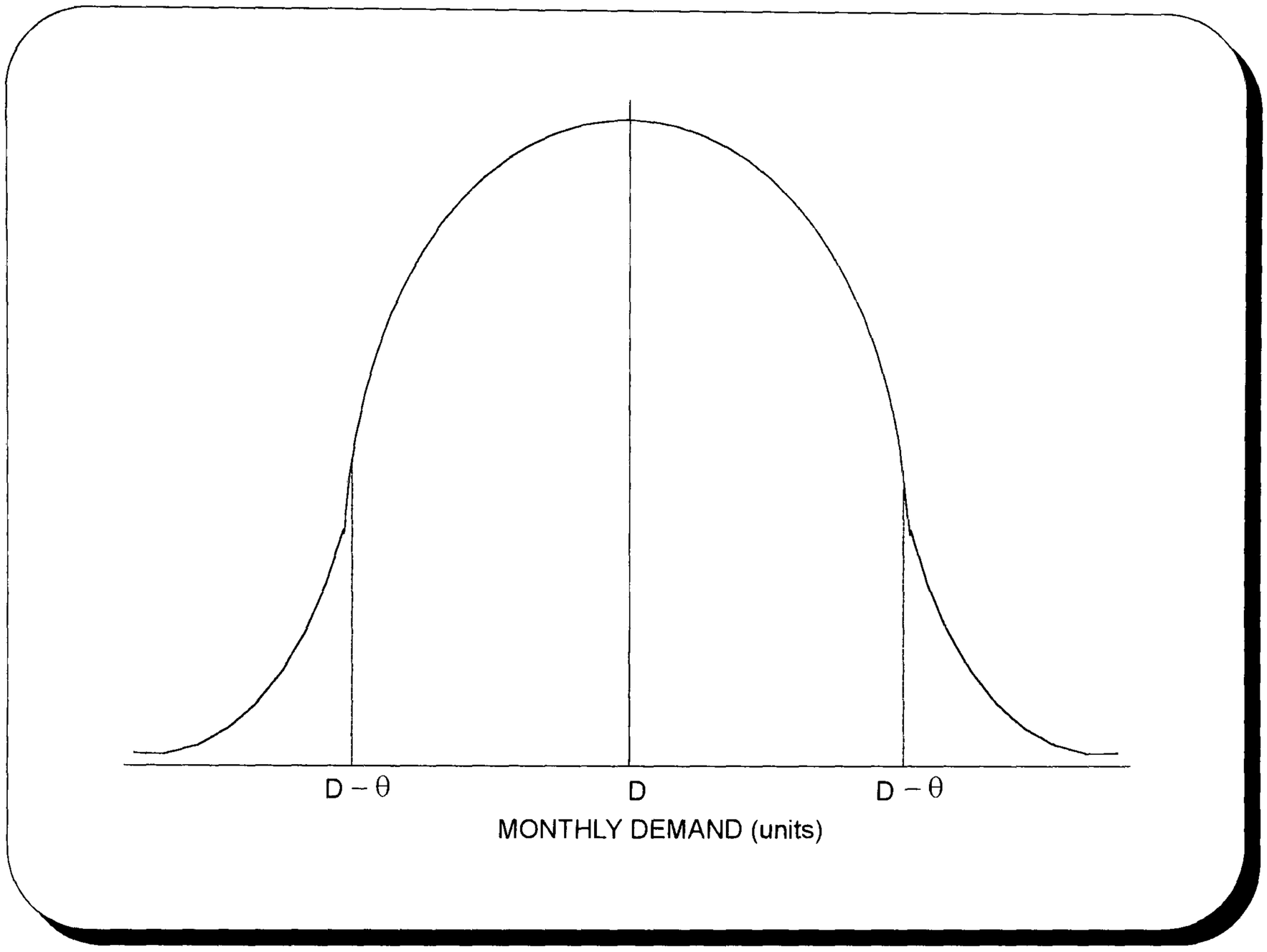

Figure 2.5: Monthly demand profile: from Hutchinson and Sinha

As with all types of forecasting methods, there is an element of uncertainty not just about the demand quantities but also the growth phases. This method or any other method cannot provide the answer but it will attempt to evaluate the risk involved with any investment option that is selected. Getting the length of time for the phases for the life cycle could mean that the investment is too late or too early.

Petri nets have been used as a method of evaluating the flexibility of Flexible Manufacturing Systems. Barad and Sipper (1988) said that Petri nets model the static properties of a discrete event system concentrating on two basic concepts: events and condition. Most of the theoretical work on Petri nets is based on a formal definition of

Petri net structures which consist of a set of places representing conditions, a set of transitions, representing events, an input function and an output. A Petri net models the system's behaviour through a sequence of transitions which represent discrete events. Petri nets take into account the processing time by using a maximum and minimum processing time as modelled by Ramamoorthy and Ho (1980) in Barad and Sipper (1989). Sifakis (1977) modelled processing time by adding a delay time after firing each transition.

Dubois and Stecke (1983) used timed Petri nets to model the behaviour of a real time deterministic production processes. Their model represented resources by places and activities by the set of transitions. In this way they were able to model the blocking effect of a Flexible Manufacturing System.

Kumar (1987) defined measures of flexibility which he called "Entropic Measure of Flexibility". In his observations he noted that the flexibility of a system depends on the decision options or the choices available and on the freedom with which various choices can be made. Kumar (1987) went on to develop a number of axioms, of which he defined some as essential and some desirable, as a basis for a function of the measure of flexibility.

The theory based on entropy may be useful for understanding the concept of a complex system such as flexibility. It has been used to measure the degree of disorder and randomness of probabilistic systems. However, these measures must be related to the day to day activities and parameters that are used to control manufacturing processes, if they are to be useful. The measures need to more transparent so that they can be implemented and controlled easily.

Gustavsson (1984), in an attempt to compare flexibility and productivity in complex production systems, challenged the common beliefs that surround these important issues. Although it is a decade since these issues were discussed, most manufacturing companies are struggling with the same problems at present. These issues are to do

with the general perception of productivity and flexibility. Some of the general beliefs are as shown below.

a) It is believed that flexibility reduces productivity as shown in Figure 2.6.

b) It is believed that the cost of investment increases very much to obtain increased flexibility as shown in Figure 2.7.

c) It is believed that the efficiency of a system is reduced with increased flexibility as shown in Figure 2.8. Gustavsson (1984) said a good system should be able to maintain its efficiency with increased flexibility. However, the "good system" shown here does not only maintain its efficiency, it actually increases with increased flexibility.

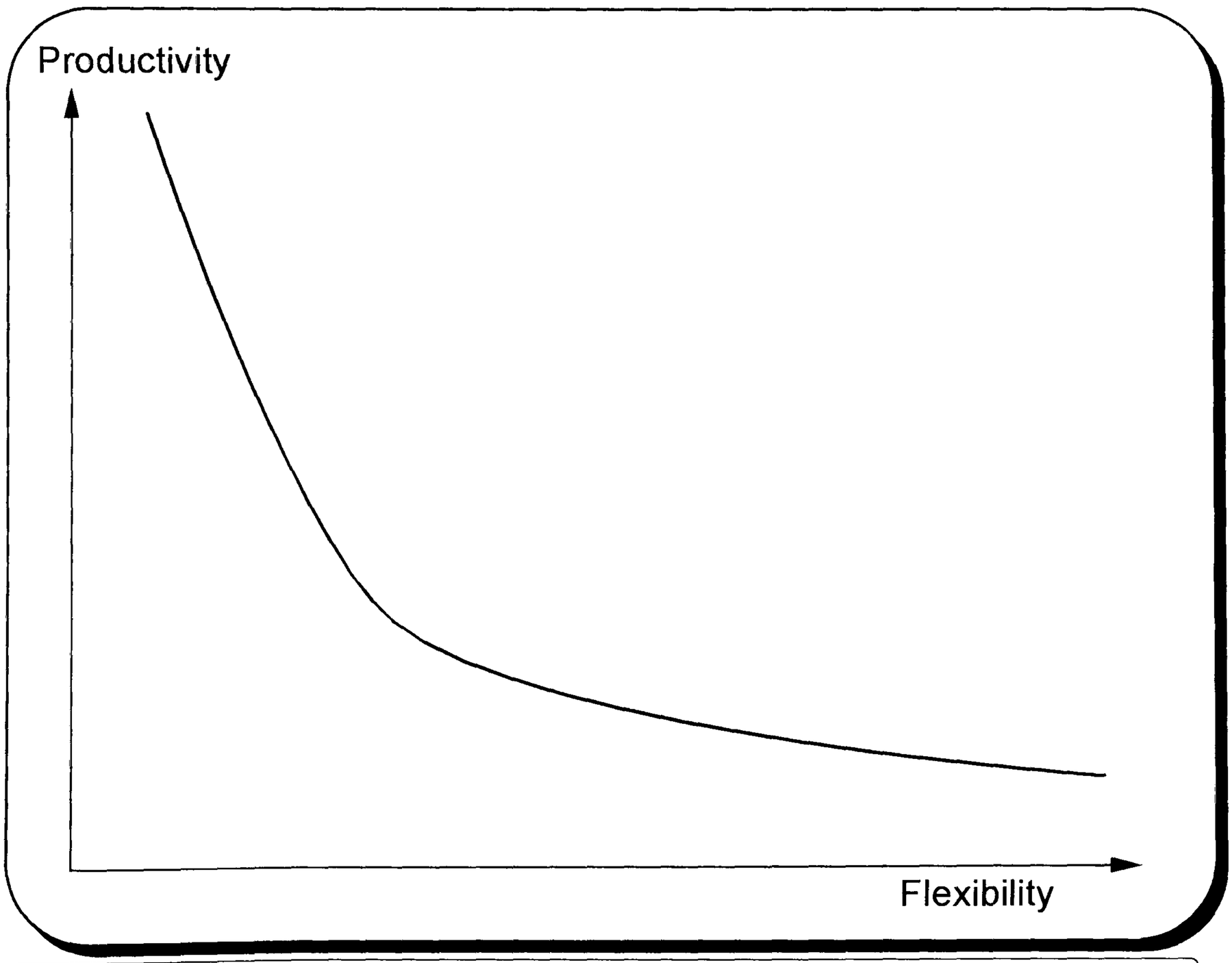

Figure 2.6: Productivity and flexibility: from Gustavsson (1984)

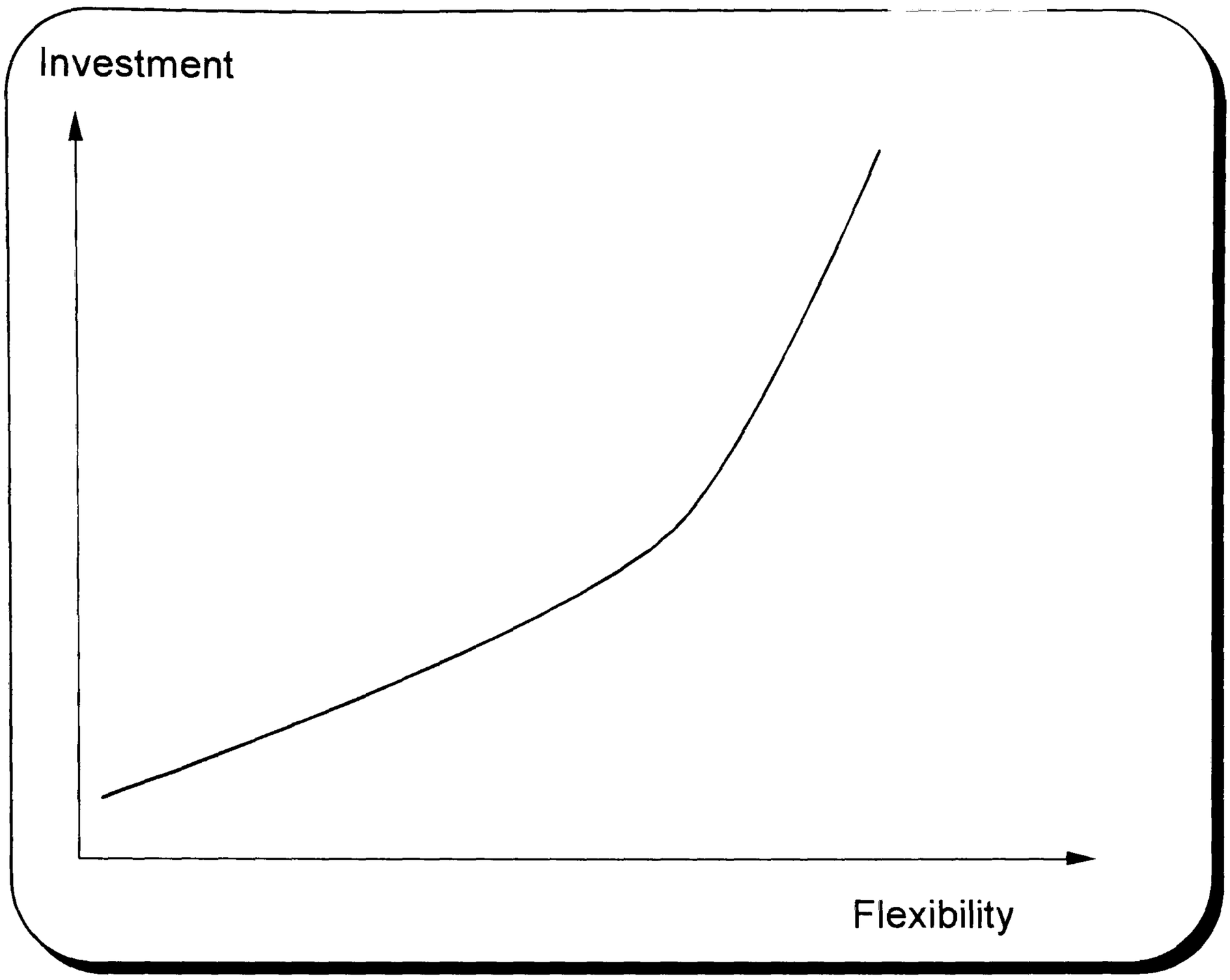

Figure 2.7: Investment and flexibility: from Gustavsson (1984)

Gustavsson (1984) also suggested some ways of measuring flexibility in order to compare different processes. Two examples for measuring machine flexibility and product flexibility were given as follows:

1) Flexibility of machinery can be measured as the ratio of the investment's residual value for the next product model to the original investment, i.e. an index between 0 and 1.

2) Product flexibility can be measured as a ratio of the residual value of the old model to the new model divided by the original value for the old model, i.e..

$$\frac{\textit{residual value of old} - \textit{value of new}}{\textit{original value of old}}$$

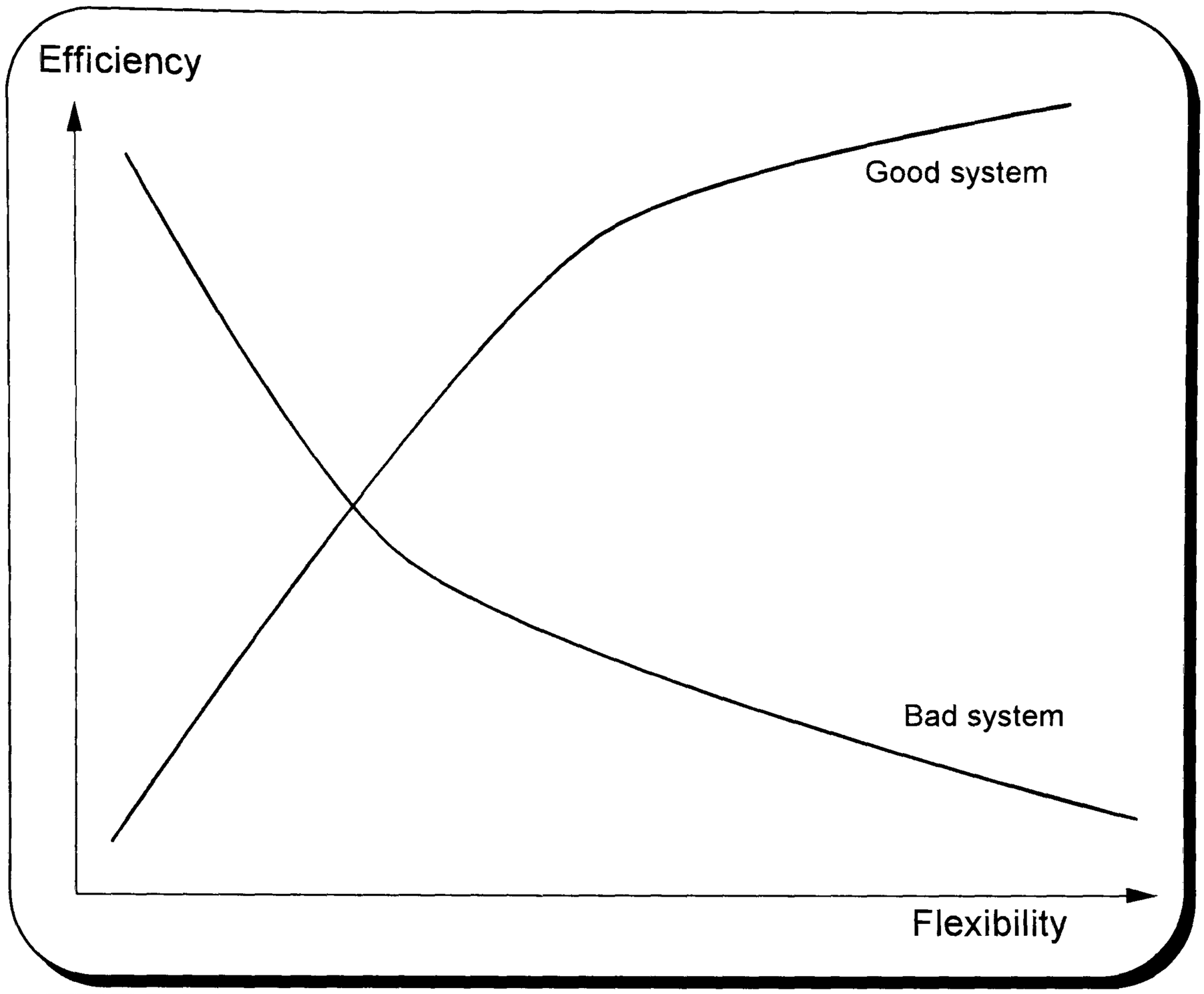

Figure 2.8: Flexibility and efficiency: from Gustavsson (1984)

Three ways of calculating "optimal" flexibility and some strategies for the assessment of flexibility versus productivity were discussed as shown below.

i) All starting-up costs and all other costs are grouped under 'life-cycle costs' to facilitate optimisation. These costs include product development, prototypes, testing grounds, buildings, tools, jigs, fixtures, etc.

ii) Only model-restricted machinery is optimised in the 'life-cycle'. The costs are separated into model-restricted and model-free categories.

iii) Expensive machinery is made to be used irrespective of model and has been standardised to the extent that it can be used generally.

2.6.2 ECONOMIC MEASURES OF PRODUCTIVITY, QUALITY AND FLEXIBILITY IN ADVANCED MANUFACTURING SYSTEMS

Stalk (1988) analysed some observations in relation to time based competition. It was observed that manufacturing costs can be categorised as those that respond to scale and those that respond to variety. He observed that scale related costs decline as demand volume increases. He also observed that variety related costs reflect the costs of complexity in manufacturing, these costs increase with increased variety. The complexity brought about by increased variety is in the form of changeover or set-up, materials handling, inventory and other overheads of the factory.

The sum of the scale related and variety related costs represents the total cost of manufacturing. When the market is good, companies tend to increase volume by increasing variety, even though this means increased manufacturing costs. When times are bad, companies reduce variety to minimise manufacturing costs.

In a flexible manufacturing system, variety driven costs start lower and increase more slowly as variety grows. Scale costs remain unchanged. Thus the optimum cost point for a flexible factory occurs at a higher volume and greater variety than in the traditional factory. Therefore the need for trade-off between scale and variety reduces.

Son and Parks (1987) defined manufacturing flexibility as "... the measure of manufacturing performance which indicates a manufacturing system's adaptability to change in manufacturing environments". The authors proceed to discuss four types of flexibility: equipment, product, process and demand. These are initially evaluated as partial measures and then total flexibility is given as shown below.

a) Equipment flexibility

Equipment flexibility is said to be the capacity of equipment to accommodate new products and some variants of existing products. Flexibility has been measured in

terms of idle time for the equipment. This is the measure of the opportunity of equipment to add value to raw material. Flexibility for any given period (F_E) is given as:

$$F_E = \frac{O_T}{C_I}$$

Where:

O_T = total output

C_I = idle cost of equipment

Using this measure, a machine making just one product at full capacity would be considered as being very flexible because the equipment has not got excess capacity. To make the measure more meaningful, the time spent on changeover should be considered to be more relevant to equipment flexibility than the idle capacity.

b) Product flexibility

Product flexibility is considered as the adaptability of a manufacturing system to changes in product mix. If smaller batch sizes are to be made it means that there will be more set-ups, thereby losing some of the equipment capacity.

Product flexibility for a specific period is given as:

$$F_P = \frac{O_T}{A}$$

Where; A = set up cost

This equation assumes that the set-up costs are all to do with the product. However, there are mainly three main factors generally contributing to the length of a changeover: similarities in the products being changed, the ease of changing the machines and the experience of the person that is carrying out the changeover, if the changeover is not automatic. It would not be correct in this case therefore that all of the set-up costs should be attributed to product flexibility.

c) Process flexibility

Process flexibility is defined as the adaptability to various changes in processing, such as in equipment and tool breakdown, random access of product mix, process schedule, etc. Process flexibility is given by:

$$F_S = \frac{O_T}{C_W}$$

Where; C_W = waiting cost of parts processed.

One would have to be very careful in measuring waiting time as there could be many different reasons for parts to wait for processing. For example, bad planning could cause parts to wait for necessary resources to be available for work to continue. This would not be attributed to the process or equipment but to the infrastructure.

d) Demand flexibility

Demand flexibility is defined as the adaptability to change in demand rate. Two types of demand are discussed: customer demand for finished goods and manufacturing system demand for raw materials.

Demand flexibility is given as:

$$F_D = \frac{O_T}{H}$$

Where; H = inventory costs of finished goods and raw materials. Inventory costs consist of carrying costs and shortage costs.

It is possible to carry a lot of stock and still not meet the demand because the stocks carried are not the right type of stock. It may be more useful to measure the orders that are met in full and the cost associated with it. In this case again, it may be

necessary to know the reason why the stock was carried; it may just be that planning is not good enough.

e) Total flexibility measure

Total flexibility over a given period of time (TF) is defined as:

$$T_F = \frac{O_T}{(C_I+A+C_W+H)}$$

It may be more meaningful to attach a weighting factor to these measures of partial flexibility added together to form total flexibility. The weighting factor is necessary because some costs may not carry the same importance as others on different products over the same period of time. For example, if a changeover does not reduce the capacity of the manufacturing system, it may be better to attach more weight to, say, demand flexibility.

2.6.3 FINANCIAL JUSTIFICATION

Slagmulder and Bruggeman (1992) used field research to examine the justification of investment in Flexible Manufacturing Technologies (FMT). It is shown that traditional capital budgeting practice fails to fulfil their proper function with respect to proposals for the acquisition of FMT. Traditional budgeting methods ignore long term returns by over emphasising short term profitability. Furthermore, the Discounted Cash Flow (DCF) calculations do not capture the full range of benefits, given that future economic benefits from new technologies are often hard to quantify, in particular the intangible advantages such as improved quality, increased flexibility and reduced delivery lead time.

However, Slagmulder and Bruggeman (1992) argued that financial justification is important, but there is no consensus on proper use of accounting and capital budgeting techniques. Justification of investment proposals cannot be based on faith alone.

This section of the chapter has examined methods used for analysing the flexibility of manufacturing systems. The shortcomings of each measure has been highlighted.

2.7 FLEXIBILITY AND AUTOMATION

Gerwin (1985) suggested a framework for analysing the flexibility of manufacturing processes to enable the selection and evaluation of manufacturing processes. The framework was suggested with the background of most large American companies having to consider changing from large batch, mass production to making small batches because of the change in the marketplace. The example used in the analysis was from a computerised body framing process. The analysis showed that computerising of the process increases some dimensions of flexibility while others were reduced. This was one of the first frameworks that took into account flexibility in terms of a man-machine system rather than just equipment. It is argued that organisations facing uncertainty use their flexibility as an adaptive response. It, therefore, means that there are a corresponding number of types of flexibility to the types of uncertainty. The aspects of flexibility are closely associated with manufacturing strategy.

Gerwin (1985) developed a classification of uncertainty, flexibility and objectives. For each one of these he gave six examples as shown in Table 2.9. The types of flexibility defined here were used to evaluate the effect of automation.

Table 2.9: Uncertainty, flexibility and objectives: from Gerwin (1985)

Nature of Uncertainty	Flexibility Type	Principal Objective
Demand for the kinds of products offered	Mix	Diverse product line
Product life cycle	Product (component)	Product innovation
Appropriate product characteristics	Modification	Customer responsiveness
Machine down time	Re-routeing	Meet customer due dates
Amount of aggregate product demand	Volume	Meet the production schedule
Nature of raw materials	Material	Product quality

Two body framing processes from two different companies were chosen and these are referred to as BA1 and BA2. A scoring method was used to determine the change that had occurred after computerising the processes. Each question employed a five point scale ranging from -2 to +2 to ask whether a particular characteristic had decreased a lot, decreased, not changed, increased, or increased a lot. The results of the questionnaire are shown in Table 2.10.

Table 2.10: Computerisation of a production system: from Gerwin (1985)

	BA1	BA2
MIX FLEXIBILITY		
Number of components	+1.0	+2.0
Range of component characteristics	-1.0	-1.0
COMPONENT (PRODUCT) FLEXIBILITY		
Ability to accommodate major design changes	-1.0	+2.0
-1 (Time to accommodate major design changes)*	-1.0	0
-1 (Process constraints on major design changes)*	-2.0	-1.0
MODIFICATION FLEXIBILITY		
Ability to accommodate minor design changes	+1.0	+2.0
-1 (Time to accommodate minor design changes)*	0	+1.0
RE-ROUTEING FLEXIBILITY		
Ease in long run re-routeing	-2.0	+2.0
Ease in short run re-routeing	-2.0	-1.0
VOLUME FLEXIBILITY		
Degree of flexibility	+0.7	+1.0
MATERIAL FLEXIBILITY		
Degree of flexibility	-1.5	-2.0
-1 (Interdependence of sub-systems)*	-1.0	-2.0

*This characteristic has been redefined in the table so that increases (decreases) in it will correspond to increases (decreases) in the flexibility dimension with which it is associated.

From these results it can be concluded that hard automation does not always increase flexibility. The areas where both systems experienced increased flexibility are number of components, ability to accommodate minor design changes and volume flexibility. Lessons learned form the experience of attempting to increase productivity through automation show that automation in many cases decreased flexibility. However, the results cannot be taken as conclusive because of the small sample of firms involved and the improvement in automation technology.

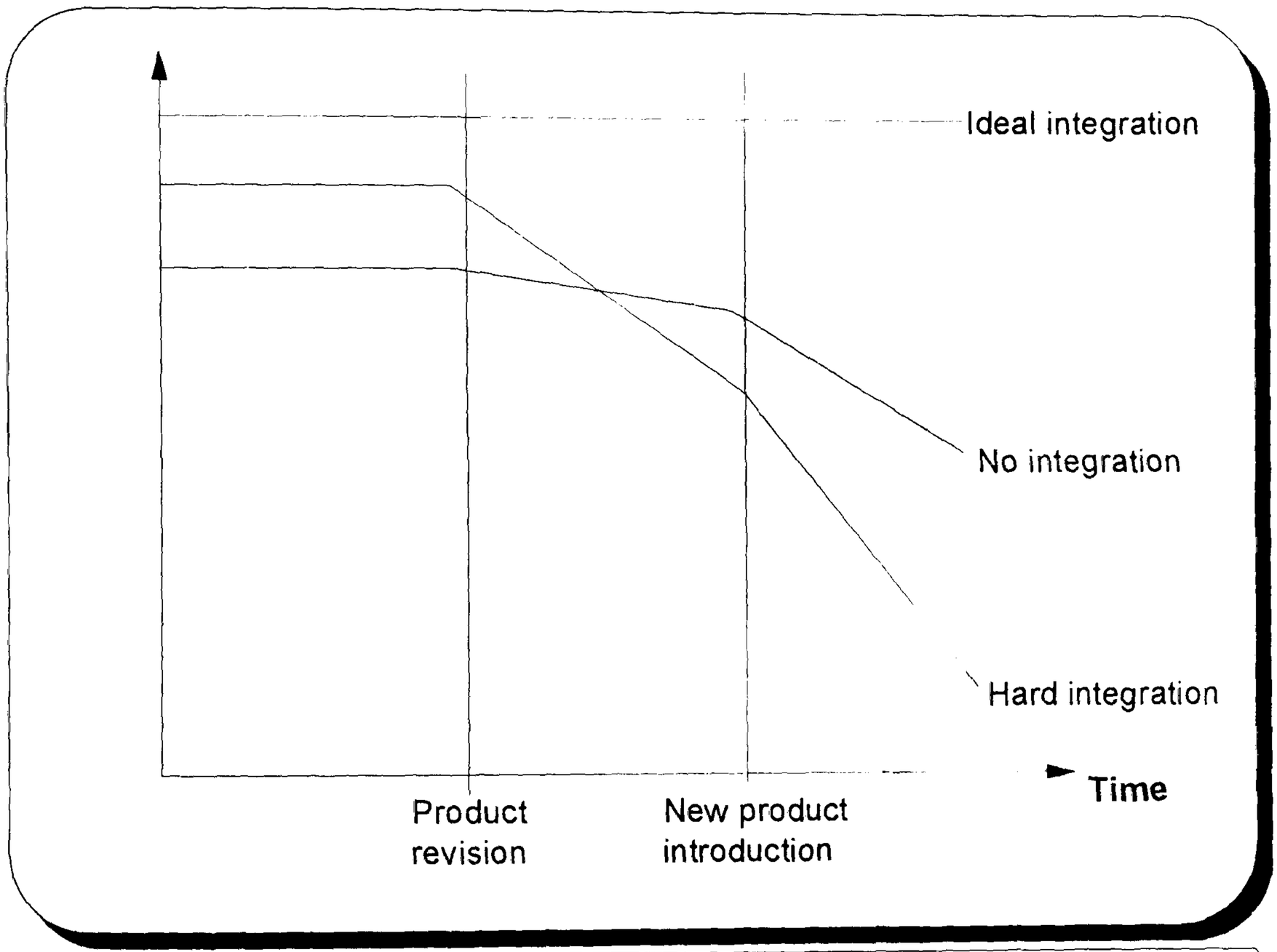

Figure 2.11: The effect of automation: from Crowe (1992)

Crowe (1992) likened the automation in the 1970s to integration, and observed that hard integration could actually reduce flexibility rather than enhance it. In many cases systems that are seen to be flexible and productive turn out to be less flexible when required to make a new product range. Figure 2.11 shows the effect of hard integration compared to non-integration and ideal integration. Integration carried out properly can enhance flexibility. Ettlie and Penner-Hahn (1995) said new automation

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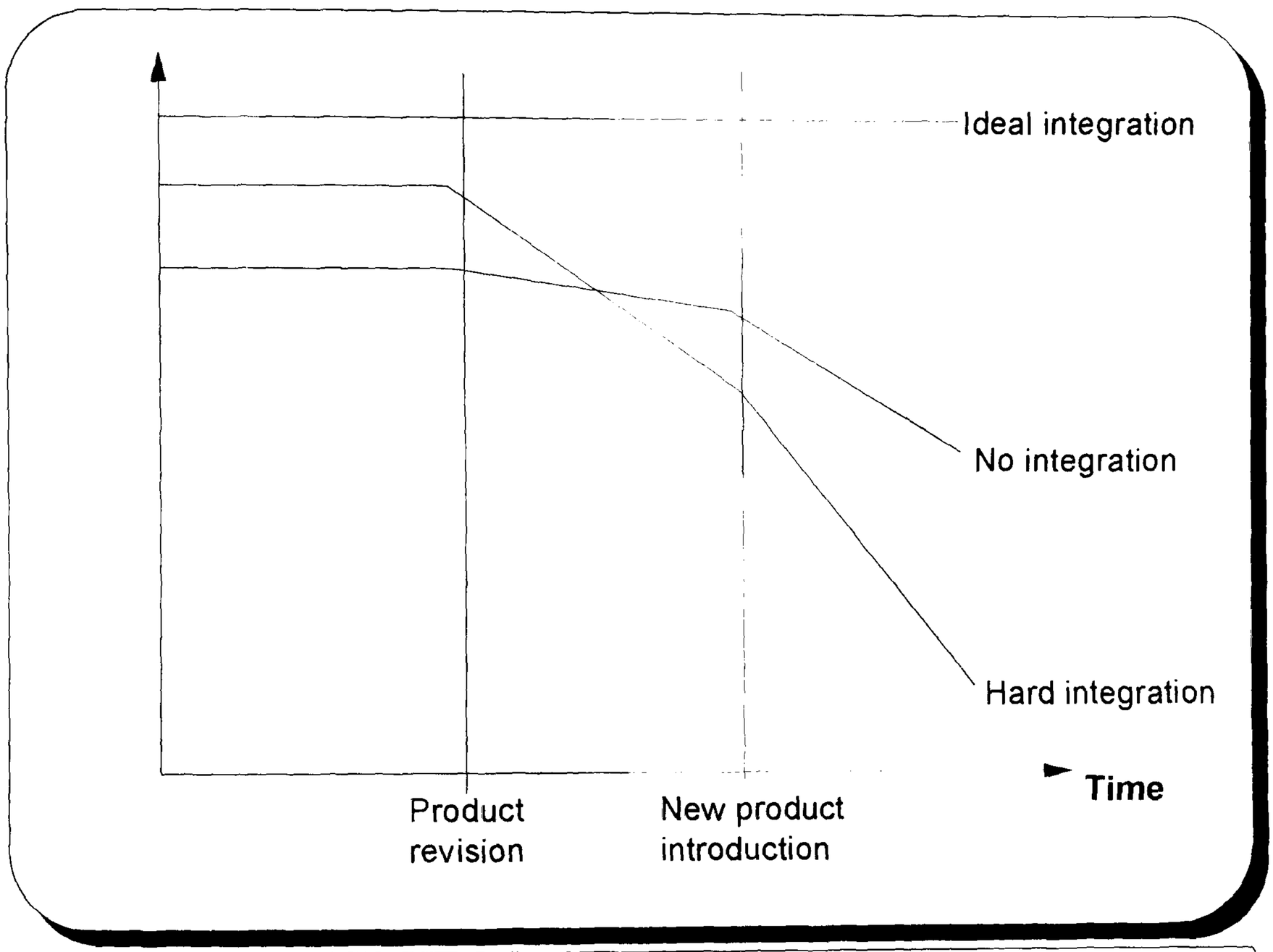

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systems are significantly more likely to have shorter changeover times per part family. However, it is important to consider the effect of introducing a completely new product family in specifying a new system.

2.8 THE DYNAMIC SIMULATION MODEL

This section examines the meaning of simulation, discrete event simulation in particular, from the literature. Simulation is increasingly being used to evaluate the performance of systems numerically. Typical problems that can be solved using discrete event simulation will also be presented in this section.

Pegden et al (1990) said that in an increasingly competitive world, simulation has become a very powerful tool for the planning, design, and control of systems. No longer regarded as the approach of "last resort", it is today viewed as an indispensable problem solving methodology for engineers, and managers.

2.8.1 THE MEANING OF SIMULATION

The Oxford English Dictionary defines simulation as, "The technique of imitating the behaviour of some situation or system (economic, military, mechanical, etc.) by means of an analogous situation, model or apparatus, either to gain information more conveniently or to train personnel".

Carrie (1988) said that simulation modelling is a means of studying the behaviour of a system as a whole by defining in detail how its various components interact with each other. He also stated that the more complex the system the more inappropriate theoretical equations become and the more appropriate simulation becomes. Since most manufacturing systems are complex, simulation is the most suitable tool for analysis.

Pegden et. al (1990) defined simulation as the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operation of the system. The use of simulation follows the steps shown below.

1. Describing the behaviour of the system
2. Construct theories or hypotheses that account for the observed behaviour.
3. Use the model to predict future behaviour.

Various issues relating to the operation of a system such as policies, operating procedures, decision rules, information flows, bottlenecks and materials flows can be modelled and evaluated.

Law and Kelton (1991) defined discrete event simulation as the modelling of a system as it evolves over time by representation, in which the state variables change instantaneously at separate points in time. These times are the ones at which an event occurs. An event is defined as an instantaneous occurrence that may change the state of the system.

2.8.2 TYPES OF SIMULATION MODELS

Baines et al. (1995) proposed a model taxonomy based on two layers as shown in Table 2.11. In the first layer models can be categorised as physical or symbolic. Within the physical category were replication, quasi-replica and analogue models, and within the symbolic category contain mathematical, simulation and schematic models.

Table 2.11: Model taxonomy: from Baines et al. (1996)

Main class	Sub-class	Definition
Physical	Replication	A spatial transformation of an original physical object in which the dimensionality 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.

Carrie (1988) said that many aspects of manufacturing systems, in the broadest sense, can be studied by use of equations, which depend on explicit analytical formulae describing known relationships. He also said "Generally, however, for manufacturing systems as a whole the necessary conditions do not apply, there are no such analytical relationships, and the behaviour of the system cannot be described in this way". However there are various rules about the internal behaviour of the system which can be stated. A logical model of a complex system may be built by incorporating many such simple relationships and hence we may be able to predict the behaviour of the whole system.

Pegden et al (1990) said that simulation models can be classified as iconic or symbolic. Iconic simulation models look like the real system, for example a flight simulator. Symbolic simulation models are those in which the properties and characteristics of the real system are captured in mathematical and/or symbolic form.

These simulation models cannot generate an optimal solution on their own as analytical models can, they can only serve as analytical tools for the analysis of system behaviour under specific conditions. The exception is a simulation model used to find the optimum values for a set of control variables under a given set of inputs.

Simulation is different from other types of modelling because it is time based and the system that is being modelled can assume different states as time moves on. This really is the best way of representing the behaviour of a dynamic systems.

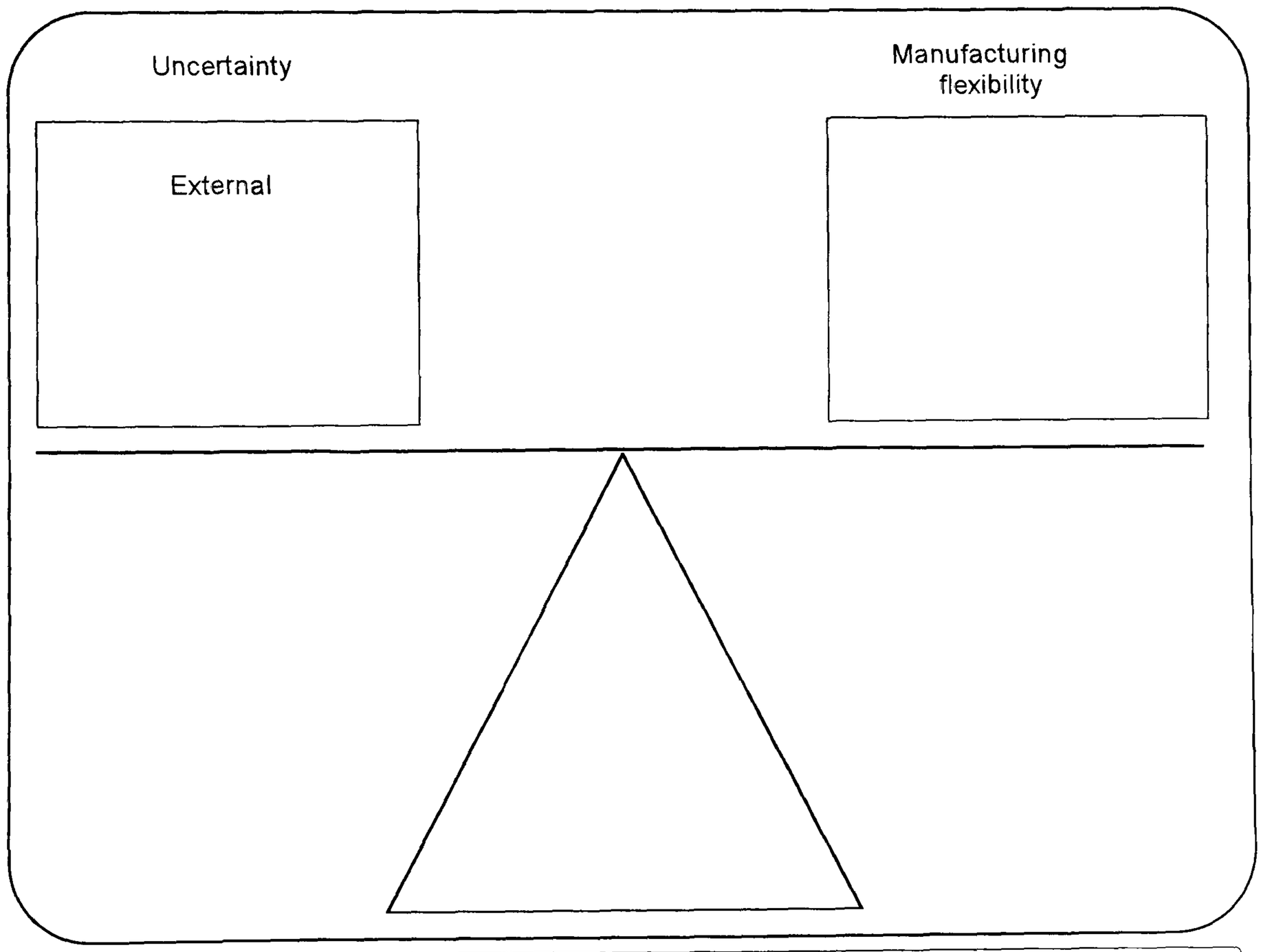

Figure 2.12: Flexibility dynamic model: from Newman et al (1993)

2.8.3 THE DYNAMIC NATURE OF MANUFACTURING SYSTEMS

Product life theory suggests that different strategies are appropriate during different stages of the cycle. This means that if a static model is used, it will only give a snapshot of a moving picture. A dynamic model is required to model a dynamic situation.

Newman, et al. (1993) developed a model which showed that the basic balance between the manufacturing flexibility of a process and the external uncertainty that it is intended to accommodate is a dynamic equilibrium which must be achieved and maintained. The competitive marketplace is one in which customers' expectations change. Hence, it is possible that a process, originally well balanced to satisfy customer expectations could move out of balance and become less competitive over time. Figure 2.12 shows the balance that has to be maintained at all times.

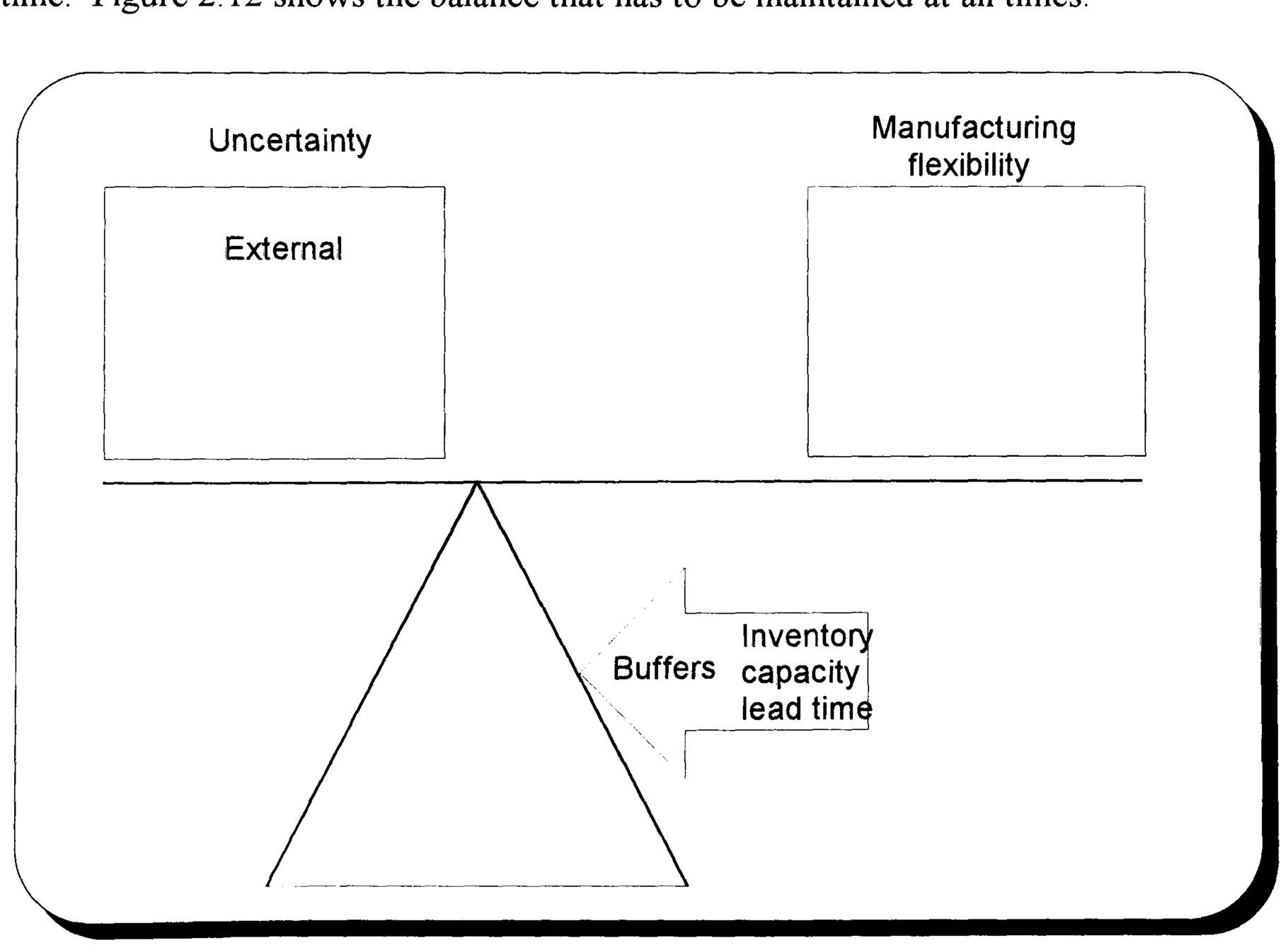

Figure 2.13: The effect of buffers: Newman et al (1993)

Most manufacturing companies carry some inventory to cover against uncertainty but carrying a lot of inventory to avoid the need for flexibility could disadvantage a company. Figure 2.13 shows the magnitude of lead time, inventory and capacity as the distance by which the point of balance is removed from the anchor of the manufacturing flexibility.

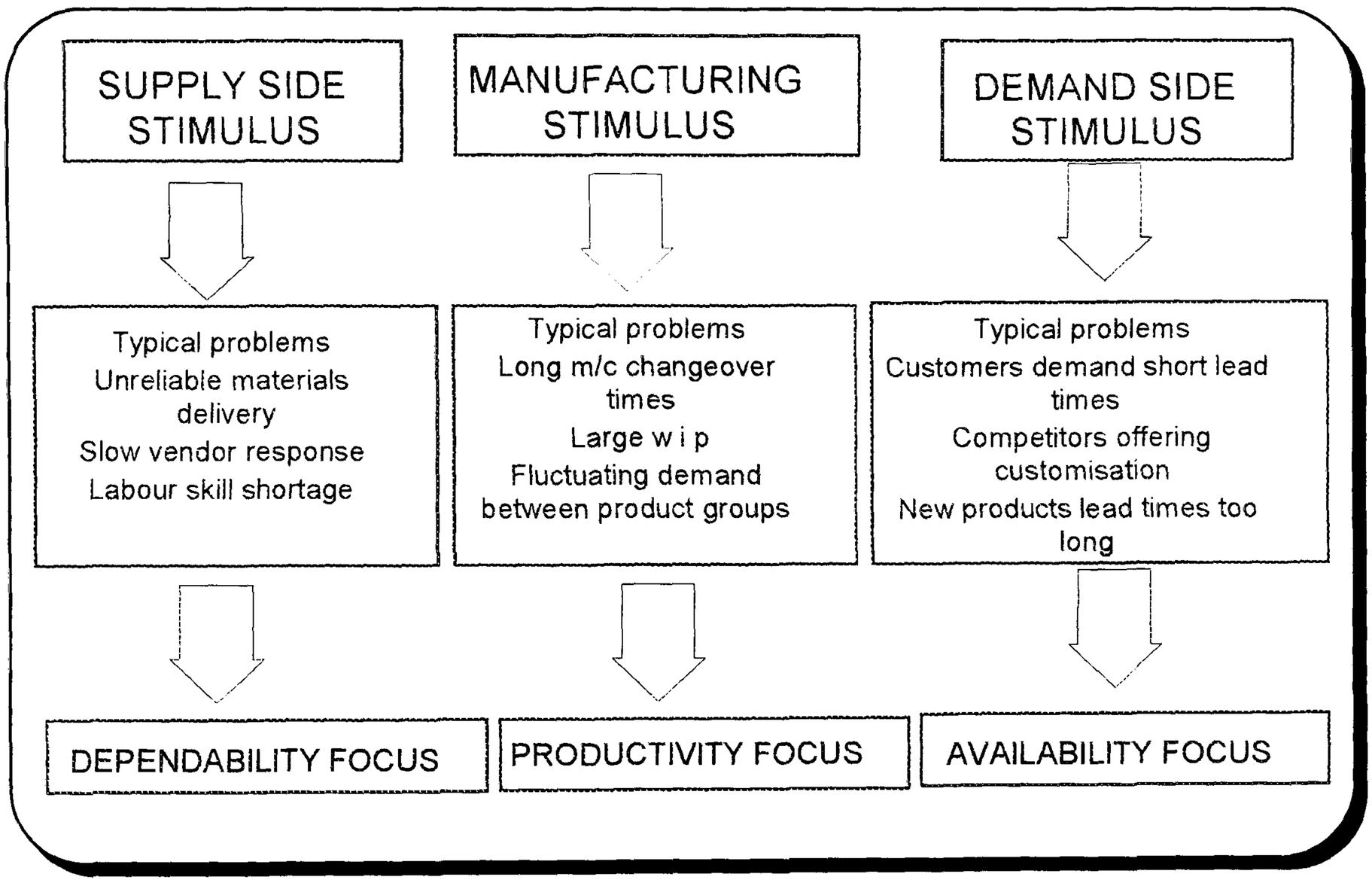

Figure 2.14: Different types of stimuli: from Slack (1987)

Slack (1989) found that sales and marketing managers on the demand side of the company seemed to focus on flexibility as a solution to the problem of availability of finished products. Those on the manufacturing side seemed to focus on the productivity while those on the supply side focused on dependability of raw materials or parts delivery. These are shown in Figure 2.14. Correa and Slack (1996) used the idea of stimuli to develop a framework to analyse flexibility of unplanned changes in a manufacturing system.

Simulation these days is mostly carried out by the use of computers which display the model on the screen graphically. Interaction is made possible so that the person carrying out the analysis can change the behaviour of the system quickly. Hurrion (1986) called this technique Visual Interactive Modelling. He said that the technique of Visual Interactive Modelling consists of:

i) Developing a model of the system under investigation.

ii) Incorporating a method of animating the model which then enables the user to:

iii) Interact with the model in order to explore alternative decision strategies.

Simulation of the whole of the supply chain enables examination of local changes in the flow of information, materials and finished goods and their effect on the whole of the supply chain. Representing such problems using equations presents a daunting prospect which may be very difficult and could take long but using simulation to examine the effects the whole process is made easier.

2.9 THE NEED FOR FURTHER RESEARCH

The need for further research in manufacturing flexibility has already been shown through the literature. Below are some examples showing the reasons for further research in the subject.

Slack (1983) said "A quantitative scale of flexibility seems so far to have eluded researchers".

In the example where Dunlop (1982) in Slack (1983) discusses process technology (robot) flexibility he said "Flexibility is recognised by most robot salesmen as a major feature of their product, however they have no means of quantifying it. Indeed...flexibility...has been viewed as a conceptual Gordian Knot by those who have

dealt with it...it seems to fall in the same class of immeasurables as 'Moral'..., undeniable but indefinable force in business".

It is important to justify capital investment but the right measures have to be used. The evaluation may have to be done by the use of more than one method to get satisfactory measures to justify investment in flexible systems.

"Yet for all its new found popularity, flexibility seems to be the least understood of manufacturing objectives, the very word flexibility is used by different managers to mean different things", Slack (1989)

"As yet, though, no totally satisfactory methods exist for assessing a company's flexibility needs, auditing its flexibility capability or (perhaps of most immediate use) evaluating in a broad sense change or investment proposals involving the enhanced flexibility of production systems", Slack (1989).

Kumar (1987) saw that the essential problems hindering the implementation of flexibility measures in design and operation of manufacturing systems included the following:

i) lack of a unified structure of various types of flexibility in a manufacturing system;
ii) a difficulty in implementation of flexibility operationally due to a lack of any set means of measurement;
iii) The lack of a knowledge base to relate this manufacturing objective to other objectives.

2.10 SUMMARY

In this chapter the concept of manufacturing flexibility has been introduced and the research that has been undertaken in the subject has been examined. It is very clear that flexibility is a very wide and complex subject. It has been shown that flexibility is an objective which fulfils other business objectives which enhance the performance of the manufacturing organisation. The gaps in the literature have been identified. The next chapter will analyse the research literature and develop a hypothesis for definition and analysis of manufacturing flexibility. The methodology will aim to provide a way of clearly defining flexibility and to analyse it using some simulation modelling methods.

CHAPTER 3

THE FRAMEWORK

3.1 INTRODUCTION

In the previous chapter it was shown through the work of De Meyers (1989) and Slack (1987) that flexibility is a very important manufacturing objective. It was also shown that flexibility is an objective that enables the fulfilment of wider business objectives which enhance the performance of the whole manufacturing organisation. Slack (1983) showed that manufacturing flexibility is multi-dimensional, in operation it has dynamic qualities which assist the manufacturing system to maintain equilibrium at all times. However, Hill and Chambers (1991) said adequate measures for assessing flexibility have not yet been developed. Many researchers have concentrated on explaining how to be flexible. In some cases requirements and the provision of flexibility are mixed and interchanged. This chapter proposes a framework for separating the process of defining what it is that we want to be flexible about from how to be flexible. Emphasis was placed on defining measurable requirements of flexibility for a manufacturing system in order to enable assessment of the capability of the delivery mechanisms. The framework provides a methodology for translating business objectives into manufacturing flexibility requirements. The requirements are then used to define the means for providing the capability to be flexible.

3.2 HYPOTHESIS

Simulation modelling can be used as a quantitative method to effectively predict the flexibility that is demonstrated by a dynamic manufacturing system in operation or during the design process. It can also be used to assess the way in which flexibility contributes to the overall manufacturing objectives. The dynamic nature of a manufacturing system in

operation means that the demonstrated flexibility of the system can only be effectively evaluated by the use of a dynamic model.

3.3 AIMS

This research was designed to develop a methodology, together with techniques and tools, for assessing the demonstrated flexibility of a manufacturing system. For this purpose the objectives listed below were set.

3.4 OBJECTIVES

1. To develop a methodology which would provide a structured approach for assessing the demonstrated flexibility and the prioritisation of flexibility requirements of a manufacturing system.

2. To provide a model which adopts a holistic approach in defining the flexibility of a manufacturing system during its design and operation.

3. To establish the relationship between different types of manufacturing flexibility and methods of their assessment.

3.5 THE FRAMEWORK

This section defines a framework which translates manufacturing objectives into requirements for modelling the flexibility of a manufacturing system. The framework sets out to provide the process through which flexibility requirements can be derived and a method by which the mechanisms for meeting the requirements are defined. The main characteristics of the framework are:

1. The ability to separate definition of requirements from solutions.
2. It provides a structure for effective problem and solution definition.
3. It demonstrates the interdependence between various flexibility requirements.

The framework focused on formulating the problem and making issues regarding flexibility better understood. Formulation of the problem is seen as the most important phase of any project or modelling process. The importance of formulating the problem was emphasised by Pegden et al (1990) who described the importance of defining the problem by quoting Albert Einstein who said that the proper formulation of a problem was even more essential than its solution. Pegden et al (1990) also mentioned that each year millions of dollars are spent to come up with elegant and sophisticated answers to the wrong question. The analyst has the responsibility to convert vague descriptions of general problems or symptoms into precise definition of the problem.

Shown below are some examples which illustrate the vagueness with which flexibility is described.

"A multinational manufacturer of mechanical seals was looking for ways to use and improve its flexibility. For many years, this industry had been comparatively stable, and manufacturers had competed on the basis of cost and quality. It became clear that the market was changing, and that the firm was unable to compete effectively in the more standardised sub-segment of their market. It therefore decided that it needed to use and develop its flexibility in order to remain competitive.", Upton (1994).

"The management of the United States' second largest manufacturer of modems says that the success of the firm resulted from the fact that it had a flexible strategy. It was able to endure despite a volatile market." Upton (1994).

The above statements are attempting to describe flexibility but what is it exactly that is meant by the word flexibility? This is the question that this chapter will attempt to answer. To describe manufacturing flexibility Upton (1994) used dimension, time horizon and elements to define flexibility. These steps defines the flexibility requirements. Here dimension and elements are defined in sequence and a mechanism for assessing flexibility requirements will also be defined.

1. Flexibility requirements: defining exactly the reason for which flexibility is required.

2. Time horizon: the time horizon over which the response or change will be required.

3. Supporting mechanisms: the methods of delivering the required flexibility.

3.5.1 MANUFACTURING FLEXIBILITY REQUIREMENTS

It can be seen from the definitions of flexibility as presented in the previous chapter that there is confusion in the way flexibility is defined. For example, Slack (1987) defined types of flexibility as volume flexibility and variety flexibility. These types of flexibility refer to the type of requirement that needs to be met by some means which may be machines, people or processes or a combination of these. This is not defining the way in which the requirements are met. There may be different ways of achieving the requirement. For example, if the demand volume rises and falls from week to week, there may be a choice of using a machine with adjustable production rate or run additional shifts or overtime.

Other types of flexibility were defined by Browne et al (1984) as:

- Machine flexibility
- Process flexibility
- Product flexibility
- Routing flexibility
- Operational flexibility
- Volume flexibility
- Expansion flexibility
- Production flexibility

These define the potential or demonstrated capability of a system to meet a set of flexibility requirements.

From the examples shown above it can be seen that flexibility requirements must be defined independently from the means by which flexibility is to be provided.

It is not the aim of this thesis to deal with the development of manufacturing strategy. However, since it is through the development of manufacturing strategy that most flexibility requirements will be defined, it is necessary to mention it at this stage. The manufacturing company has to decide all the key business issues that have to be fulfilled through manufacturing, setting out clear objectives, measures and strategy. This will include the stages shown in Figure 3.1, and these were also discussed in Matupi and Kay (1996).

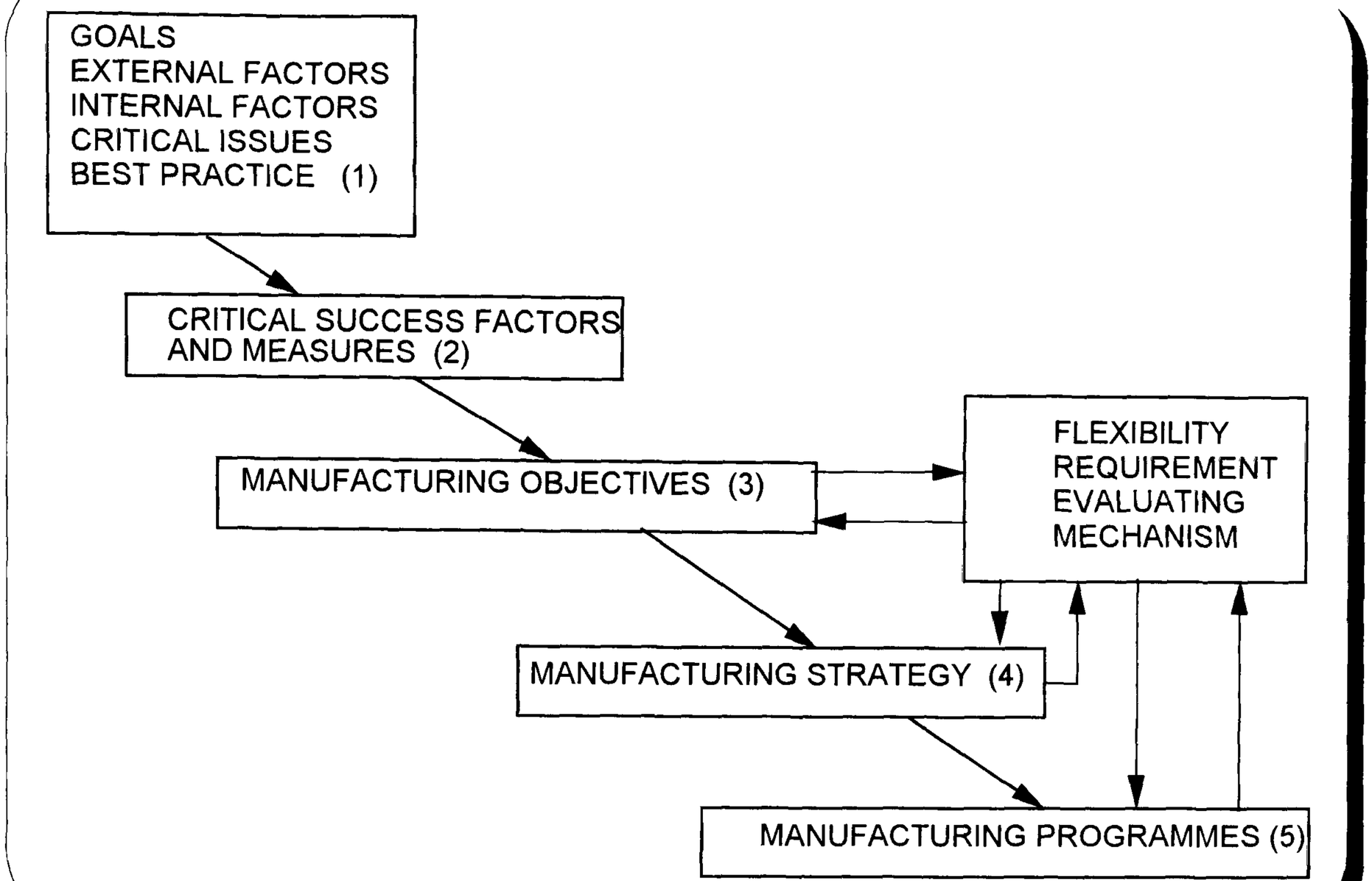

Figure 3.1: Manufacturing objectives and flexibility

1. The first stage includes the complete analysis of the strengths and weakness of the firm taking into account the following issues:
   - market requirements;
   - technological developments;
   - internal constraints;
   - goals to develop the manufacturing organisation into the future;

2. The second stage is concerned with defining success factors against which measures can be set and then used to form objectives and monitor the performance of the organisation. These measures must be precise enough to enable formation of long term and short term objectives.

3. The third stage sets out clear objectives using the precise measures set in stage 2. These objectives will show the direction of the firm for the long term and short term.

4. The fourth stage sets the strategy, which defines how the objectives will be met. By defining how to achieve the objectives, issues concerning flexibility will be part-and-parcel of the strategy. Applying the same measures used to set objectives, flexibility needs may be defined.

5. The fifth stage deals with the implementation of the strategy taking into account the possible alternatives. At this stage the context of the flexibility and the capability required will be implemented through manufacturing programmes.

Running in parallel with these five steps is the process of defining flexibility requirements which can then be prioritised if there are several ways of achieving the same goal (see Figure 3.1). After considering all issues concerned with the flexibility requirements, a mechanism for evaluating the requirements should be used to prioritise the possible ways of approaching the problem and evaluating alternatives. The evaluation process also removes repetitive and redundant requirements.

3.5.2 THE FLEXIBILITY REQUIREMENTS EVALUATING MECHANISM

Flexibility can be used to respond to change or to initiate change. In order to initiate change, objectives and strategy may have to be changed depending on the requirements. Manufacturing priorities may be different depending on local requirements. To get a balanced view of the overall objectives, it is necessary to bring together all the individual

local needs and formulate overall balanced objectives which will focus the requirements of manufacturing flexibility.

The flexibility requirements evaluation mechanism shown in Figure 3.2 can be used to evaluate trade-offs between individual perceived requirements and for developing coherent objectives to meet the business requirements. The mechanism will prioritise the flexibility needs and eradicate redundant perceived needs and repetitions.

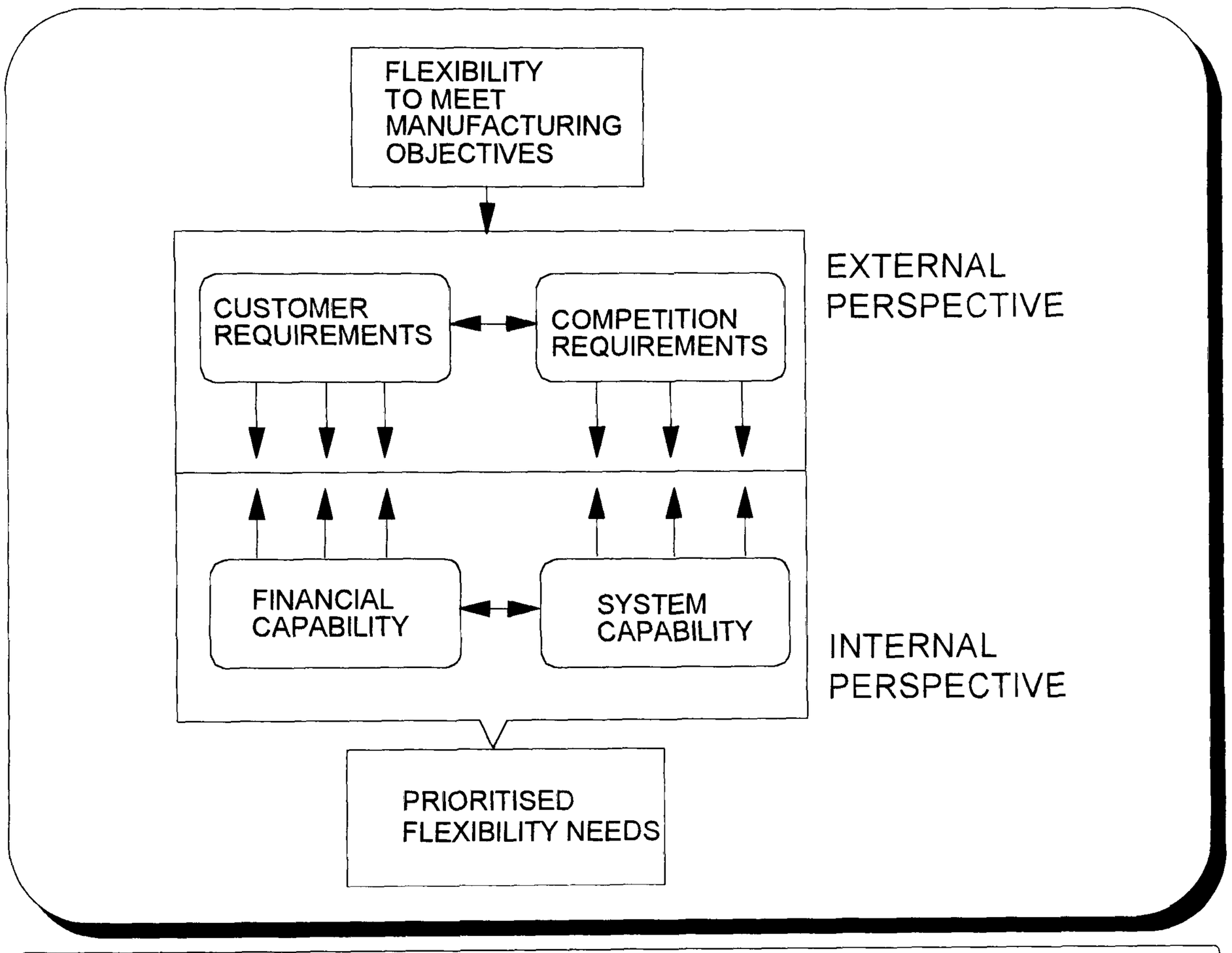

Figure 3.2: The Flexibility Evaluating Mechanism

The key issues examined using the requirements evaluating mechanism can be loosely put in four groups: customer requirements and competition which are external; the firm's capability and innovative requirements which are internal to the company.

3.5.2.1 EXTERNAL REQUIREMENTS

This is a view that focuses on customer requirements and the behaviour of the demand. It is necessary to design systems that will give a competitive advantage in order for the company to take full advantage of new developments and thereby create new external requirements. This may lead to gaining more customers but at the same time setting new standards. For example, if every supplier is capable of supplying products with a certain lead time, and that is the accepted level, it may be advantageous to reduce the lead time considerably. Customers demand high service levels, dependability and an ability to meet the customer's requests to change orders at short notice. Often at the same time, competition may be driving the price down.

3.5.2.2 INTERNAL CONSTRAINTS

The aim of every manufacturer is to meet all the needs of its customers but it may not be possible because of other constraints within the system or the organisation. These constraints could be financial or physical ones. Any suggested flexibility needs have to be examined to ensure that they could be successfully implemented without detriment to the whole system. For example, it would not be reasonable, in the long term, that a new flexible machine should be purchased if it increases operating costs without any benefits to the customer or the company. The firm has to be able to supply products at a reasonable cost. Therefore, any issues concerning flexibility must show benefits before the system can be improved to provide more benefits than already does.

3.7.2.3 COMPETITION

The market place for most fast moving consumer goods is very competitive and the competition is global. In order to be ahead or match the competition it seems sensible to put in place the flexibility capability that will enable the organisation to pre-empt or react quickly to competition. The capability to provide customer satisfaction, good value for money and getting new products to the market quickly provides the competitive edge. To maintain the competitive advantage the firm must have the capability to bring out new products at the right time and have the means to support it.

3.5.2.4 INNOVATION

A company may often create good products but the manufacturing organisation must have systems in place to take advantage of such opportunities. The manufacturing system needs to be flexible to take on board new technological developments. Financial help and time must be allowed for implementation of innovative ideas.

The outputs from the focusing mechanism are prioritised coherent flexibility requirements which can be used to formulate manufacturing strategy. Some of these flexibility requirements may not change the strategy but may influence some manufacturing programmes (see Figure 3.1). The next stage would be to decide what to do with these requirements. The prioritised list of manufacturing flexibility requirements obtained through the evaluation mechanism has to be made more specific in order to get the exact provisions to meet the requirements.

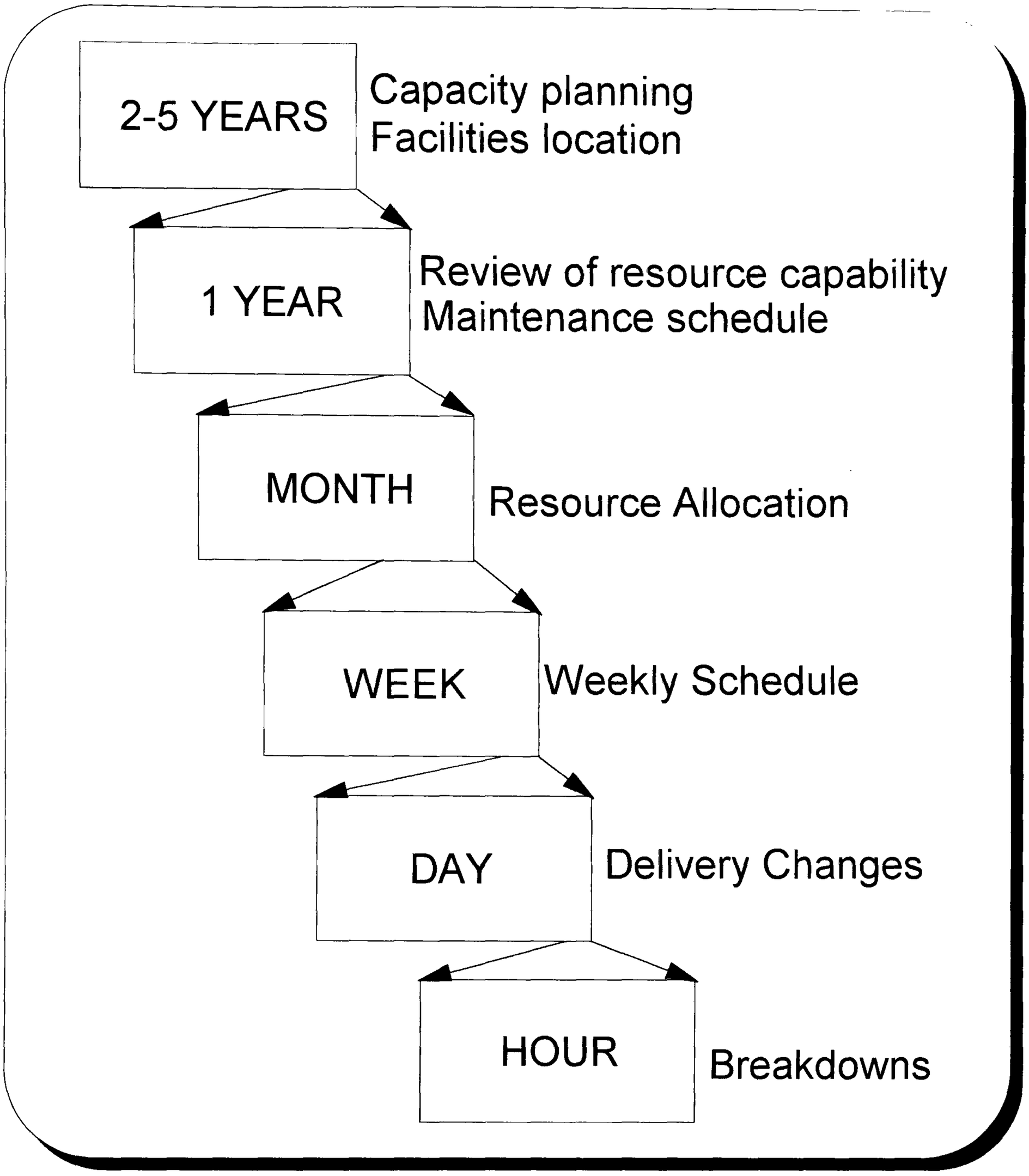

Figure 3.3: Time horizon and events

3.6 TIME HORIZON OF MANUFACTURING FLEXIBILITY REQUIREMENTS

Over any time horizon the system may need to use its various capabilities to cope with demand and other disturbances in the system. In order to assess the capability of the system individual types of flexibility as shown in Figure 3.3 were investigated within their time horizon.

Here it is suggested that flexibility needs be classified into three levels of planning, ie. strategic, tactical and operational. It is necessary to have different levels primarily because different characteristics of a system require different response time. It must be recognised that flexibility concerning a strategic change may take longer to achieve than a mere changeover of a machine to make a different product. To simplify the process, flexibility requirements will be placed in one of the three groups: long term, medium term and short term.

LONG-TERM

This level is concerned with assessing the manufacturing organisation's position in the market place and the setting of its objectives to meet the requirements. It is at this level where decisions are taken to enable the manufacturing organisation to be positioned competitively. Flexibility issues should be considered even at this level, for example, flexible supply and sourcing.

The most important aspect of flexibility at this level is how quickly the required market position can be attained, and considering the number of options that are available to achieve the objectives. Some of the factors that will most certainly affect the manufacturing strategy to be considered at this level are listed below:

i) volume growth, focusing of the manufacturing facilities, product variety, harmonisation of products, diversification.

ii) introduction of new products;

iii) responding to directional change in market competition;

iv) developing of the future structures and infrastructure;

v) location of resources in relation to the market place;

vi) setting of operational measures.

vii) new markets.

MEDIUM-TERM

This level is concerned with determining the means by which the objectives are met. This level involves the translation of objectives into practical solutions. The activities include determining quantity and quality of machines and people, and also the setting up of basic manufacturing policy. This is the stage that will ultimately determine the potential of the operational system to deliver the requirements of the objectives.

This is the tactical level which will select the correct inherent qualities of the systems. These qualities can be gained through the way products are designed, the way production machines are designed, the way the infrastructure is designed, the way the organisational structure is designed and the way the work force is trained and organised.

SHORT-TERM

This is the operational level where flexibility is about making effective use of the characteristics which have been designed into the manufacturing system and the products by using procedures and controls. This flexibility is mainly concerned with using the time available to each resource in the most effective manner to meet the required demand and to cope with disturbances in the system. Many manufacturing organisations are discovering that time should be managed in the same way costs, quality and inventory are managed. Effective management of production time helps to improve customer service at the same time keeping operational costs low. It is therefore considered that operational flexibility deals with the short term fluctuations and the gradual changes in the system.

On close investigation it was decided that this thesis should concentrate on the flexibility at the tactical level which is also called the medium term horizon.

Hyun and Ahn (1992) defined a decision hierarchy similar to the framework defined in this chapter, but Nilsson and Nordahl (1995) defined a slightly different structure, also with three levels:

1. The strategic level - external flexibilities are defined in the marketplace between the company and its suppliers or customers.
2. The production system level - the characteristics of the production system defined on a tactical level.
3. The production resource level - the resource characteristics are defined on the operational level.

3.7 MEANS OF MEETING FLEXIBILITY REQUIREMENTS

In order to define the means by which flexibility requirements can be met, the requirements need to be precise. The flexibility requirements can generally be seen to fulfil two main objectives: firstly, to react to change from without and within the system; secondly, to initiate change. The ability for the customers to change orders or the ability for a system to maintain its output despite breakdowns is a reaction process. However, the ability to introduce new products to the market quickly can be used as a competitive advantage, provided there are new products to be introduced.

3.8 EVALUATING REQUIREMENTS - AN EXAMPLE

To demonstrate the process of defining requirements for meeting flexibility requirements, an example was chosen. If, for example, the requirement of the company was to increase the product range provided to the customer, there will be a number of issues that would have to be considered in order for this to be done effectively. Some of the issues may be long-term and some short-term. In order to reflect the importance of the time scales in which the decisions are taken the effect of these requirements were grouped in long-term, medium-term and short-term.

STAGE 1

The first stage is to establish the goals for which the change is required. The market requirements and internal factors are then assessed to establish the gaps between what it is that is required and the resources available. From these the critical issues can then be identified. In this example the goal is to increase the product variety but the question (why?) must be asked. The reason may be to create a completely new customer base or to compete directly with a company providing similar products. Critical issues may included

the customer being able to perceive the product differentiation and therefore appreciate the wider choice. The other critical issue for manufacturing and creation of the infrastructure mentioned frequently in literature is the speed at which the product is introduced to the market. When a product is being introduced it is important that planning systems, production and distribution systems are able to deliver the requirements.

STAGE 2

Critical success factors may include raising enough awareness to the customers regarding the variety being offered. The company may wish to measure the time it takes to get the product from conception to the market. The measures for the possible customer base and the speed of product introduction can be measured directly and compared to the market research and competitors.

STAGE 3

This stage involves defining the manufacturing objectives. The manufacturing objective may be to introduce and produce the variety of products with minimum increase in cost or indeed without increased costs within a specified period of time. Provision of variety assumes that there is product flexibility. This is just an example. The objectives will depend on the extent to which the manufacturing system is capable of meeting the new requirements.

STAGE 4

This stage defines the "How to do it". The typical questions may include whether to make in-house or to use third party at the beginning of the product life. There may be the assessment of whether the variety may be accommodate by using a flexible machine which

will make all products. Changeovers would require machine. The gradual increase in variety may increase the volume produced. This requires volume flexibility. Therefore, the manufacturing system may need to have variable production rate or the increased capacity may have to be phased over a period of time. The evaluation mechanism would be required to make the right choices to provide the required flexibility. These evaluations could be in the form of a model or a number of models. The results of the evaluation can then be fed back to formulation of the objectives.

STAGE 5

The manufacturing programmes deal with operational issues which are often short-term decisions to meet the objectives set above. For example, which products should be made together. What the sequence and frequency of production should be. What the routeing should be. This assumes routeing flexibility. Increased variety does increase the need for decision support to resolve such issues by the use of planning and scheduling tools which could part of the evaluation mechanism. The decisions made here can be fed back to the strategy level and manufacturing objectives.

3.9 SUMMARY

The method described above clarifies flexibility issues in order to formulate the perceived flexibility problem into measurable requirements then the mechanisms for achieving the flexibility needs are determined. Models can then be used to evaluate the implications of each flexibility need. It has also been shown that flexibility is multi-dimensional, therefore a requirements evaluating mechanism is required to get a balanced view of the real requirements. The next chapter defined the measures necessary to implement the defined capabilities.

CHAPTER 4

KEY PERFORMANCE MEASURES

4.1 INTRODUCTION

This chapter reviews the key financial and non-financial measures that are used to assess the performance of a manufacturing system. In here only the measures relevant to the operation of a manufacturing system will be discussed. The suitability of these measures for assessing the performance of a manufacturing system will be discussed.

Performance measures are necessary for any productive team of people or organisation to function properly. As Meyer (1994) said "Trying to run a team without a good guidance system is like trying to drive a car without a dashboard". This applies to any team or organisation. Without a dashboard in a car the driver would not have any indication of the speed at which the car is travelling and would not have pre-warning if petrol was to run out. The same applies to a manufacturing system , there have to be measures to guide those that operate it in order for them to make the right decisions for the direction of the organisation.

Maskell (1993) said appropriately selected performance measures give a clear signal to all people in the company about the priorities that are important to senior managers and people will concentrate on measures by which their success or failure is measured. Therefore it is important to ensure that appropriate measures are used in the most direct simple and understandable way possible.

Mills and Robertson (1993) said a manager's performance can only be measured in relation to the assets under his or her control. It is for this reason that corporate ratios, and liquidity ratios, which are not seen to be influenced directly by flexibility, were not included in this thesis. Maskell (1991) said that manufacturing strategy is centred around issues such as quality, reliability, lead time, flexibility and customer

satisfaction. Performance measures must directly measure the success or failure of each of the manufacturing strategies.

This chapter is divided into two sections:

1) Financial measures

2) Non-financial measures

4.2 FINANCIAL MEASURES

The primary financial performance measures shown in a hierarchy of ratios in Figure 4.1 form part of a structure which can be extended to encompass other areas of analysis. The primary financial performance ratios will be examined in this chapter. These are:

1) Return on capital employed
2) Profit margin
3) Capital turnover

4.2.1 RETURN ON CAPITAL EMPLOYED

The normal ratio used in companies is return on total assets and it is measured at company level. The return on capital employed ratio is calculated by dividing operating profit by capital employed. The measure takes into account all the company assets as is shown by Mills and Robertson (1993): total assets include fixed assets such as land, buildings, plant, machinery and current assets such as stock, debtors and cash. This ratio measures how effective managers have been in using the capital which they have been given to invest in the business.

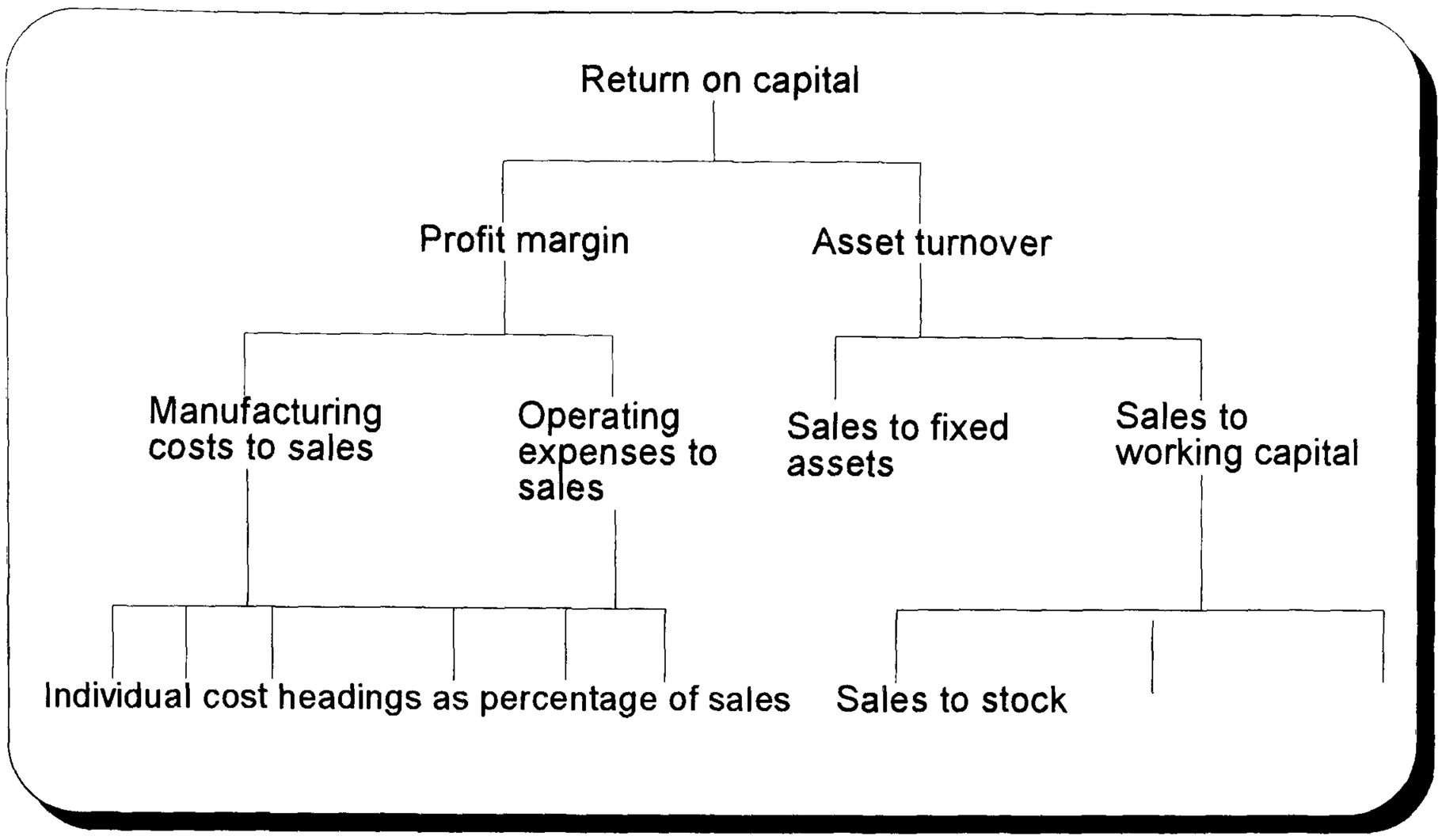

Figure 4.1: Financial performance ratios

The measure may not always be useful for every financial comparison as it is shown in the following example. If, for example, there were four products to be made and the choice was a dedicated machine for each product or a flexible machine to make all four products assuming both types of machines have similar capacity over a period of time then debtors and cash are outside the scope of the selection decision. The assets would also only include the cost of machine the area occupied by the machinery and the stocks produced as a result of the production technology chosen.

4.2.2 PROFIT MARGIN

Profit margin is another measure of profitability. As for return on capital employed, profit margin is based on profit before tax because it relates to trading performance. Profit margin as a percentage is calculated by dividing profit by sales and multiplying by 100.

Regarding flexibility of a manufacturing system it may be difficult to relate sales directly to the performance of a manufacturing system. However the profit could be affected by the cost of manufacturing which could be influenced by flexibility.

4.2.3 CAPITAL TURNOVER

Return on capital employed and profit margin are not used in isolation. They can be linked together by a third ratio of profitability and productivity, i.e. the capital turnover ratio. The capital turnover ratio represents the number of times the capital employed in a business has been turned over and it is measured by dividing sales by capital employed.

The three primary ratios link together to help interpret change in profitability i.e. profit margin multiplied by capital turnover equals return on capital.

The three ratios mentioned above are the key criteria of measuring financial performance but where data is available further ratios which require more detailed data can be applied. These performance ratios include:

i) Manufacturing costs to sales
ii) Operating expenses to sales
iii) Sales to fixed assets
iv) Sales to working capital

4.3 NON-FINANCIAL MEASURES

Maskell (1993) said that performance measures must be directly related to manufacturing strategy so that they measure the success or failure of each strategy. He also said that strategy might differ from one company or site to another but will centre around such issues as quality reliability, lead time, flexibility, innovation, or customer satisfaction. Therefore performance measures should relate to these issues.

Goals are set to measure how well it is achieving the goals set down in the manufacturing strategy. It is important to relate performance measures to strategy, Maskell (1993) gives two reason for why it is so important:

1) A company needs to know how well it is achieving the goals laid down in the strategy. It is important to choose a small number of pertinent performance measures that enable the company manager to assess progress constantly.

2) People concentrate on what is measured. If a firm measures and reports the results of someone's work, the person will be motivated to improve. The choice of measures can steer the direction of the company.

The key non-financial measures are as listed below:

1. Customer service level
2. Inventory level
3. Ability to change the production schedule
4. Time to introduce a new product.

There are other measures at a lower level than these four. The lower level measures may evaluate directly the cause of the above.

4.3.1 CUSTOMER SERVICE

A manufacturer has to meet customer demand with a certain level of service and at a reasonable cost. The customer may demand a specified level of service, if this is not met the business may be taken elsewhere. If the costs are too high to meet the level of service demanded by the customer, the manufacturer will soon be out of business.

Meyer (1994) writing about team performance measures, said "Because a team is responsible for a value delivery process that cuts across several functions (like product

development, order fulfilment, or customer service), it must create measures to track the process". In this statement it has been shown that order fulfilment and customer service are not just a measure at the end of a process but they are affected by the performance across the several functions of the system. This means that there must be a correlation between measures with a system in order to supply the right product, in full, at the right time, in the right place. This is the aim of every manufacturer whether there are disturbances in the system or not. The simplest form of the measure of service level is given by:

$$S = \frac{Q_s}{Q_o}; \qquad \text{with } S \leq 1$$

Where:

S is the customer service
Q_s is the quantity supplied
Q_o is the quantity ordered

This measure assumes that the manufacturer will not oversupply.

4.3.2 INVENTORY LEVELS

In many cases a manufacturer carries inventory in order to compensate for the inability to manufacture to customer order. Some manufacturers carry excess capacity in order to compensate for the inability to change over quickly from one product to another so as to produce the variety required by the customer.

This was supported by Newman et al (1992) who said that while any manufacturing process will have some inventory, some manufacturers must carry higher levels in order to remain competitive with other manufacturers who are able to offer shorter lead time and/or variety because of their higher level of flexibility. Newman (1992) also said that while the inventory buffers insulate the process from the direct implications of external uncertainty, enabling the manufacturer to respond to a higher

level of it without any increase in manufacturing flexibility, they are not without a cost. The costs are incurred through the cost of holding the inventory. Inventory for some products may become redundant, this causes waste in raw material, production time and storage space.

There are two main external factors which cause the manufacturer to carry inventory that is over and above safety inventory: a) fluctuations in demand volume b) change in product mix.

a) Fluctuation of demand volume

Changes in demand volume are cyclical and seasonal, or permanent. Permanent changes require additional or less capacity. It is the cyclical and seasonal changes that are difficult to deal with. For these the production system has to have a variable production rate so that when required the system can produce at a higher rate. This is an equivalent of carrying excess capacity. Where the change in production rate is not possible, the alternative is to carry higher inventory levels.

b) Changes in product mix

The customer may choose not to order exactly the same products in every order. This will cause the manufacturer to provide a different mix of products from period to period.

In order to provide manufacturing flexibility, changes have to be made to the physical structure of the manufacturing system and to the infrastructure. For example, if set-up times were to be reduced, the scheduling system must also be changed so that it is capable of scheduling with higher product mix and smaller production batch sizes.

4.4 SUMMARY

As it was said by Maskell (1993), performance measures currently in widespread use are not only irrelevant, but make people do the wrong things. Performance measures must be relevant if they are to be used by production personnel, supervisors and managers and they must inform directly of success or failure.

CHAPTER 5

MODELS

5.1 INTRODUCTION

The previous chapter examined measures that might be used to assess the performance of a manufacturing system. The importance of applying the correct measures to the right level of the organisation was discussed. This chapter concentrates on modelling of the manufacturing system.

As every manufacturer wants more flexibility, many have made the decision to design or purchase a system that possesses many of the characteristics of a flexible system as described by Hill and Chambers (1990). However, it was shown in Chapter 3, a system may have several flexibility attributes but they may still not enhance the overall performance of the manufacturing organisation. The aim of the models was to evaluate the potential benefits contributed to the manufacturing organisation by each flexibility attribute being considered. Once the levels of contribution by each attribute were known, it was then possible to set priorities. This ensured that the system had just the attributes it needs and not everything else which may not be necessary. The initial study, before modelling began, considered future changes in the market place and changes in technology in order to design or select a system that would meet future requirements. It is worth mentioning that the models were used for decision support but the options were generated through a process of analyses using the knowledge of the market place. The main steps followed in order to evaluate the options are a summary of the process for setting the manufacturing strategy as described in Chapter 3. These can be summarised as below and shown in Figure 5.1:

1. Set competitive priorities.
2. Analyse the capability of the system.
3. Evaluate the flexibility needed to meet the priorities.
4. Identify the gaps.
5. Formulate investment and improvement or operating plans.

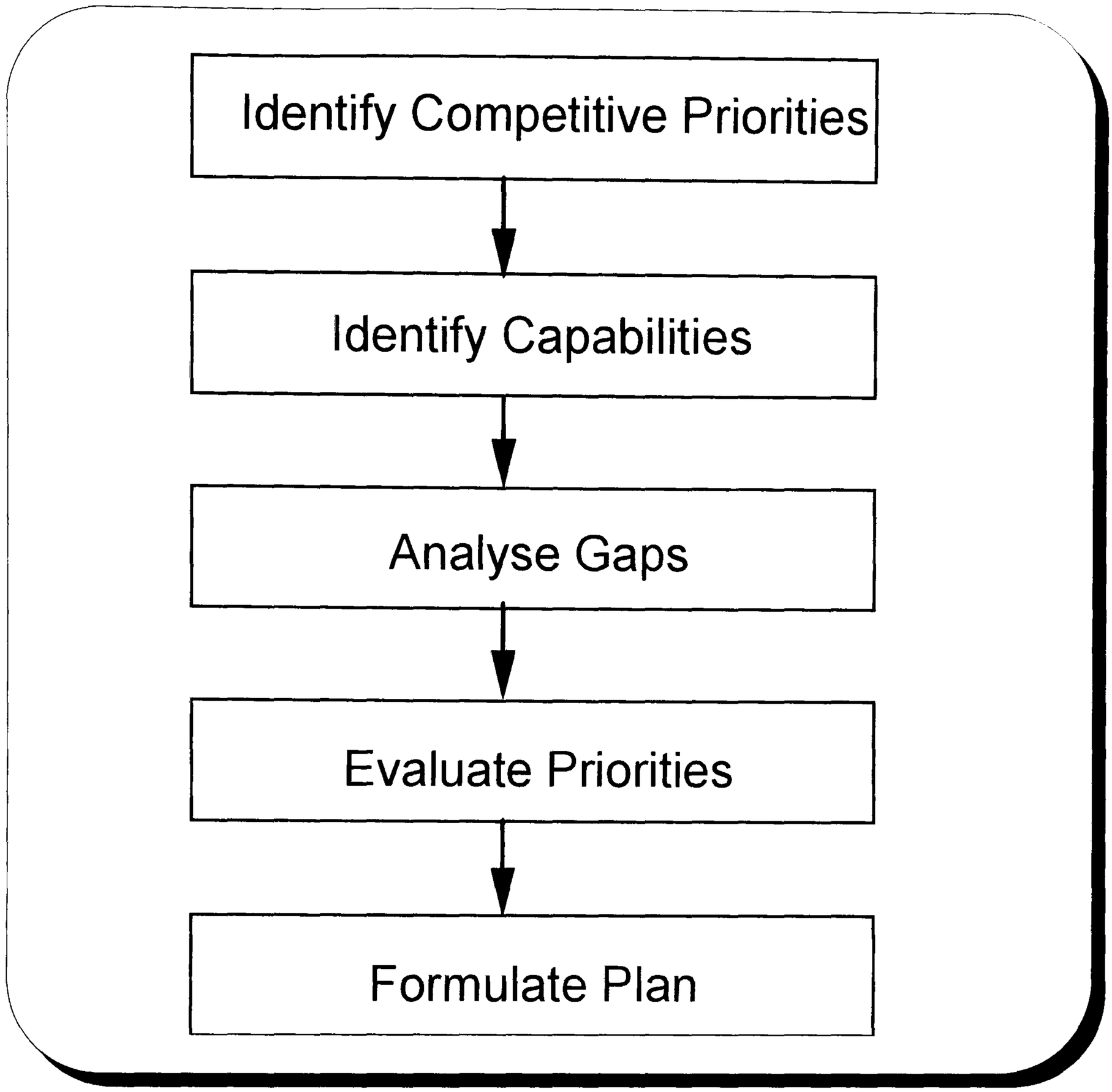

Figure 5.1: Setting flexibility priorities

For example, De Meyer, et al. (1989) listed the top eight competitive priorities set by manufacturers from Europe, North America and Japan as shown below. The order in which these priorities were ranked was different for the three groups but they all had the priorities listed below within the top eight places.

1. Low prices
2. Rapid design changes
3. Consistent quality
4. Dependable deliveries

5. Rapid volume change
6. High performance products
7. Fast delivery
8. After sales service

As was discussed in Chapter 3, manufacturing decisions may be classed as long term, medium term or short term. In terms of flexibility there are issues at all levels which must be considered. Examples are shown in Table 5.1.

Table 5.1: Flexibility requirements and time horizon

LONG TERM	- Location of warehouses and distribution centres - Selection of production technologies - Development of a product range - Establishment of raw materials and packing materials suppliers - Selection of types of transportation systems
MEDIUM TERM	- Product mix - Production cycles - Batch sizes - Overtime - Seasonal labour - Distribution quantities
SHORT TERM	- Production sequence - System failures - Shift patterns - Finished goods dispatch - Raw materials and packing material receipts

The simulation model was mainly concerned with the medium term decisions. However, when modelling tactical issues the relationship with strategy and the implementation process was considered.

5.2 THE MANUFACTURING SYSTEM

The system which was modelled included the lead time for supply of raw materials and the production and dispatch of finished product to the customer as shown in Figure 5.2. Whilst there are other important requirements for flexibility, such as fast introduction of new products, this model was concerned mainly with customer service levels and operating costs as influenced by tactical level decisions.

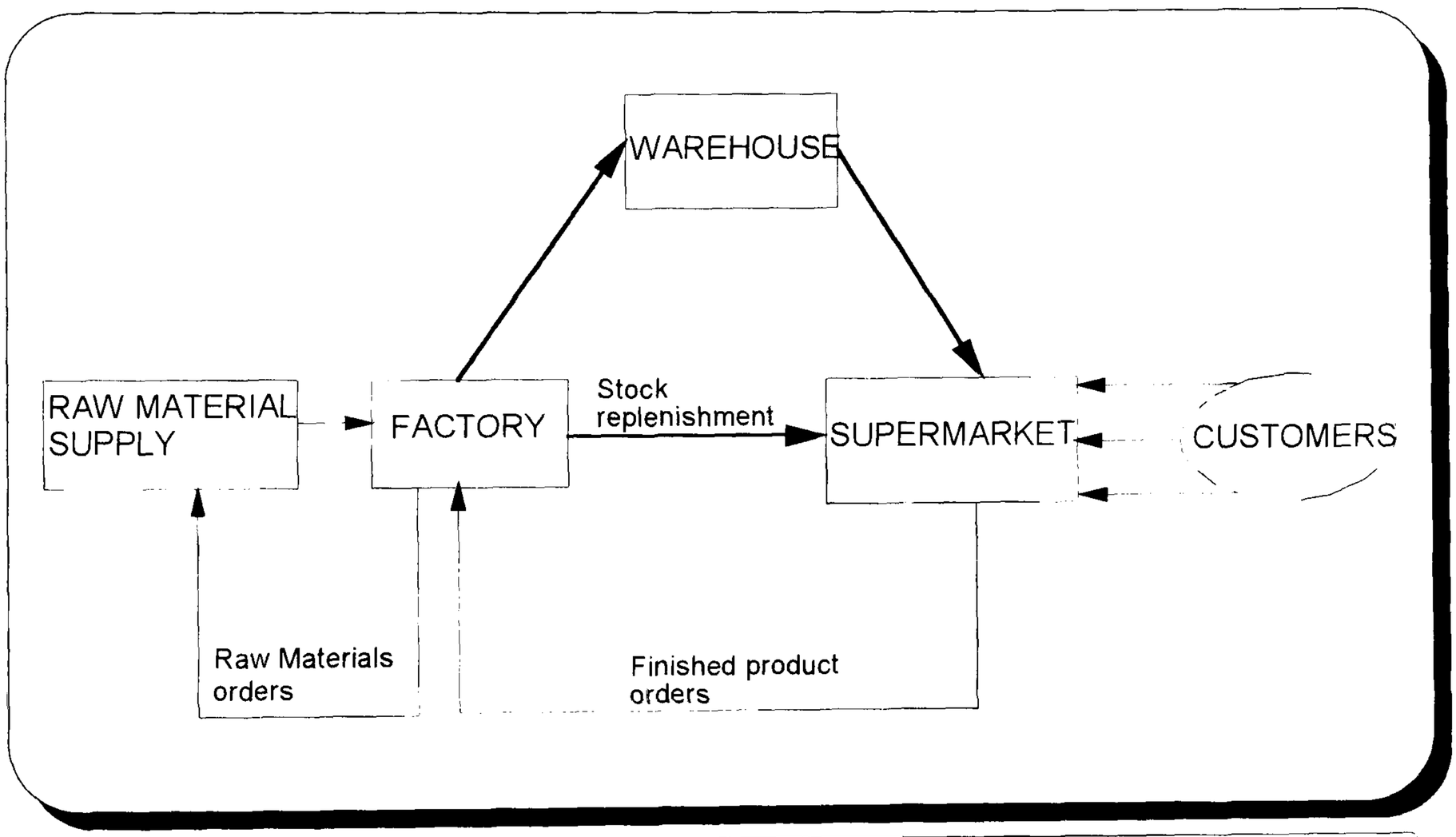

Figure 5.2: Material and information flow

5.3 THE SIMULATION MODEL

The main simulation package used to model the manufacturing system was a purpose built supply chain simulator. At the time it was used for this work it was in the process

of being developed from a bespoke simulator named SLAP (Stock Level Analysis Package) to a commercial supply chain simulation package named INTASTOK.

The thinking behind the simulation model was that the supply chain of a manufacturing organisation can be thought of as a pipe line, with raw materials coming in at one end and finished products being delivered to the customer at the other end. The activities within the supply chain fell into three main areas:

-The purchase and stock control of raw materials
- The control of production within the factory
- The movement of products from the factory to the customer.

These three parts of the supply chain work together as an entity using feedback loops. The simulation enabled the evaluation of various strategies to increase the performance of the whole system and not just the individual parts of it.

The technique of supply chain modelling enables the user of the package to investigate the design parameter and operational strategies that will improve the performance of the whole manufacturing system and achieve the company objectives. These design parameters and operational strategies are tested using simulation before they are implemented.

The model used the technique of discrete event simulation to provide the dynamic picture of events occurring within the system. The distribution part of the model used replenishment rules to replace stock. The manufacturing part of the model used planning and scheduling rules to ensure that the right products were produced in the right quantities and at a reasonable cost. In every situation the model was used to increase service levels and to reduce stock but at the same time minimising operational cost.

5.3.1 INPUT DATA FOR THE MODEL

After completion of development, the simulation package was completely data driven. The main data required for the model included:

- The structure of the manufacturing system, which defined the flow of products from purchase of raw materials to delivery of the finished product to the customer.
- Stock replenishment rules and their parameters. The model had a choice of fixed or variable reorder quantities and adjustable reorder levels.
- Forecasting methods used with the replenishment rules. These included the use of simple exponential smoothing, or moving average, or generating values based on a distribution, or by using data from an external system.
- Production planning and scheduling rules. The model used two methods of planning, these were optimisation and back scheduling. The optimisation method worked in such a way that products would be produced when they are required. However, if there was a shortage of capacity the products with the least marginal cost would be the ones not to be produced. The back scheduling method worked by planning the most urgent requirements first.
- Planning and scheduling parameters, for example, production capacity and the calendar of its availability, production rates, batch sizes, production sequence, changeover time and changeover cost.
- The lead time for production and order fulfilment and their parameters of variability.
- Historical demand data or expected demand patterns.
- The bill of materials.

5.3.2 OUTPUTS FROM THE MODEL

The model had a number of financial and non-financial statistical outputs as reports from the model runs which are shown below.

NON-FINANCIAL STATISTICS :

- Customer service level achieved.
- Average stock.
- Number of batches.
- Average batch size.
- Stock turns.
- Average back order quantities.
- Resource utilisation.
- Forecast error.
- Sales quantity.
- Lost sales quantity.

FINANCIAL STATISTICS

- Total revenue (turnover).
- Marginal cost.
- Marginal profit.
- Transport cost.
- Stockholding cost.
- Lost sales in monetary value.

5.4 MODEL DATA

Sets of empirical data were collected in order to define the behaviour of the manufacturing system. The data were analysed and then the results were used to generate new data with which the model was constructed and run. New data had to be generated in order to provide sufficient and consistent data to construct and run various scenarios. Separate data were generated for setting of parameters.

5.4.1 CUSTOMER DEMAND

At the local corner-shop or supermarket, the customer purchases items from a shelf. The number of times the supermarket replenishes the stock on the shelf from its warehouse depends on the size of the shelf and the quantity and frequency of the demand. The manufacturer replenishes the supermarket warehouse stock from its warehouse or directly from the factory. The manufacturer also obtains raw materials from suppliers.

The factory is not likely to make, for example, a tin of peas or baked beans every time a customer makes a purchase from the supermarket. Therefore, there will be a mismatch between the frequency of production and the amount of the product that is coming off the shelf in the supermarket at any one point in time. The manufacturer makes products based on a forecast, but forecasts are never absolutely correct. This means that inventory has to be held between the manufacturer and the supermarket shelf. If the situation arose where the customer's preferred product is not on the shelf, very often, an alternative product will be available. It may very well be a competitor's one. This is what makes the fast moving consumer goods way of manufacturing different from that where the consumer places an order and is able to wait for the goods to be manufactured and delivered. For example, consumers will wait for the right car or aircraft to be available, but will not wait for weeks to get the right make of soap or margarine. The supplier has to decide how to deal with the variation in demand, disturbances in the manufacturing process and the effect of order lead time. The type of flexibility a manufacturing system must provide will depend on the nature of the problem but the aim will be to provide the highest service level possible at as little operating costs as possible.

Weekly demand data were collected and the distributions for the individual products were analysed and a summary of the results are shown in Figure 5.3. The demand was

not broken down into individual customer orders, consequently it had the following limitations:

a) The data did not show the number of orders within a specified time;

b) The number of different products or variants per order were not known;

c) The frequency of order per customer per product was not known;

d) The volume per order was not known.

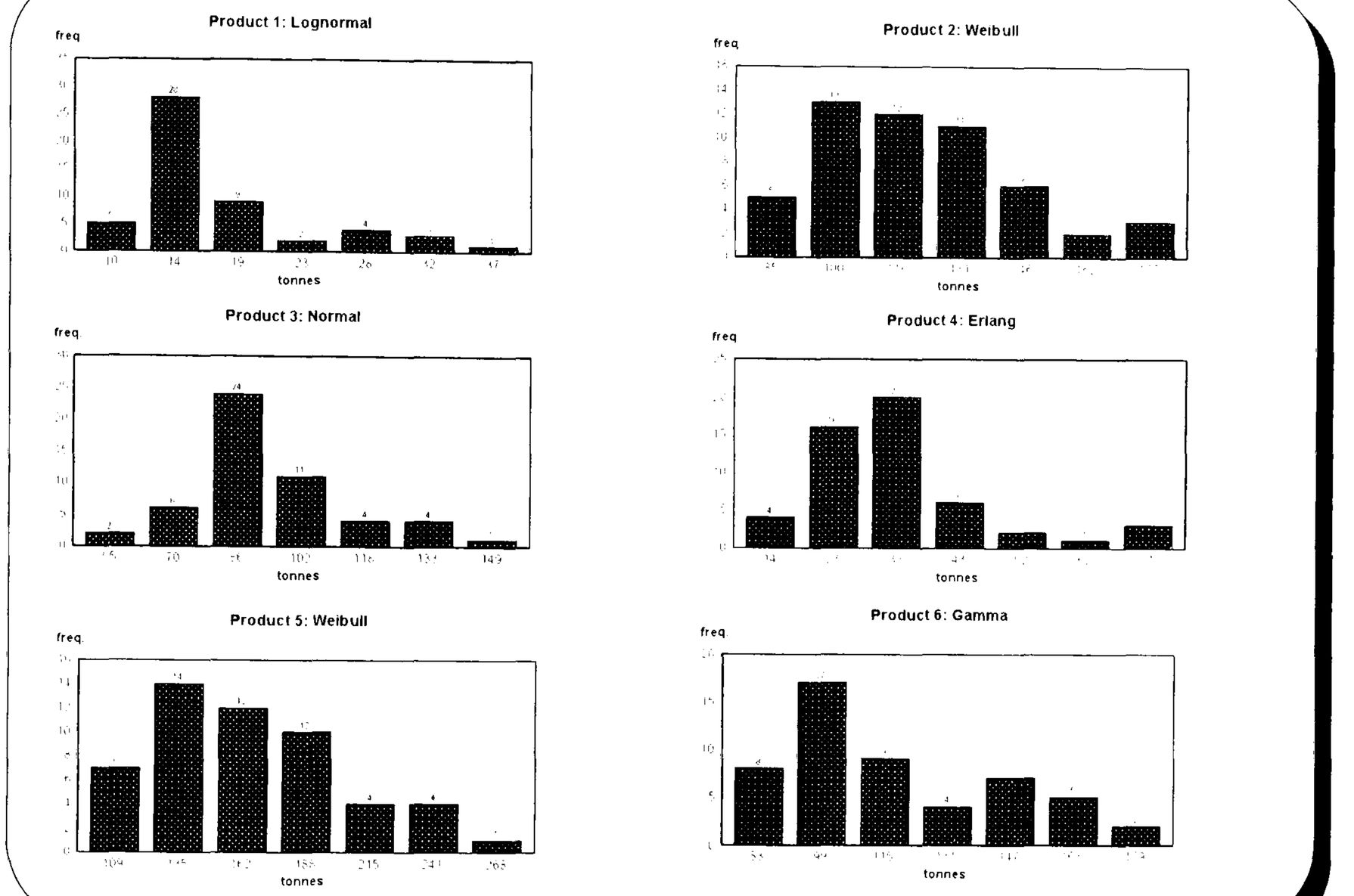

Figure 5.3: Demand distribution of the example data

As it can be seen from the distributions that smaller demand quantities occurred more frequently than large demand quantities causing a skewed normal distribution; the skew was different from product to product. In this model the best fit distributions were used. A summary of the results of the best fit distribution and also the full details are shown in Appendix I. A separate distribution was used for each product knowing that different product profiles may represent different customer behaviour, as there may be a different dominant customer for each product or different ordering patterns may apply to different products.

Ideally, daily demand data would be required for this type of model. Daily data can show trends that occurred within the week, if there are any, and therefore give a better picture of the behaviour of the system. In this model new demand data were generated based on the coefficient of variation of a sample of daily data which had a pattern of 0.13, of the total sold in a week, normally distributed in the first 5 days; 0.27 on the sixth day; and only 0.08 on the seventh day.

The coefficient of variation for the weekly demand was calculated by $v = \left(\frac{\sigma}{\bar{X}}\right)$.

Where σ was the standard deviation and $\bar{X}$ was the mean of the demand. This was later used to generate new demand.

Table 5.2: Summary of properties of the example demand

	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Mean	29.48	227.29	171.27	57.34	304.47	220.68
Std. div.	13.62	47.25	40.41	27.4	77.34	56.4
Coef. of var.	0.46	0.21	0.24	0.48	0.25	0.26
Max. qty.	72.2	353.4	297.6	141.2	535.4	357.2
Min. qty.	11.4	141.2	79.2	10.6	165	135.2
Range	60.8	212.2	218.4	130.6	370.4	222

5.4.2 PRODUCTION MACHINES

A typical production system consisting of four main stages: mixing, filling, case packing and palletisation is shown in Figure 5.4. Production demand comes in by pack size and type of product. There may be many pack sizes of the same product and many formulations of the same pack size. These have to be converted to the equivalent demand quantities at each stage of production. Sequencing of production at

various stages has to take into account the stage before and the stage after. The main production issues are concerned with production quantities, frequency of production, sequencing of the products and the size of in-process buffers between production stages.

The production rates were based on the output per hour for the whole line. This was determined by the bottleneck machine, which was the filler. The production rates per product are as shown in Table 5.3.

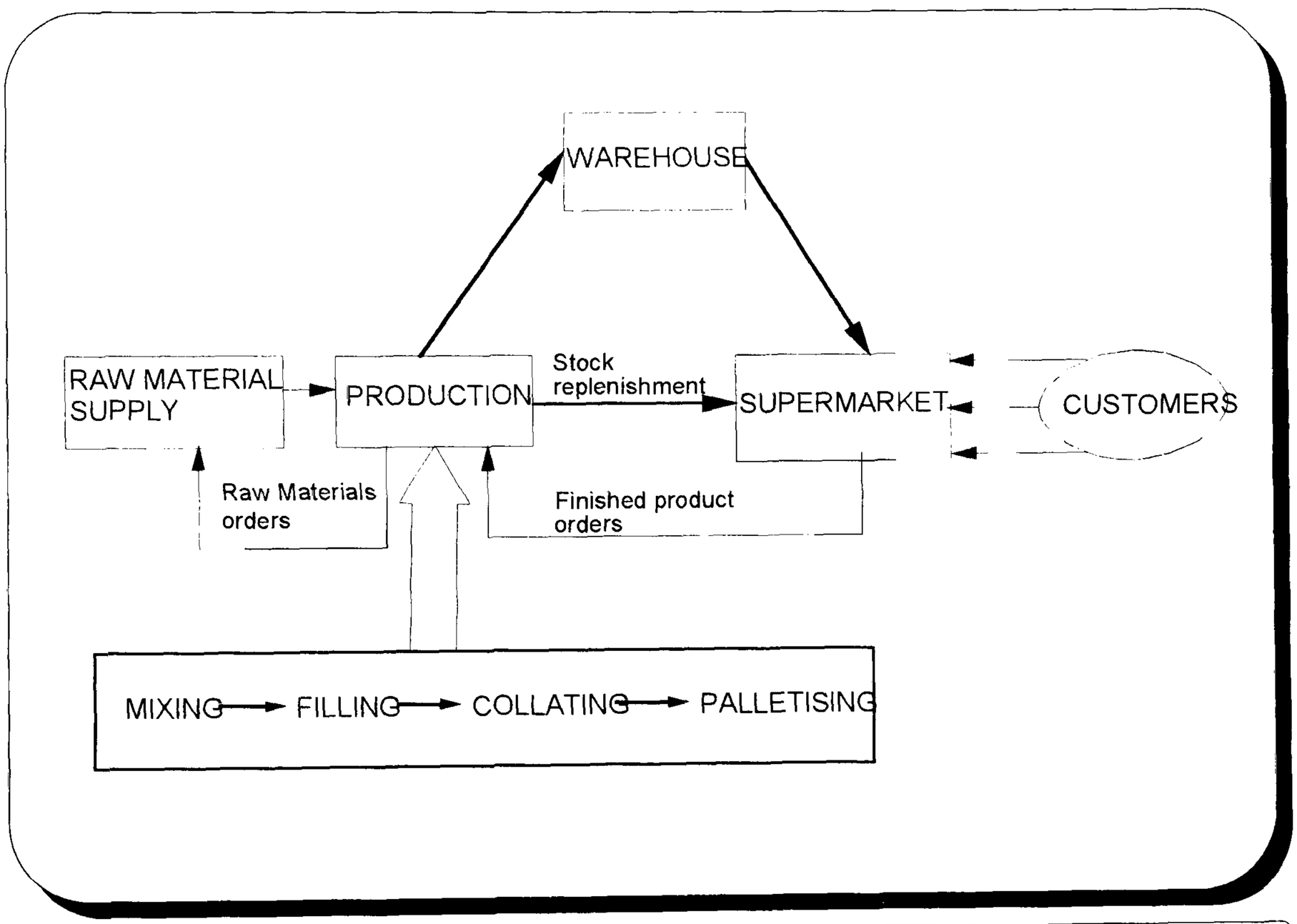

Figure 5.4: The production system

Table 5.3: Production rates (Tonnes/hour)

	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Line 1	3.5	3.5	3.5	4	4	4

5.4.3 CHANGEOVER TIME

The generalised changeover structure described in terms of changeover time was represented in terms of size change, formulation change or label change. If the label change was at the same time as the pack size then the duration for the pack size change was used. If formulation change is required at the same time as the size change then the greater duration of the two was used.

The changeover time was taken as the total time the machine was not in operation as a result of a changeover. At the time the changeover data shown in Table 5.4 was collected, the factory always made products in a pre-defined sequence, i.e. from product 1 to product 6 which in an increasing order of changeover time. However, for the purpose of this exercise it was assumed that the changeover time from one product to another would be the same if the sequence was reversed, so the changeover matrix would be symmetrical.

Table 5.4: Summary of changeover time (Hours)

	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6
Product 1	0	1	2	2.5	4	4
Product 2	1	0	2.5	2	4	4
Product 3	2	2.5	0	1	4	4
Product 4	2.5	2	1	0	4	4
Product 5	4	4	4	4	0	1
Product 6	4	4	4	4	1	0

5.4.4 MACHINE DOWN TIME

Data regarding the production line production efficiencies were collected. However, this data was not used. Reactive scheduling, which enables routing flexibility, was not the main issue under consideration in this thesis.

5.4.5 PROCUREMENT OF MATERIALS

Often manufacturers produce more than one product in a factory, and each of the products requires many types of raw materials and packing materials, obtained from different suppliers. The key issues concerning the control of the supply of materials are evaluated by two main questions, i.e. when to order and how much to order. These are both factors of demand and lead time. There are also issues involving the storage and handling of materials.

5.5 THE MODELLING PROCESS

The modelling process commenced with the definition of what it is that the manufacturing organisation wanted to be flexible about. This included the requirements from the market place and the wishes of the manufacturing company in order for it to improve its competitiveness. In addition to high service levels and low costs the organisation might want to have the capability to introduce new products quickly, increase turnover and increase profit margin.

The process followed in developing the simulation model is shown in Figure 5.5 as defined by Law and McComas (1990).

A simulation model was designed to demonstrate the evaluation of factors that are important in the assessment of manufacturing flexibility. The main areas that the model aimed to demonstrate were the assessment and prediction of the importance of various types of flexibility. In this model, a production line making six products with different

formulations was selected. The model was concerned with the performance of the whole system and not just the individual parts of it. Once the assessment of the flexibility requirements had been carried out, the factors which had the most impact on the overall performance of the system were prioritised. The priority was based on the impact that each of the factors had on the service levels and the relevant operating costs of the whole system.

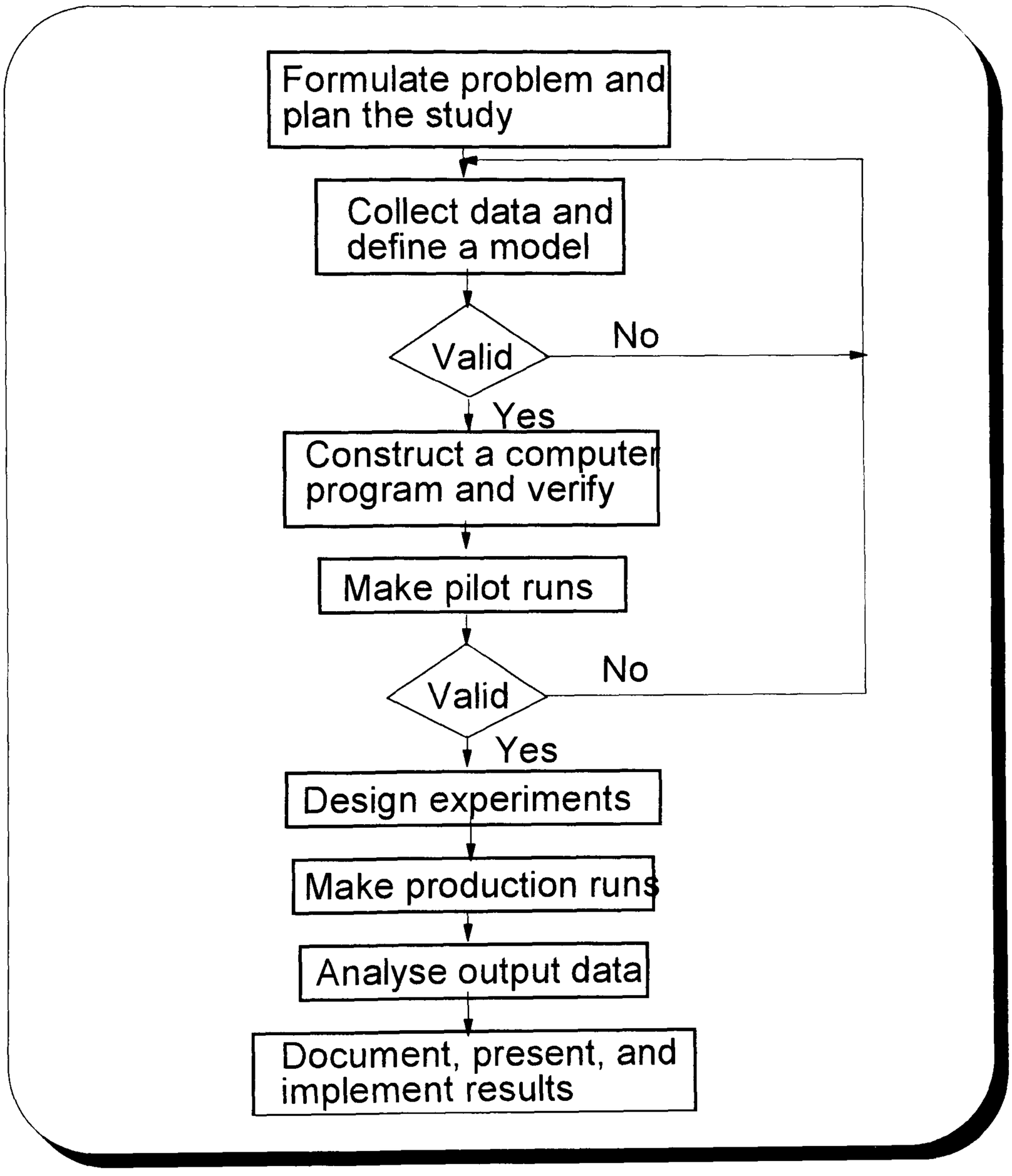

Figure 5.5: The simulation process - Source: Law and McComas (1990)

The flow of information and the sequence of activities in the model are shown in Figure 5.6. The run of the simulation model began by updating the starting conditions and then going through all the stages of the planning process and actual production.

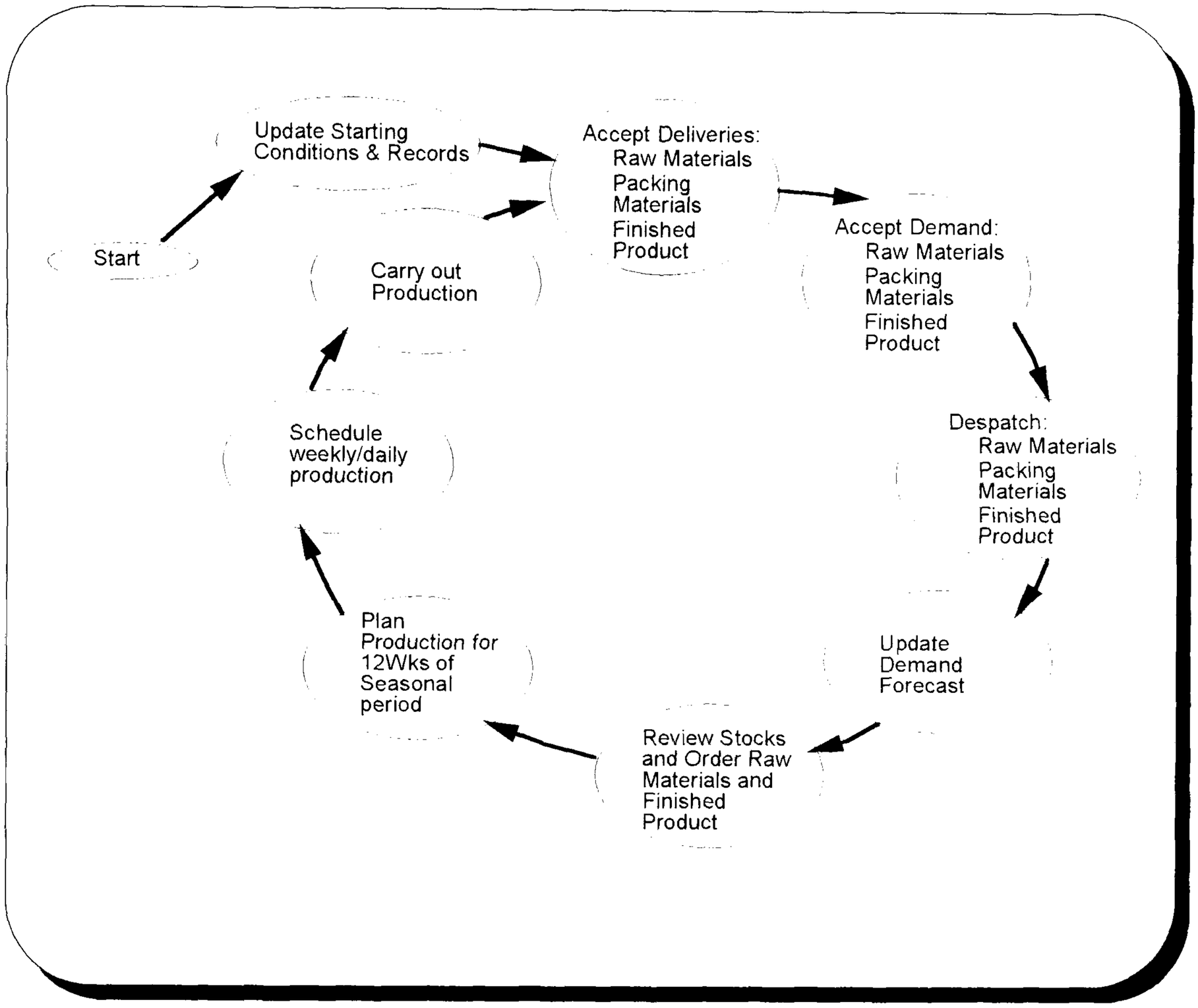

Figure 5.6: The model sequence of activities

5.6 SCENARIOS

Two scenarios were selected on the need to demonstrate structural flexibility and infrastructural flexibility.

1. The effect of the ease of changing production equipment.
2. The effect of freezing schedules.

5.7 THE EASE OF CHANGING PRODUCTION EQUIPMENT

The first set of models were used to demonstrate the effect of the frequency of changing over production from one product to another. This also determined how often a product is made within a period of time. The model used the frequency of scheduling to control the number of changeovers. Before production planning took place, a check was executed to determine the forecast demand and stock requirements for the next period. If it was not necessary to make the product during the period it would not be made. This meant that the number of changeovers may be less than planned but will not be more. The main assumption in this scenario was that if changeovers take a long time to complete the run length would be longer as well and the opposite is true. However, one may choose to do otherwise, if for example, there is excess capacity.

5.7.1 CHANGEOVER COST

In order to calculate the changeover cost only the direct costs were considered. The total direct costs for the production line changeover were made up of personnel and materials costs. Personnel time was charged at a rate per hour for the duration of the changeover. During changeover there was a cleaning time for which materials were used and there was waste of some materials.

The cost of labour may be fixed for some manufacturing organisations, so the assumption made in this model would not apply. If the labour cost was fixed it would be excluded from the calculations as direct cost for the purpose of determining the number of changeover but would still be included as opportunity cost. If staff were not carrying out changeovers they would be doing some other productive work.

For the purpose of this example, the costs used were as follows:

i) Labour cost: £25 per hour per person;

ii) Wasted product was calculated to be equivalent to 10 minutes of production at the nominal production rate.

The total changeover cost was calculated as shown below.

$$C_c = (T_l \times C_l) + (T_p \times R_p \times C_p)$$

Where:
C_c = Total changeover cost (£);
T_l = Labour time (hours);
C_l = Labour cost per unit time (£ per hour);
C_p = value of the product (£ per tonne);
T_p = Time for flow of waste (hours);
R_p = Rate of production (tonnes per hour).

5.7.2 STOCK COSTS

Ballou (1992) categorised stock costs as being made up of:

i) Space cost: The cost of the space required to store products. This was charged at the rate of £8 per tonne of finished product per week.

ii) Capital cost: This is the cost of the money tied up in the stock. This was charged at the rate of 10% of the value of the stock. The charge rate can be taken as the prime rate of interest or opportunity cost of capital.

iii) Stock service cost: This is the cost of insuring the stock against, for example, theft, fire and storm. The level of the charge was dependent on the levels of stock.

iv) Stock risk costs: This is the cost associated with deterioration, damage, obsolescence, contamination, spoilage, pilferage. This is the stock that has been produced but unfit for sale.

v) Out of stock cost: As backordering was not allowed in the simulation model, there were some lost sales. The cost of lost sales was assumed to be equivalent to the marginal profit that would have been earned had the stock been available.

In the calculations for this model stock costs ware assumed to be 20% of the value of the product. The calculation in this model was approximated, in real life the cost of stock may not be directly proportional to the amount of stock, especially where space is rented in blocks. This means that the total stock cost may be a combination of step cost and directly proportional costs.

5.7.3 THE SIZE OF A BATCH

The production run-length or batch size was considered to be the result of a balance between changeover cost and storage cost. Some formulae have been devised to determine the batch size based on changeover cost and stock costs. For example, the multiple-product formula with deterministic, static demand can be used when stocks consist of several items produced using the same facilities with limitations on capacity for storage or production. The optimal values for the production quantity of product *i* can be calculated using the formula as shown below, Fogiel (1985).

$$q_i = \sqrt{\frac{2r_i c_{2i}}{c_{1i}}}$$

Where: q_i = optimal batch size;

r_i = demand rate;

c_{1i} = stock cost

c_{2i} = set-up cost.

However, it is important to be aware that this formula makes the following assumptions which my not reflect the real life situation.

i) Demand has a fixed known rate;

ii) Lead time is zero or is known exactly;

iii) Production is instantaneous;

iv) No shortages are permitted.

The economic batch size calculation could have been used to provided a starting point for the trade-off between changeover costs and stock costs. The eventual batch size was not fixed because the demand was not constant and in certain weeks there was some under production or over production due to forecast error or capacity constraints. However, the economic batch calculation can provide a starting point to determine the economic cycle time but the simulation model was used in order to take into account the short comings of the formula as listed above.

5.8 FIXED SCHEDULES

The idea that freezing schedules can bring stability to the manufacturing process was examined. Freezing a production schedule means that the quantities and the sequence determined at the time the schedule was formed could not be changed even if things changed dramatically.

Two types of models were used to demonstrate the effect of freezing a schedule. If lead time for calculation of safety stock is taken as equal to the frozen period, as in the first of the two models, too much safety stock may be carried. If the lead time was calculated to be equal to the cycle time, as in the second of the two models, the safety stock would not be sufficient. If the period under which the schedule is frozen is longer than the cycle time, the benefit of frequent changeovers may not be felt. A higher level of safety stock may have to be carried to cover uncertainty over the whole of the period that the schedule is frozen. This presented a new challenge for setting safety stock to meet the required fixed schedules. It was decided that this was outside the scope of the thesis. This meant that flexibility could not be measured by both service level and stock level. Instead only stock costs and changeover costs were used because the service levels would be distorted by the levels of safety stock.

5.9 SUMMARY

In this chapter, the structure of the model and the data collection method have been defined. Some assumptions were made about the generation of new demand data to enable the use of characteristics from one set of data in several scenarios. This may cause problems where the data has hidden factors, such as promotions and seasonal festivals effects. Such characteristics may be lost by regenerating the data. The data used here had very few of such characteristics.

CHAPTER 6

RESULTS

6.1 INTRODUCTION

The results analysed in this chapter were related to the actions that the manufacturing system may take in order to make a change or respond to change within its environment. Factors which prevent the manufacturing system from being changed effectively were noted. As was shown in the previous chapters, flexibility is about the ability of a manufacturing system to change. The change could be one initiated from within the system to create competitive advantage or it could be in response to changing circumstances.

Models were used to demonstrate assessment of the three measures identified by Slack (1987), viz.: availability, dependability and productivity. Availability and dependability were associated with how well the manufacturer meets the demands placed by the customer on the system whilst productivity was associated with inward looking measures which show the effectiveness of the manufacturing system in meeting the demand.

The three key elements that are required by a manufacturing system to produce a product are people, equipment and procedures. The decisions regarding these elements can be strategic, tactical or operational. The model concentrated on tactical issues. However, as it will be seen from the results, tactical decisions cannot be completely independent from strategic and operational ones.

6.2 SIMULATION SCENARIOS

Two parameters, shown below, were selected to demonstrate methods of assessing specific forms of manufacturing flexibility representing structural and infrastructural

elements of the flexibility of a manufacturing system. Their effect on product availability and therefore dependability, and productivity were monitored.

1. The effect of the ease of changing machines to make a different product. Here the main issues were changeover time and the costs associated with changeover.

2. The effect of frozen schedules. Management may choose to fix schedules to avoid changes to the current and the immediate future period in order to establish stability to the planning and production process.

To demonstrate flexibility of a manufacturing system, service level and stock levels were used as parameters for evaluating the effectiveness of the system. These also show the availability, dependability and productivity of a manufacturing system. Ballou (1992) said that the reasons for carrying stock relate to customer service or to cost economies derived from them. If the service level is low it means that some sales have been lost.

There are two possible outcomes from a lost sale which has resulted from lower service levels:

i) the customer never comes back following the disappointment of not getting the product wanted in the right quantity in time;

ii) the customer goes elsewhere to satisfy the demand but comes back the next time round.

In this scenario it is assumed that the customer goes away but comes back for the next order.

Stock may be kept for various reasons, for example, safety stock, as described earlier, or pipeline stock which represents work in progress or strategic stock which involves building up of stock for future special events and cyclic stock which is due to batch

sizes. The stock that is of interest in this model is the cyclic stock and there were no special events requiring the building up of stock.

The main assumptions in all the models for both scenarios were as follows:

1. Forecast error was assumed to increase further into the future, but the figures used were the same for all scenarios.
2. There was no variability in capacity availability. However, a percentage of time was deducted from the total available time to obtain the effective available production capacity.
3. Scheduling occurred at pre-determined intervals in line with the cycle time and could not be changed within the cycle period.
4. Production time could not be increased even if there was a shortage of capacity.
5. Changeover time depended on the sequence of production, but it was the same between two products when changing from one to the other.

6.3 THE EASE OF CHANGING PRODUCTION EQUIPMENT

Long production runs reduce the total changeover time but they increase the need for stock. In this scenario it was assumed that the production manager may try to balance the number of changeovers with the amount of stock that could be carried within the system.

The scenario for establishing the effect of the ease of change of the machine was demonstrated by gradually reducing the cycle time which reduced the batch size, in turn increasing the number of changeovers. The principle followed here was that long run-lengths are required for long changeover times. The other main assumptions made in this model were as shown below.

1. Although the cycle time was fixed, thus it was known in which week production for each product would take place, the sequence of production

depended on the urgency of stock requirements from period to period. This means that the sequence of production could be different in each period. The lead time from the day of scheduling to the day of production may be different in each period because of this.

2. Production quantities could not be changed within a cycle time even if it was known that the forecast error was larger than expected.

3. The safety stock was calculated as being equal to $3\sigma'$ by using the following formula:

   $\sigma' = \sigma\sqrt{l}$; where σ is the standard deviation of sales and l is the lead time. In this case the lead time was taken to be equal to the cycle time.

A summary of the results from reducing the cycle time were as shown in Table 6.1. An example output of detailed results for Product 1 for a one week cycle is shown in Appendix 2.

Table 6.1: Results for reducing the cycle time.

Cycle Length (Days)	Safety Stock (Tonnes)	Service Level (%)	Average Total Stock (Tonnes)	Year Stock Turns (Ratio)
70	2,490.48	96.6	12,482.6	4.21
63	2,362.68	96.8	12,380.6	4.24
56	2,227.56	96.7	10,195.3	5.15
49	2,083.69	99.2	10,335.8	5.08
42	1,929.12	97.3	8,333.8	6.3
35	1,761.03	99.2	8,115.6	6.47
28	1,575.12	98.2	5,363.4	9.79
21	1,364.09	99	4,534	11.58
14	1,113.78	98.7	2,686.9	19.54
7	787.56	99.7	1,596.7	32.88
1	297.67	100	318.3	164.95

Eleven models were run, starting with a cycle time of seventy days, and then reduced one week at a time up to seven days, and then finally the model was run with a cycle time of one day. As it can be seen from the results in Table 6.1, the service levels increased from 96.6 to 100% and the stock reduced from 12482.6 to 318.3 as the cycle time was reduced, representing increased flexibility. An example of the screen output of the results for Product 1 with one week cycle time are shown in Figure 6.1.

Although a visual inspection could show some form of relationship between the flexibility of the plant and the stock and the service levels, linear regression analysis was carried out to evaluate this relationship. The results of a regression in Table 6.2 show a very high correlation, with R Squared equal to 0.98, between flexibility and the stock levels, which is one of the measures used to measure the performance of the manufacturing system. The correlation factor can then be used to predict possible values of stock based on flexibility levels. The regression line prediction is calculated using the linear equation shown below.

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x + e$$

Where:

$\hat{y}$	is the predicted value of *y* (in this case it is the stock level)
$\hat{\beta}_0$	is the sample estimate of the *y*-intercept β_0
$\hat{\beta}_1$	is the sample estimate of the slope β_1
e	is the coefficient of error.

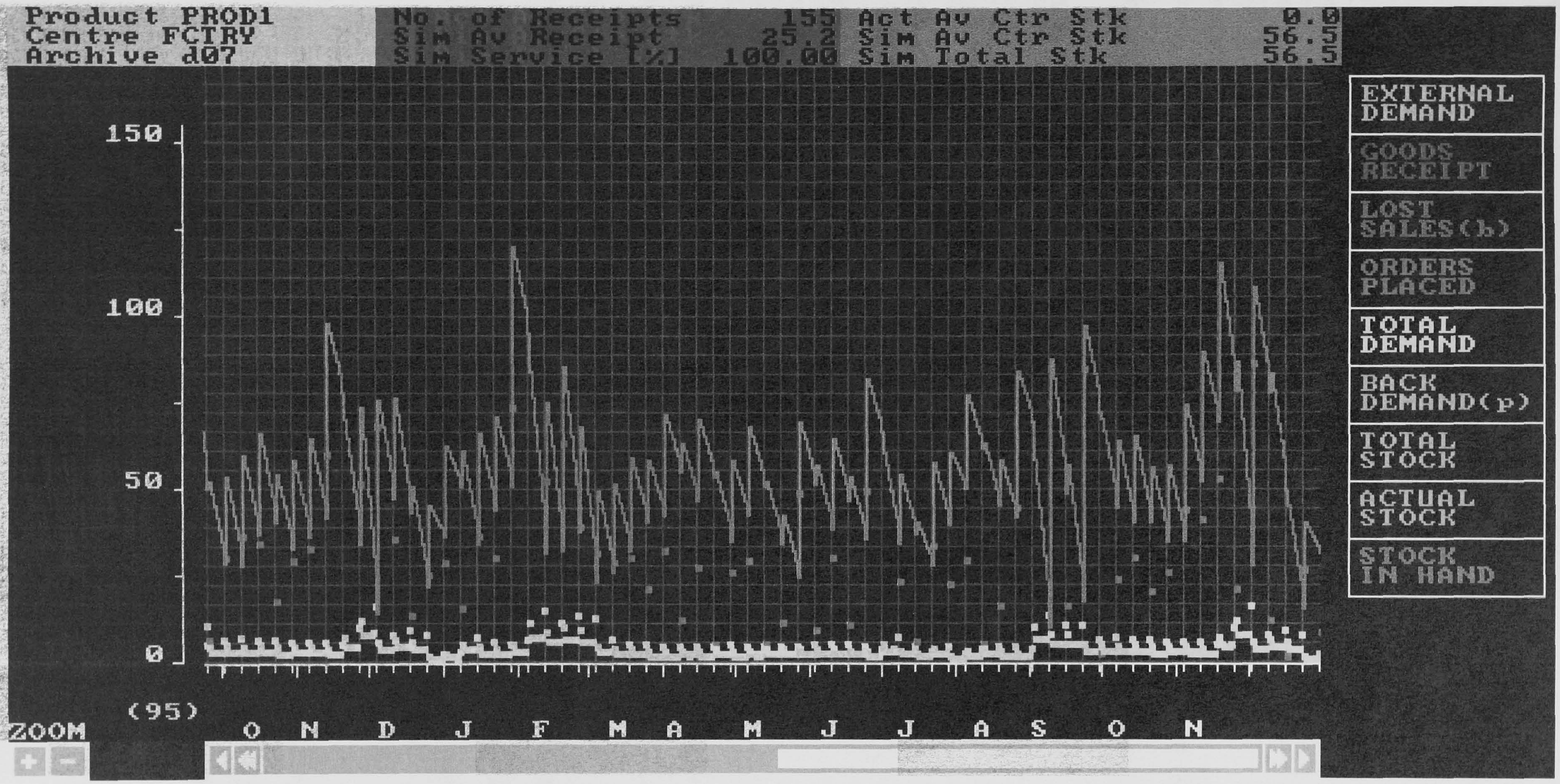

Figure 6.1: Example of simulation output for product 1 and lead time equal to cycle time (equal to 7 days)

Table 6.2: Regression output for stock against flexibility

Constant	472.17
Std Err of Y Est	645.91
R Squared	0.98
No. of Observations	11
Degrees of Freedom	9
X Coefficient(s)	184.32
Std Err of Coef.	8.85

There was also seen to be a significant correlation, R Squared equal to 0.71, between flexibility and the service levels achieved by the production system, see Table 6.3.

Table 6.3: Regression output for stock against service levels

Constant	99.92
Std Err of Y Est	0.72
R Squared	0.71
No. of Observations	11
Degrees of Freedom	9
X Coefficient(s)	-0.05
Std Err of Coef.	0.01

The ease of changing production equipment was measured by the amount of time it took to change the machine and the cost associated with the change. The time it takes to change a machine may be a combination of the complexity of the machine, the skills of personnel changing the machine and the difference in characteristics between the two products. However, the modelling activity was only concerned with the effect of changeover time on the performance of the whole of the manufacturing system at the tactical level.

From the results shown above it was demonstrated that the performance of the system can be improved by reducing the changeover time and hence reduce the batch size. This was implemented by showing the correlation between the cycle time or batch size and the resulting service levels and stock levels. A system that has too much stock is deemed to be inflexible and a system that cannot achieve high levels of service is also

deemed to be inflexible. The measures are suitable for this type of model, but they may not be in other situations where the trade-off is not between changeover cost and stockholding costs.

Service level and stockholding cost may be used separately as a means of measuring performance. It may also be possible to have an overall performance measure in terms of cost, if a cost penalty is applied to each service level point lost. To obtain an overall cost measure it must include changeover cost, stockholding cost and service level penalty. It may be difficult to obtain suitable penalty parameters for service levels. In this model it was decided to take the minimum level of penalty which is the loss of marginal profit on the product that was not sold because of lack of stock.

If customers did not get the service they required, at worst they may choose to take their custom elsewhere and not come back, at best they may choose to order the quantity again in the following period.

By using the changeover cost and stockholding costs, as described above, and the service level penalty at 10% of the value of the product, results from the ease of change were costed as shown in Figure 6.2 and listed below are the issues that were observed. In this model it was assumed that changeover time reduced proportionally to cycle time.

i) The balance between stock cost and changeover cost occurs around a cycle time of one week. This figure is not the optimal but will be very near the optimal. It cannot be the optimal because of the cycle time intervals used in the simulation. To be anywhere near optimal, finer intervals would have to be used for the exact cross-point between changeover cost and storage cost to be found by simulation.

ii) The changeover cost starts to level out as it approaches the cycle time of five weeks. As it can be seen in Figure 6.2, changeover cost reduces sharply from one day cycle to one week cycle. However, in Figure 6.3 where changeover

time was not reduced, there is little change. The changeover cost needed further examination to determine whether reducing changeover time was sufficient to reduce the total cost.

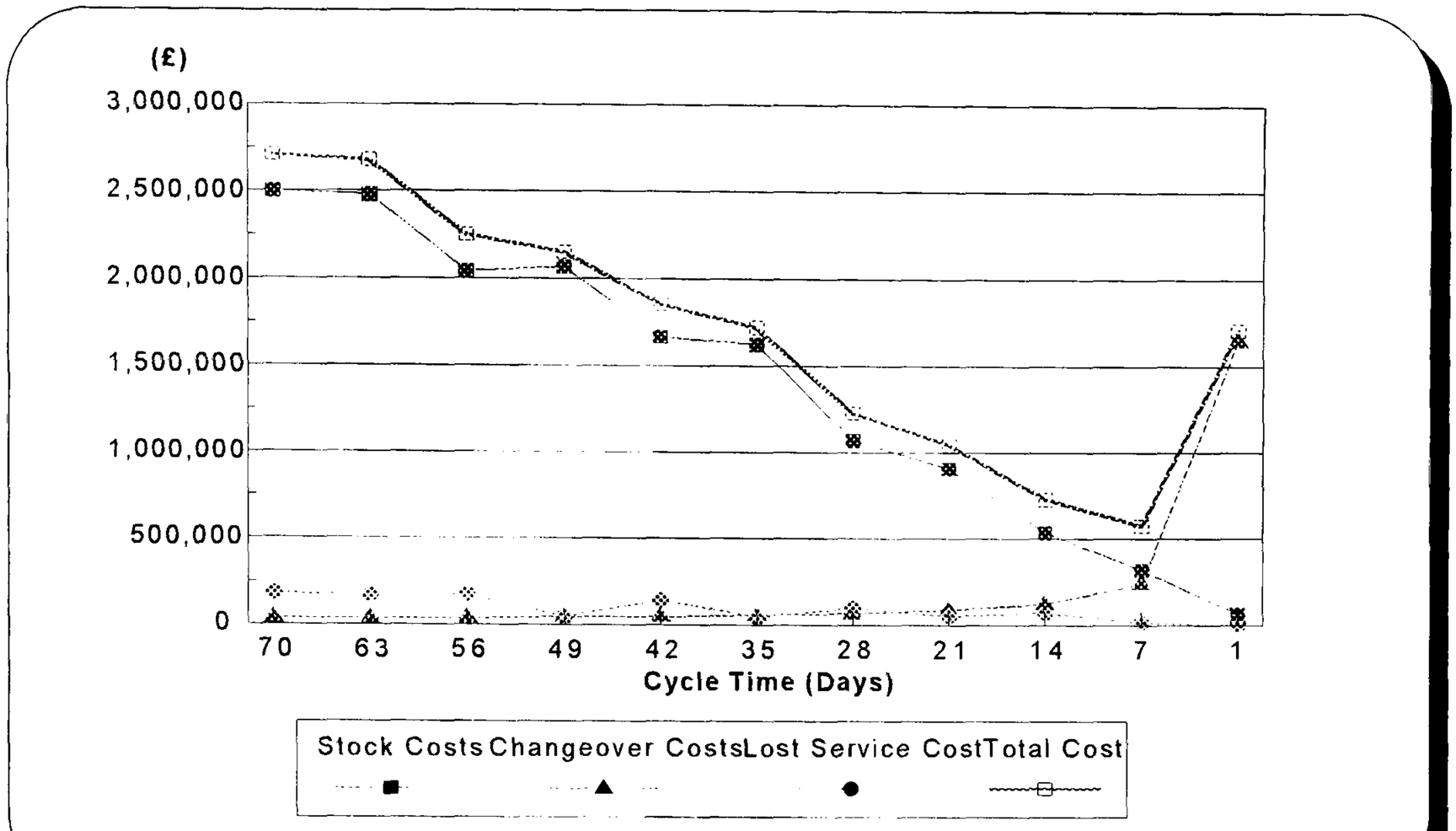

Figure 6.2: Changeover time reduction proportional to cycle time reduction

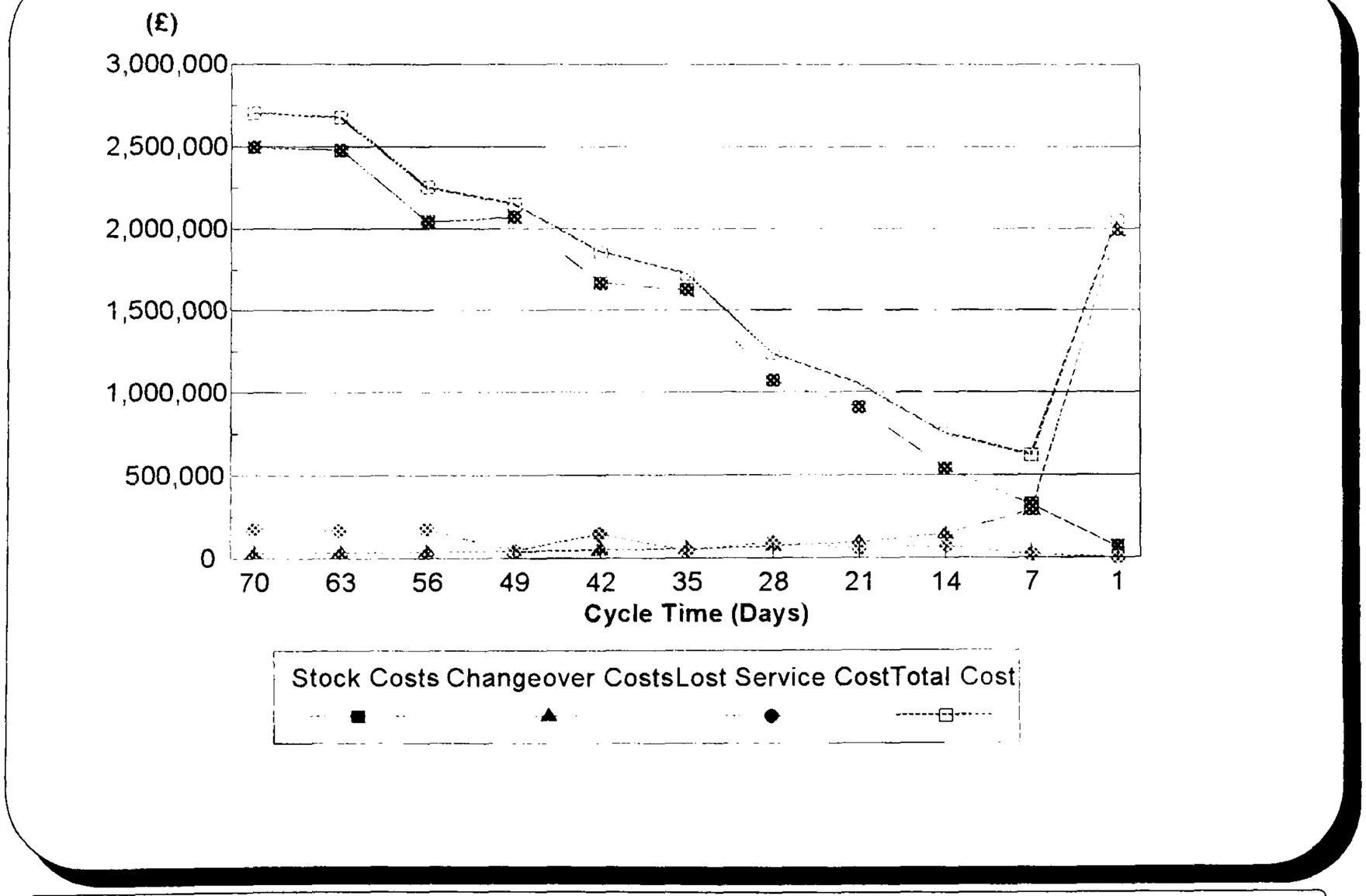

Figure 6.3: Cycle time reduced but not changeover time

The simplified form of the changeover function is defined as shown below.

$$C_f = (P_c \times N) + (M_c \times N)$$

Where:

C_f = the total changeover cost

P_c = product related changeover cost which is fixed per changeover. This is due to product waste and cleaning materials.

N = number of changeovers per year.

M_c = machine time related cost.

In this model personnel changeover cost remained constant as the changeover time was reduced proportionally to the reduction in cycle time. Figure 6.4 shows that personnel costs were insignificant. Product related changeover costs were the dominant factor.

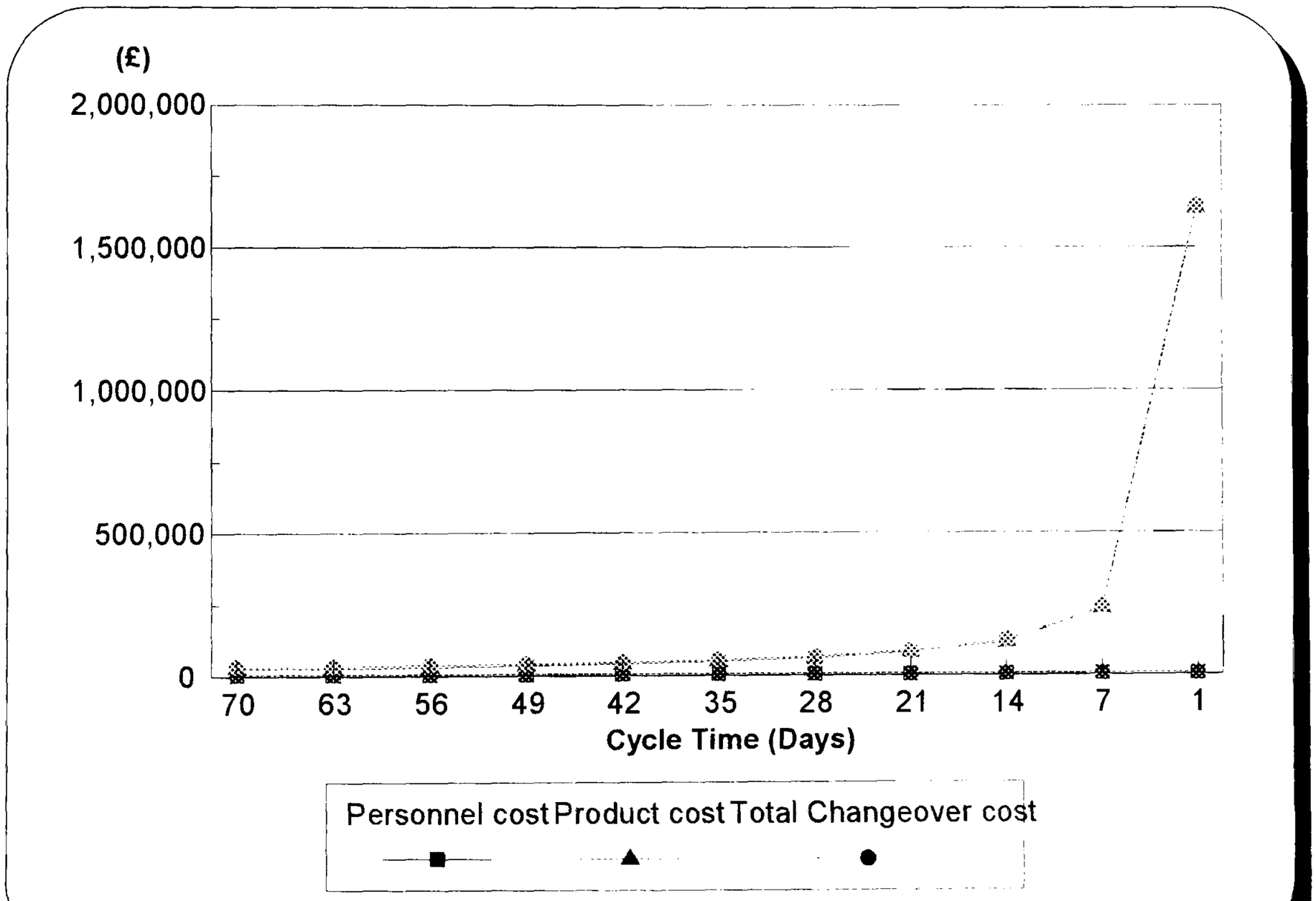

Figure 6.4: Details of changeover cost with reduction in changeover time

Figure 6.5 shows the graph of the changeover costs if the changeover time is not reduced at all while the cycle time changes. This still shows that the product related changeover cost is the dominant factory. To improve the performance of the system flexibility the characteristic of the product must be modified to enhance product flexibility.

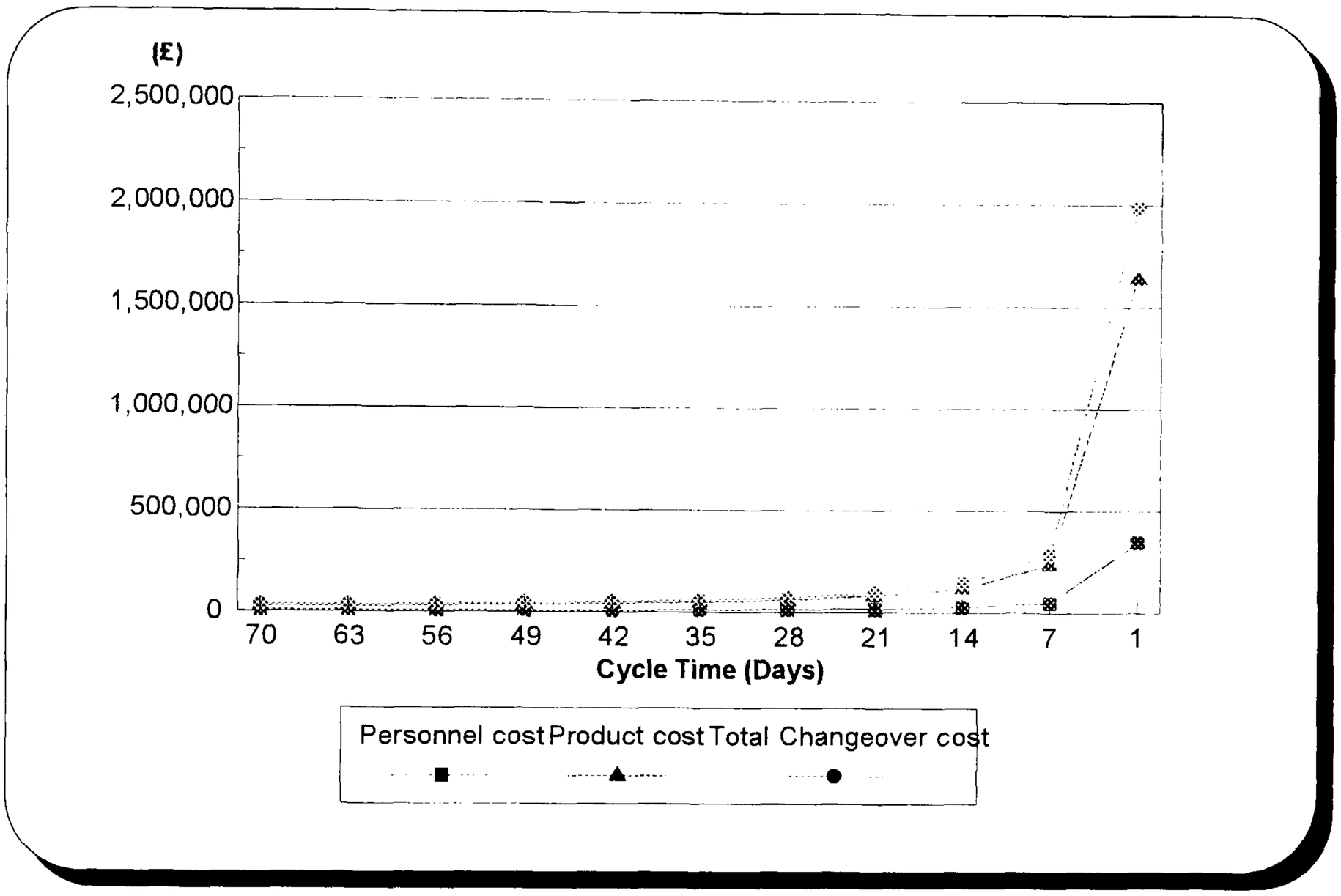

Figure 6.5: Changeover cost details without reduction in change over time

6.4 FIXED SCHEDULES

Often, during the scheduling process part of the schedule is frozen, prohibiting change to the active schedule. The main purpose that freezing a schedule serves is to bring stability to the planning, production and materials supply processes. Resources are allocated to do certain tasks, production quantities are set, raw materials and packing materials orders are agreed. All parties know that the schedule will not change over the period that is frozen.

The idea that freezing schedules can bring stability to the manufacturing process was examined. Freezing a production schedule means that the quantities and the sequence determined at the time the schedule was formed could not be changed even if things changed dramatically.

Two types of models were used to demonstrate the effect of freezing a schedule. If lead time for calculation of safety stock is taken as equal to the frozen period, as in the first of the two models, too much safety stock may be carried. If the lead time was calculated to be equal to the cycle time, as in the second of the two models, the safety stock would not be sufficient. If the period under which the schedule is frozen is longer than the cycle time, the benefit of frequent changeovers may not be felt as higher levels of safety stock may have to be carried to cover uncertainty over the whole of the period that the schedule is frozen. This presented a new challenge for setting safety stock to meet the required fixed schedules. This was outside the scope of the thesis. This meant that flexibility could not be measured by both service level and stock level. Instead only stock costs and changeover costs were used because the service levels would be distorted by the levels of safety stock.

These results also demonstrate that the further away the delivery date is, the more difficult it is to make accurate schedules. This leads to the violation of the two main customer driven flexibility requirements, viz., availability and reliability.

The effect of freezing a schedule was measured by the availability of stock to meet demand. This was measured by customer service based on the number of units ordered against those actually delivered in time. The second measure to evaluate the effect is the amount of stock left after meeting the demand. This is due to the system not being able to respond to changes in demand.

The formula for calculating safety stock takes lead time into account. With freezing the schedule the lead time is made up of two factors:

a) the cycle time which was fixed to one week in this model

b) the length of the frozen period, including the cycle time. Where the frozen period is less than the cycle time the frozen period was used as lead time.

The effective lead time cannot be equal to the sum of the two lead times nor can it be equal just to the cycle time. The lead time in the calculation of safety stock cannot be equal to the cycle time because the frozen schedule may be shorter or longer than the cycle time. It is not the sum of the two lead times because during each planning cycle the quantities to be produced are revised based on work in progress, stock, forecast and capacity constraints. The forecast error for the current period was compensated by increasing or reducing the quantities of the new cycle being added to the frozen schedule. As there was no existing formula to meet this requirement, two types of models were constructed.

The first model took the lead time as being the frozen period including the cycle time. A summary of the results is shown in Table 6.4. An example of Product 1 with a frozen schedule of 70 days, in Figure 6.6, shows that there was an excess amount of stock. This needed to be addresses by reducing the safety stock. Flexibility is still demonstrated by the reduced levels of average total stock from 3093.4 to 318.3 tonnes, but the service levels are not significantly affected due to the unnecessary levels of safety stock, they remained between 99.0% and 100%.

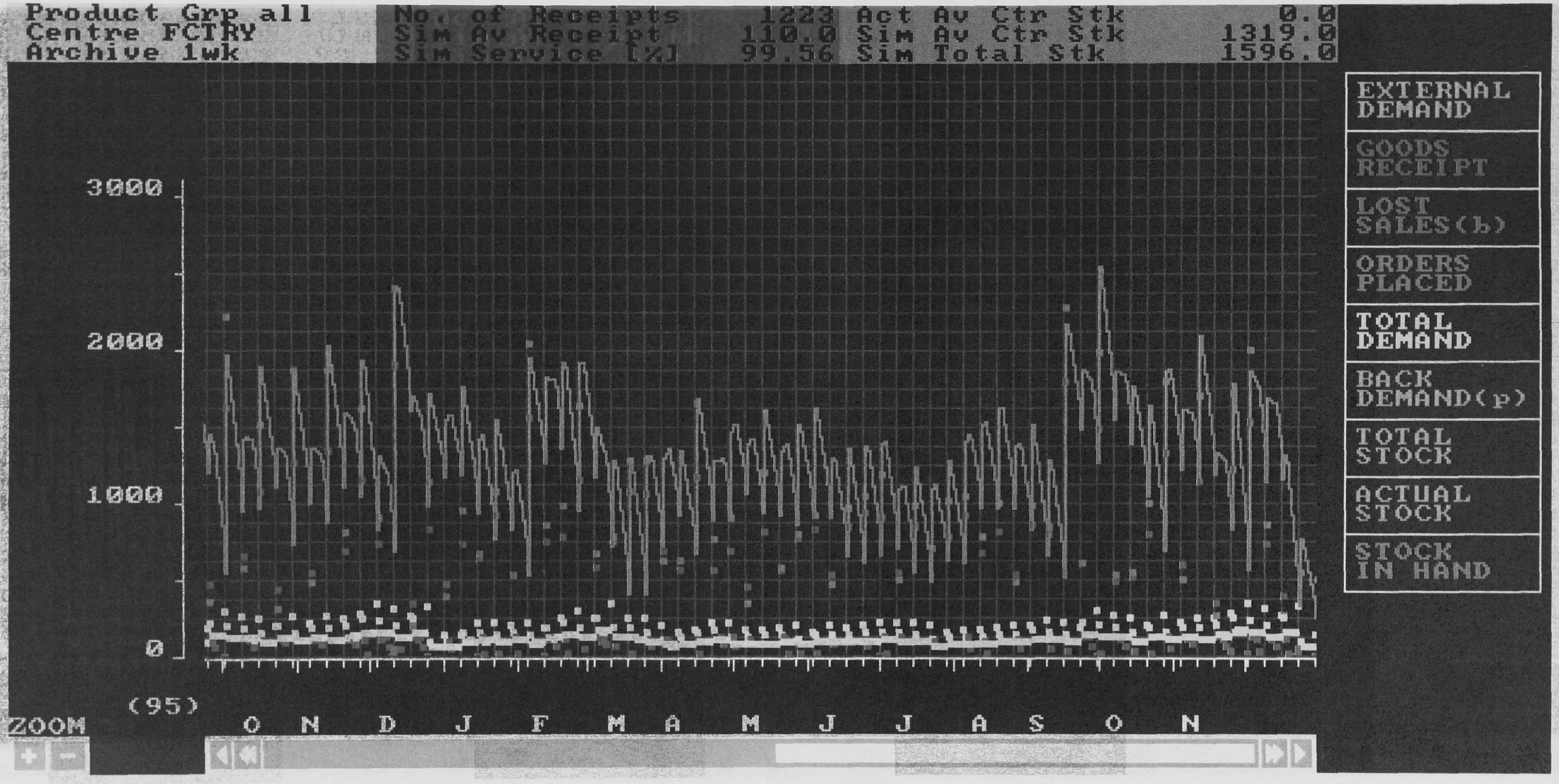

Figure 6.6: Excess stock from standard safety stock formula

Table 6.4: Frozen schedule, lead time equal to frozen period.

Cycle Time (Days)	Service level %	Safety Stock (Tonnes)	Average Stock (Tonnes)	Stock Turns per year
70	99.7	2,490.48	3,093.4	17.89
63	99.6	2,362.68	2,972.7	18.88
56	99.5	2,227.56	2,800.3	20.52
49	99.5	2,083.69	2,703.2	21.57
42	99.4	1,929.12	2,558	23.39
35	99.2	1,761.04	2,403.2	25.64
28	99	1,575.12	2,237.1	28.5
21	99.2	1,364.09	2,055.2	31.92
14	99.2	1,113.78	1,844.4	35.81
7	99.6	787.56	1,596	39.81
1	100	297.67	318.3	183.38

These results show that infrastructure decisions and parameters can have an effect on the flexibility of a manufacturing system.

A regression analysis confirmed that there was a significant relationship between flexibility and stock levels with a correlation of R Squared equal to 0.82 as shown in Table 6.5.

Figure 6.5: Regression output of stock against flexibility, lead time equal to frozen period.

Constant	1,145.55
Std Err of Y Est	348.55
R Squared	0.82
No. of Observations	11
Degrees of Freedom	9
X Coefficient(s)	31.04
Std Err of Coef.	4.78

The second model used the lead time as being equal to the cycle time and a summary of the results is shown in Table 6.6. In this set of models it can be seen that the service levels increase from 57.6% to 99.7% as the lead time was reduced, representing increased planning flexibility. The levels of stock also improved from 1746.2 tonnes to 1599.4 tonnes.

Table 6.6: Frozen schedule, lead time equal to cycle time

Cycle Time (Days)	Service level %	Safety Stock (Tonnes)	Average Stock (Tonnes)	Stock Turns per year
70	57.6	787.56	1,746.2	33.66
63	61.4	787.56	1,719.7	39.7
56	65.2	787.56	1,686.4	49.26
49	68.4	787.56	1,688.5	60.37
42	73.1	787.56	1,664.9	74.31
35	79.1	787.56	1,633.2	80.95
28	85	787.56	1,621.8	95.8
21	91.1	787.56	1,605.3	109.84
14	99.6	787.56	1,596.2	119.06
7	99.6	787.56	1,598.7	135.5
1	99.7	787.56	1,599.4	141.88

Here again, regression analysis revealed a significant correlation between planning flexibility and service levels with R squared equal to 0.98, as shown in Table 6.7. It must be emphasised again that other factors such as capacity constraint can reduce the correlation between the potential flexibility and the performance of the system.

Table 6.7: Regression output for service levels against flexibility, with lead time equal to cycle length.

Constant	104.03
Std Err of Y Est	2.47
R Squared	0.98
No. of Observations	11
Degrees of Freedom	9
X Coefficient(s)	-0.69
Std Err of Coef.	0.03

6.5 SUMMARY

In this chapter simulation results have been analysed and it has been shown that simulation can be used to evaluate manufacturing flexibility. Further statistical analysis had to be carried our to evaluate the results from the simulation models. The results relate flexibility requirements directly to the performance of the whole manufacturing system.

CHAPTER 7

DISCUSSION AND CONCLUSION

7.1 INTRODUCTION

This chapter will discuss whether the results support the hypothesis. The contribution that this research has made to knowledge will also be discussed together with strengths, weaknesses and potential for further work. The hypothesis as described in Chapter 3 stated that "Simulation modelling can be used as a quantitative method to effectively predict the flexibility that is demonstrated by a dynamic manufacturing system in operation or during the design process. It can also be used to assess the way in which flexibility contributes to the overall manufacturing objectives". The two main issues here are: a) prediction of flexibility that is demonstrated by a dynamic manufacturing system in operation or during the design process; b) assessment of the way in which flexibility contributes to manufacturing objectives. Three objectives were set to satisfy the hypothesis.

1. To develop a methodology which would provide a structured approach for assessing the demonstrated flexibility and the prioritisation of flexibility requirements of a manufacturing system.

2. To provide a model which adopts a holistic approach in defining the flexibility of a manufacturing system during its design and operation.

3. To establish the relationship between different types of manufacturing flexibility and methods of their assessment.

7.2 THE FRAMEWORK

In Chapter 3, a framework within which flexibility requirements and priorities can be identified was described. The evaluation of flexibility requirements needs to be carried out on a regular basis, matching the pace of change within the market environment and to ensure competitive advantage is maintained. During the process of defining flexibility requirements it was observed that the timing of evaluation of the requirements can be defined as strategic, tactical or operational. Strategic decisions may be carried out less frequently, every one to five years. Tactical decisions are short term, involving the implementation of strategy and responding to short term changes in the market place.

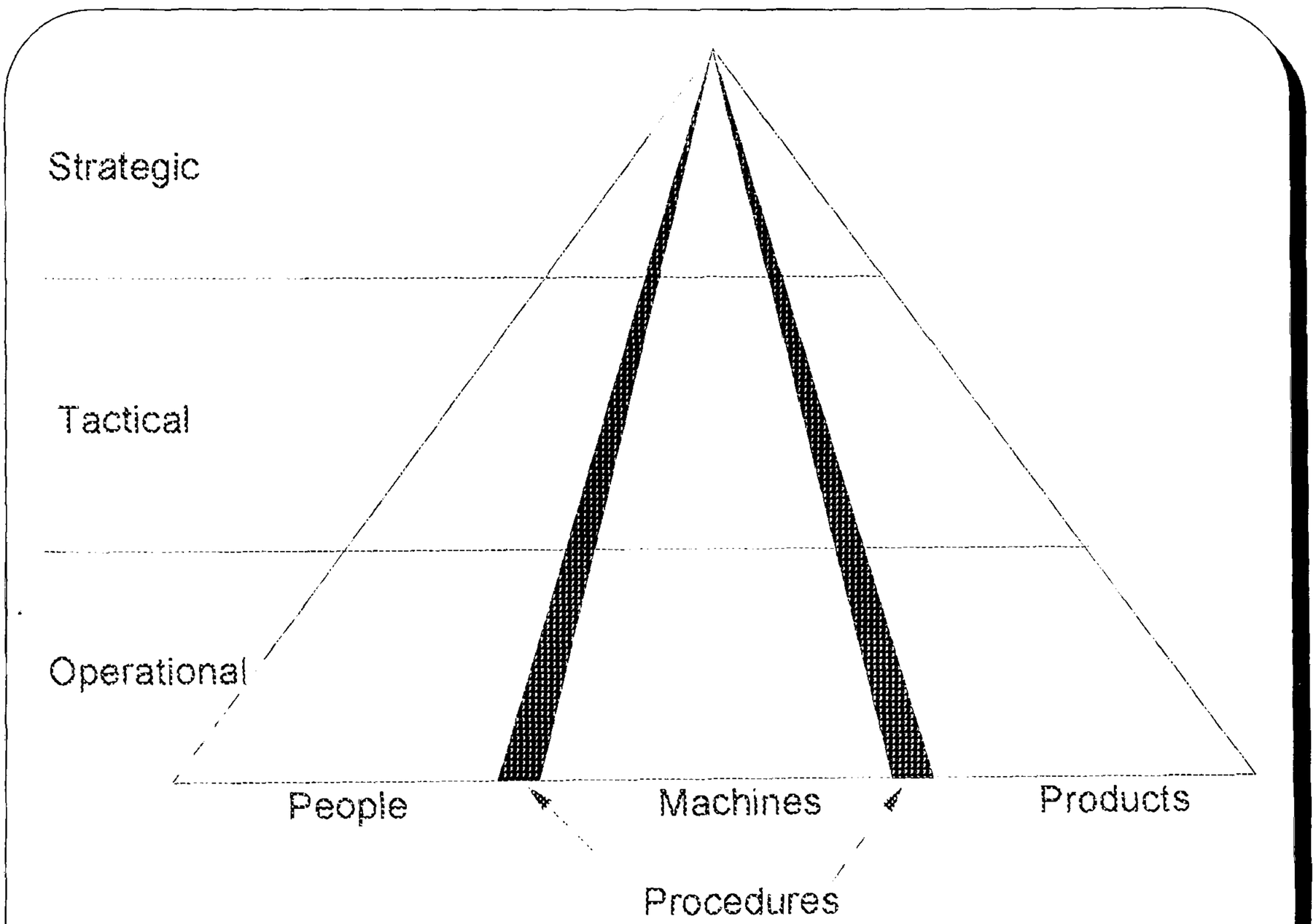

Figure 7.1: Levels of decision making

Development of the methodology to provide a framework for a structured approach was done by using a top-down approach where business objectives were analysed and decomposed to obtain manufacturing objectives from which manufacturing strategy and manufacturing programmes could be developed. The methodology emphasised a holistic approach from the development of business strategy to implementation of manufacturing programmes, but also the required flexibility to include people, equipment, products and procedures as shown in Figure 7.1. However, when scenarios for development of models were defined only certain features of the system were selected to demonstrate the effect of their flexibility on the manufacturing system.

Company objectives cover a range of issues which are related to determining the direction of the whole organisation. From these company objectives, relevant information and data could be extracted to set goals and to determine critical issues for manufacturing. From this information and data, critical success factors and measures could be set in order to develop manufacturing objectives, and finally manufacturing strategy and then manufacturing programmes can also then developed. The eventual simulation models focused on tactical issues to demonstrate the effect of flexibility on the performance of the manufacturing system.

Manufacturing strategy defined the "how to do it". It was observed that flexibility is likely to be an issue when defining strategy, so that production can meet the manufacturing objectives at a reasonable cost, with minimum effort. This raised some requirements for flexibility. A mechanism for evaluating flexibility requirements can be used for prioritisation. The mechanism is also necessary for balancing the needs for flexibility and the provisions to meet these needs. The mechanism feeds into both strategy and the resulting manufacturing programmes at the same time, and provides feedback to formulation of manufacturing objectives. The balancing mechanism in this case was a set of models.

This process provides a method for defining what it is that the manufacturing organisation wishes to be flexible about. The process flows naturally into the development of manufacturing programmes. The framework does not need to change but the flexibility requirements may change with time. There has to be some judgement as to how often the process can be carried out. However, the framework provides the structure within which analysis can be carried out, but it does not assist with the quality of the content of the decisions being analysed.

7.3 KEY PERFORMANCE MEASURES

The key performance measures were classified as financial and non-financial. It was thought important to include financial measures as these are the measures by which the whole organisation is measured. However, it was recognised that financial measures are only used for evaluation, they cannot improve the performance of the organisation by themselves. Improving direct non-financial measures will improve financial measures and therefore the performance of the business. In the model used here, for example, reducing changeover time reduces changeover cost and costs due to waste, which in turn reduce operating costs and increase profit. In this thesis direct non-financial measures were used as the underpinning measures for evaluation of performance improvement and facility design.

Company strategy may change from time to time in line with the market changes. This means that some measures may have to change to meet the new changes. As it was discussed in Chapter 4, people are motivated to improve results by which their work is measured. It is extremely important to use the right measures for these reasons.

It was seen that it is important to relate measures to goals set out through the process of formulation of strategy, but at the same time they should be translated directly into what people actually do. Personnel's understanding of how they can influence results leads to positive action. In this model service level and stock level were the two main

measures used to evaluate the effect of flexibility on the performance of the system. However, at the shopfloor level different measures may have to be used.

It was also observed that the implementation of flexibility programmes could have an impact on other areas of the system. For example, to reduce changeover time so that the machines can be change more frequently, may require the training of staff and changes in the design of machines. Tombak et al. (1988) discussed the impact of flexibility on social welfare, which is one of the wider issues.

Measuring stock availability for a product as was suggested earlier may not show the unreliability of the production system. Customer service level measures were based on the number of units ordered against those actually delivered over the whole period of the simulation. This measure does not show the whole picture of the flexibility of the system. For example, if sales of 50 tonnes of product were lost over the simulation period, this may have been lost all at once or ten times with five tonnes lost at a time. This was a limitation of the model that was accepted.

7.4 MODELS

As was discussed in Chapter 5, a model is a representation of the real system. It captures the relevant aspects only, which means that assumption have to be made and approximations have to be applied in the process.

7.4.1 THE MODEL BOUNDARY

The scope of the model was defined by a boundary which had to be decided depending on what was assumed to be within the system concerned and what was not. In some cases the boundary was not that clear. There were some elements which were neither inside nor completely outside the system under consideration. The elements outside the boundary were considered to have influence on the system but at this level of decision making it was assumed safe to apply approximations. Using a systems approach, as

defined by Carter et al. (1984), it was possible to define the boundary of the system as shown in Figure 7.2.

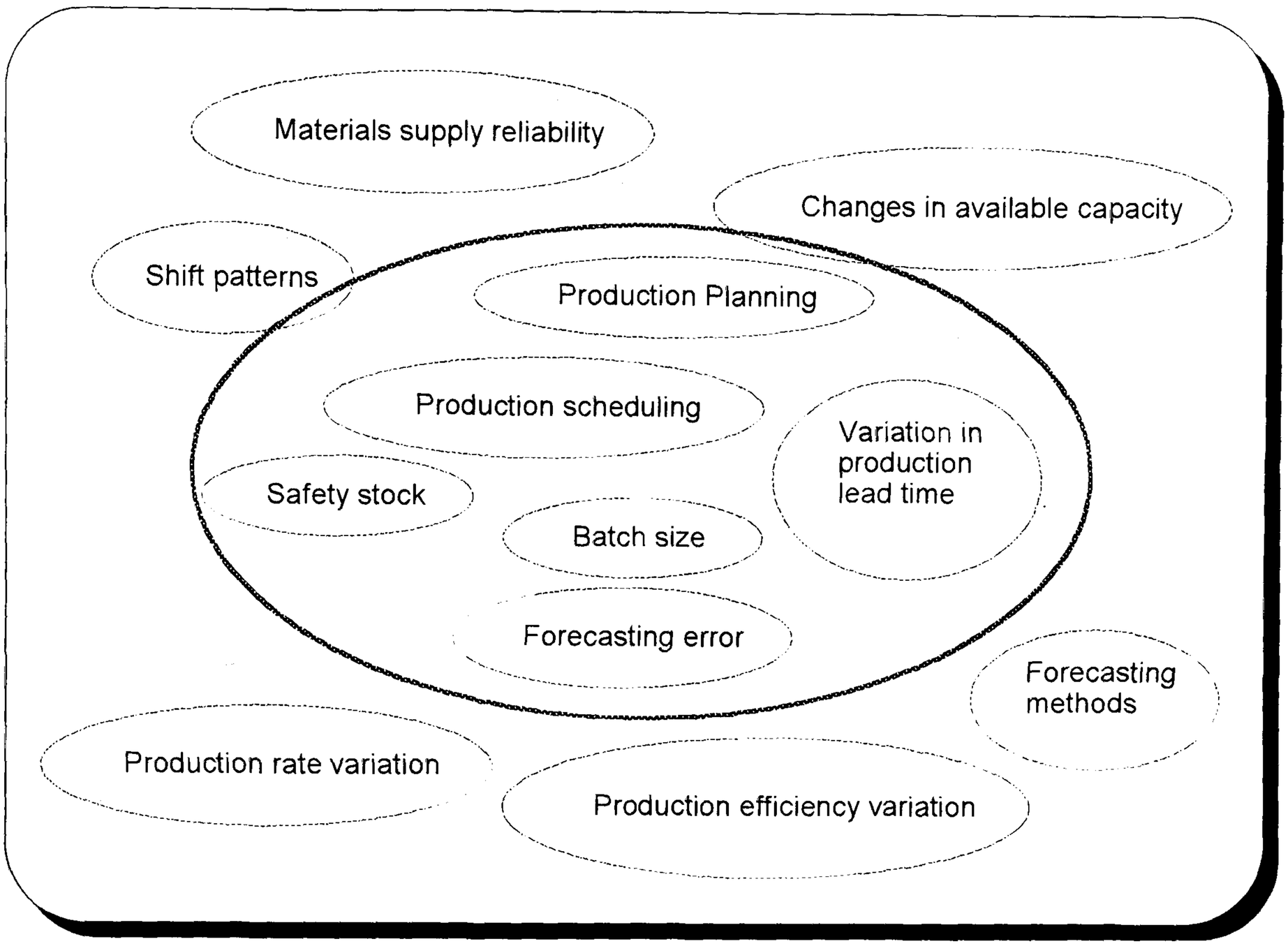

Figure 7.2: The system boundary

Issues which were not included in the model but could have significant impact on the way the system performed include the ones shown below.

i) Time lost due to machine failures was thought to be within the system but the way in which they occurred was not. However, the manner in which the breakdowns occurred may have a significant influence on the choice of decisions required to deal with making up for the time lost due to machine breakdowns. A manager may choose to move production from a machine that has broken down, to another machine, while it is being repaired. On the other hand it may not be the right decision to try and move production to another machine if setting up that machine was to take the same amount or longer than

the repair of the machine that has broken down. Instead, a manager may choose to do overtime or introduce additional shifts to make up for time lost due to machine failures. Unless it was known before hand what the basis of each action would be, it is impossible to model the exact course of action that would be taken. In this model the total available production time was reduced by an average amount of time lost through breakdowns per week. Although production efficiency variation and production rate variation are outside the system, average loss of capacity was included in determining the effective capacity of the production line.

ii) It was assumed that materials would be available as required and therefore it was not necessary to model them. In some situations this assumption may be inappropriate and the effects of late deliveries may result in severe consequences.

iii) In a real life situation it may be possible to reorganise shifts and schedules to meet the fluctuating demand, but in this model the available time remained the same from week to week. Where the demand was greater than the capacity production was carried out at an earlier time where possible.

iv) Forecast errors were included in the model but forecasting methods were considered to be outside the scope of the study. Where schedules were fixed for longer periods of time, the model was expected to encounter a higher magnitude of forecast error, as it was assumed that the further away the forecast date was from the demand date, the worse the forecast error becomes. Where the manufacturer wishes to follow closely the changes in demand, they may prefer to carry out production based on actual customer orders, if the system if flexible and reliable enough..

v) The scenarios that were chosen for simulation covered the machine aspect and the procedural aspect of a manufacturing system. However, as was shown in Figure 7.1, the capability of a manufacturing system is defined by four elements: people, equipment (machines), product and procedures. The scenarios served the purpose of demonstrating that the principles for modelling flexibility work, but did not cover all aspects of the flexibility of a manufacturing system and did not cover change in shift patterns.

It is important to note that decisions regarding all the elements within and without the boundary can be strategic, tactical or operational as shown in Figure 7.1. The model concentrated on tactical issues. However, as it was seen from the results, tactical decisions cannot be completely independent from strategic and operational ones.

7.5 THE VALUE OF SIMULATION

The hypothesis stated that simulation modelling can be used as a quantitative method to effectively predict the flexibility that is demonstrated by a dynamic manufacturing system in operation and during the design process. It was noted through the process of developing the framework and building models that as much time was spent on defining flexibility needs as was required for developing the model. This showed the importance of clearly defining the flexibility requirements. If the requirements are not defined very clearly, the modelling process would not provide the required results and may provide misleading results. The research showed the need for clearly defining the flexibility requirement.

The model used in this research was purpose built for simulating the activities of the whole supply chain. It took into account all the planning activities and the production and logistics issues. This meant that most issues of the supply chain could be investigated and their effect on the performance of the manufacturing system examined. The model can be reused if parameters changed and it can also be used as a general purpose simulation tool. However, this being a purpose built simulator, it

would be more difficult to change to meet a different level of detail. The model was used for tactical decisions. As with most simulation packages, it is easier to put in more detail than to reduce it. For this reason, it would have been possible to expand the model to the operational level but more difficult to move to the strategic decision level.

Some simulation packages require an enormous amount of data before the model can be built. The effort of building the model must be balanced with the benefits obtained from the model. Suri and Diehl (1985) stated that queuing theory models generally come within 5% and 15% of the value obtained from detailed simulation. Similarly in this case a comparison of various methods of modelling flexibility would have been useful.

For example, a scheduling model may give an indication of the effect of changeover time on the production system. Economic batch size models can be used to support the scheduling model in determining the appropriate batch sizes. Simple forms of such models may be easier to construct and can be thrown away once their purpose has been completed. The value of such models needs investigation.

7.6 RESULTS AND PERFORMANCE MEASURES

The results obtained from the simulation model were used to measure the performance of the manufacturing system. The measures themselves did not evaluate the flexibility of the system directly, but measured the way the whole system performed under the influence of certain characteristics which were thought to be enhancing the flexibility of the system. The results showed the actual change in flexibility and converted this into demonstrated flexibility to show how it affected the performance of the whole system. For example, in one of the scenarios improvement of changeover time defined the potential flexibility, and the customer service level and stock level measures defined the demonstrated flexibility. Various parameters defining the potential flexibility of the

model can be fed into the model and converted to the demonstrated flexibility of the system as shown in Figure 7.3.

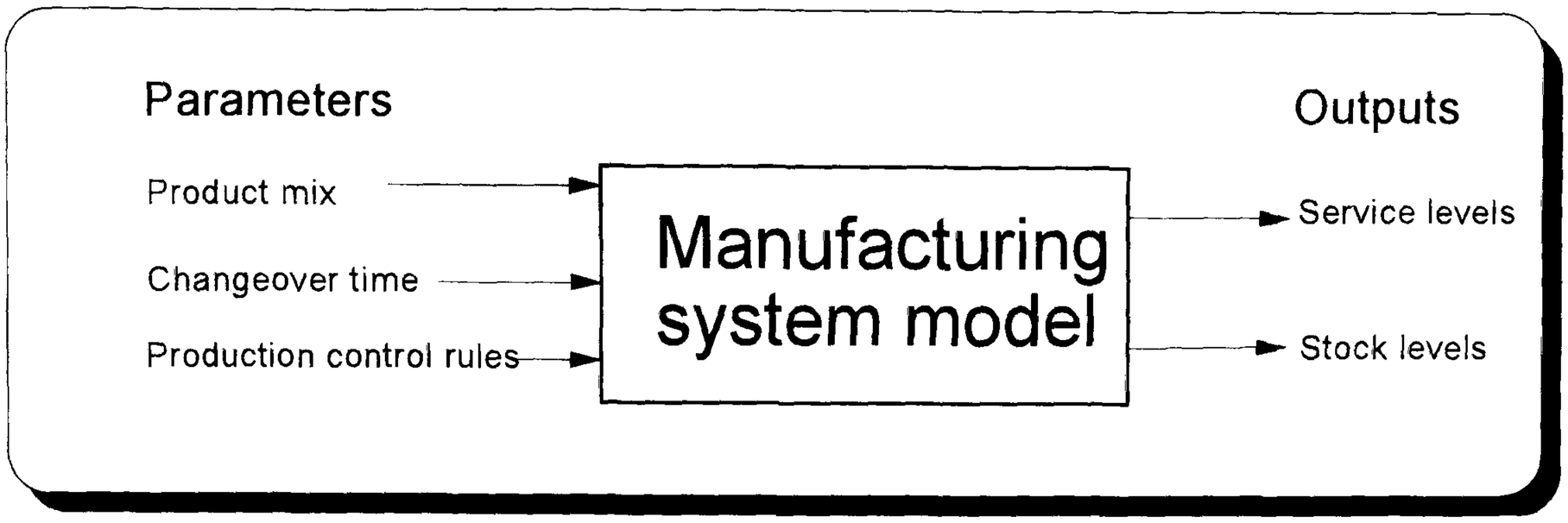

Figure 7.3: Example of parameters and demonstrated flexibility

Management need to understand the inputs to the system and the performance derived from it so that they can effectively implement the decisions from the model. This calls for the importance of transparent models.

7.7 CONTRIBUTION TO RESEARCH

This research has contributed to a greater understanding of several issues regarding manufacturing flexibility. A framework was developed to provide a structured approach to defining flexibility requirements and prioritising them.

1. The framework provided a structured approach under which flexibility requirements could be defined. The framework ensured that the flexibility requirements are derived from manufacturing objectives which relate to business strategy. Through this process all the important factors of the business as a whole were considered in the design of the manufacturing system.

2. The framework gave a greater understanding of why flexibility is not an end in itself but as a means to other ends. This is why flexibility has the potential to be

essential to the whole organisation. Flexibility becomes an issue that is driven by the business needs and not just by technology.

3. The research provided a greater understanding of converting potential flexibility into demonstrated flexibility. The potential to improve the performance of the production system through reduction of changeover time is not realised until the service levels are improved and working capital is reduced.

4. The research provided a greater understanding of how various parameters associated with flexibility relate to each other and to the performance of the system. For example, the research showed how planning constraints such as freezing the schedule can affect the safety stock required for the system and also the service levels.

Several strengths of the research were noted. These ranged from the approach to the actual measures of flexibility. The main strengths and weaknesses are listed below.

Strengths of the research:

1. The research promoted a holistic approach to the prediction and assessment of the flexibility of a manufacturing system. The framework included strategic, tactical and operational issues. It also included machines, personnel, products and procedures which are used to link all the other elements together. Often improvement in one of the elements does not result in equivalent improvement in the performance of the whole system, if the other elements are not considered in parallel. For example, it was shown that improved changeover time can be hindered by constraints in the planning procedures where the schedule was frozen.

2. The models used in this research can include several factors that represent the system without complex formulae. For example, the linking of the supply sub-system to the production sub-system is easier with simulation models than with formulae. The models can be reused and parameters changed with ease.

3. The models provided a powerful means of translating potential flexibility to demonstrated flexibility. The change in the design of a resource or procedures was able to be translated into operational performance measures such as customer service levels and stock levels.

4. Compared to empirical research, using models is a safer and cheaper way of assessing the impact of certain actions that management may wish to take to improve flexibility. The design of the system can be examined very quickly without interruption to the existing production system. If the models gave undesirable results it would not be as disastrous as where the actual system is used. The model can also be used to assess concepts that are not yet proven.

Weaknesses of the research:

1. Obtaining the right flexibility requirements depended to a large extent on the analyst's knowledge of the manufacturing system. The framework ensured that important factors were followed through from the business strategy to manufacturing programmes.

2. In the type of model used in this research, as with most simulation packages, it was difficult to reduce the detail of the model. A different model would have had to be used if it was found necessary to model strategic level issues. Adding more detail to the model would have been possible but it would have made the model complex.

3. The level of aggregation prevented the model from taking into account, the explicit randomness nature of the occurrence of system failures. This means that some types of flexibility, such as routeing flexibility could not have been demonstrated. Individual orders from the customer were not modelled. The model could not prioritise customer orders but could prioritise the sequence in which the products were scheduled for production.

Potential for improvement:

1. Further work needs to be carried out to improve the design of models to be able to increase or reduce the level of detail. This could possibly be done by modular structures which can be included in the model or excluded. The use of simple "throw away" models need to be compared with the other two options.

2. The possibility of automatically generating an initial list of flexibility requirements from manufacturing objectives requires further investigation. This would improve both the framework and the model.

3. One of the parameters required for calculation of safety stock is lead time. Where the period that the schedule is frozen is greater than the cycle time, it is difficult to establish the effective lead time. Without the lead time to calculate safety stock the simulation models take longer to establish the levels of stock as this is done by several interactions.

7.8 SUMMARY

In this chapter, the knowledge that this research has contributed to research has been discussed. The strength and the weaknesses of the research have been discussed together with potential improvements for possible future work. Results from the model have also been compared to the hypothesis.

7.9 CONCLUSION

This research has shown that simulation can be used effectively to predict the required flexibility of a manufacturing system. The results from the model showed the performance of the whole system and these were related to the contribution that flexibility makes to the overall manufacturing objectives. However, it was also observed that different types of models may be required depending on the nature of the decisions as described in Chapter 3. Strategic decisions may be better supported by single period models. The single period being a year or more. Tactical decisions may be better modelled by the use of a rolling horizon model as used in this research. Operational decisions are daily decisions with time scales of seconds, minutes or hours depending on the nature of the decision.

Through the development of the mechanism for evaluating flexibility requirements, it was observed that much time was invested in the definition of flexibility requirements and how these contributed to the manufacturing strategy. This shows that much time needs to be spent on the definition of flexibility requirements before evaluation can take place.

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Appendix I

Demand Best Fit Distributions

Data File: PROD1.DST

PRODUCT 1

Histogram Range: 5 to 37
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 5.7
Max Data Value = 36.1
Sample Mean = 14.7
Sample Std Dev = 6.88
Distribution Function: Lognormal

SIMAN USAGE: 5 + LOGN(9.98, 8.16)
Sq Error = 0.05538
Chi Square Test:
No. of intervals = 4
Degrees of freedom = 1
Test Statistic = 9.12
Corresponding p-value < 0.005
Kolmogorov-Smirnov Test:
Test Statistic = 0.138
Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density Data	Probability Density Function	Cumulative Distribution Data	Cumulative Distribution Function
0	5	9.571e+000	0.096	0.231	0.096	0.231
1	28	1.414e+001	0.538	0.361	0.635	0.593
2	9	1.871e+001	0.173	0.196	0.808	0.789
3	2	2.329e+001	0.038	0.097	0.846	0.886
4	4	2.786e+001	0.077	0.050	0.923	0.935
5	3	3.243e+001	0.058	0.026	0.981	0.962
6	1	3.700e+001	0.019	0.015	1.000	0.976

BEST FIT SUMMARY
Data File: PROD1.DST

Function	Sq Error
Lognormal	0.05538
Gamma	0.06675
Erlang	0.07864
Weibull	0.08607
Triangular	0.1076
Beta	0.1119
Normal	0.118
Exponential	0.1744
Uniform	0.1974

PRODUCT 2

Data File: PROD2.DST
Histogram Range: 70 to 177
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 70.6
Max Data Value = 177
Sample Mean = 114
Sample Std Dev = 23.9
Distribution Function: Weibull

SIMAN USAGE: 70 + WEIB(48.7, 1.83)
Sq Error = 0.002688
Chi Square Test:
  No. of intervals = 5
  Degrees of freedom = 2
  Test Statistic = 0.375
  Corresponding p-value > 0.75
Kolmogorov-Smirnov Test:
  Test Statistic = 0.06821
  Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density Data	Probability Density Function	Cumulative Distribution Data	Cumulative Distribution Function
0	5	8.529e+001	0.096	0.113	0.096	0.113
1	13	1.006e+002	0.250	0.234	0.346	0.347
2	12	1.159e+002	0.231	0.245	0.577	0.591
3	11	1.311e+002	0.212	0.189	0.788	0.781
4	6	1.464e+002	0.115	0.117	0.904	0.898
5	2	1.617e+002	0.038	0.061	0.942	0.959
6	3	1.770e+002	0.058	0.027	1.000	0.985

BEST FIT SUMMARY
Data File: PROD2.DST

Function	Sq Error
Weibull	0.002688
Triangular	0.003695
Gamma	0.004874
Beta	0.007467
Erlang	0.009248
Normal	0.009714
Lognormal	0.01805
Uniform	0.04501
Exponential	0.0627

Data File: PROD3.DST

PRODUCT 3

Histogram Range: 39 to 149
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 39.6
Max Data Value = 149
Sample Mean = 85.6
Sample Std Dev = 20.4
Distribution Function: Normal

SIMAN USAGE: NORM(85.6, 20.2)
Sq Error = 0.04536
Chi Square Test:
 No. of intervals = 4
 Degrees of freedom = 1
 Test Statistic = 9.86
 Corresponding p-value < 0.005
Kolmogorov-Smirnov Test:
 Test Statistic = 0.1258
 Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density Data	Probability Density Function	Cumulative Distribution Data	Cumulative Distribution Function
0	2	5.471e+001	0.038	0.052	0.038	0.063
1	6	7.043e+001	0.115	0.163	0.154	0.226
2	24	8.614e+001	0.462	0.284	0.615	0.510
3	11	1.019e+002	0.212	0.279	0.827	0.789
4	4	1.176e+002	0.077	0.154	0.904	0.943
5	4	1.333e+002	0.077	0.048	0.981	0.991
6	1	1.490e+002	0.019	0.008	1.000	0.999

BEST FIT SUMMARY
Data File: PROD3.DST

Function	Sq Error
Normal	0.04536
Erlang	0.04641
Weibull	0.0467
Triangular	0.05001
Gamma	0.0511
Beta	0.05172
Lognormal	0.08822
Uniform	0.1419
Exponential	0.1814

Data File: PROD4.DST

PRODUCT 4

Histogram Range: 5 to 71
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 5.3
Max Data Value = 70.6
Sample Mean = 28.7
Sample Std Dev = 13.8
Distribution Function: Erlang

SIMAN USAGE: 5 + ERLA(7.89, 3)
Sq Error = 0.02166
Chi Square Test:
  No. of intervals = 5
  Degrees of freedom = 2
  Test Statistic = 5.91
  Corresponding p-value = 0.05286
Kolmogorov-Smirnov Test:
  Test Statistic = 0.112
  Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density Data	Probability Density Function	Cumulative Distribution Data	Cumulative Distribution Function
0	4	1.443e+001	0.077	0.119	0.077	0.119
1	16	2.386e+001	0.308	0.308	0.385	0.428
2	20	3.329e+001	0.385	0.267	0.769	0.695
3	6	4.271e+001	0.115	0.161	0.885	0.856
4	2	5.214e+001	0.038	0.081	0.923	0.937
5	1	6.157e+001	0.019	0.037	0.942	0.974
6	3	7.100e+001	0.058	0.016	1.000	0.990

BEST FIT SUMMARY
Data File: PROD4.DST

Function	Sq Error
Erlang	0.02166
Gamma	0.02662
Weibull	0.03158
Normal	0.04097
Lognormal	0.04776
Beta	0.0498
Triangular	0.06596
Uniform	0.1242
Exponential	0.1293

PRODUCT 5

Data File: PROD5.DST
Histogram Range: 82 to 268
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 82.5
Max Data Value = 268
Sample Mean = 152
Sample Std Dev = 39
Distribution Function: Weibull

SIMAN USAGE: 82 + WEIB(78.4, 1.81)
Sq Error = 0.002276
Chi Square Test:
  No. of intervals = 5
  Degrees of freedom = 2
  Test Statistic = 0.5029
  Corresponding p-value > 0.75
Kolmogorov-Smirnov Test:
  Test Statistic = 0.05985
  Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density		Cumulative Distribution	
			Data	Function	Data	Function
0	7	1.086e+002	0.135	0.131	0.135	0.131
1	14	1.351e+002	0.269	0.259	0.404	0.390
2	12	1.617e+002	0.231	0.253	0.635	0.643
3	10	1.883e+002	0.192	0.181	0.827	0.824
4	4	2.149e+002	0.077	0.102	0.904	0.926
5	4	2.414e+002	0.077	0.047	0.981	0.973
6	1	2.680e+002	0.019	0.018	1.000	0.992

BEST FIT SUMMARY
Data File: PROD5.DST

Function	Sq Error
Weibull	0.002276
Gamma	0.002685
Triangular	0.003276
Beta	0.003974
Erlang	0.005294
Normal	0.01243
Lognormal	0.01349
Uniform	0.05019
Exponential	0.05167

Data File: PROD6.DST

PRODUCT 6

Histogram Range: 67 to 179
No. of Data Points = 52
No. of Intervals = 7
Min Data Value = 67.6
Max Data Value = 179
Sample Mean = 110
Sample Std Dev = 28.5
Distribution Function: Gamma

SIMAN USAGE: 67 + GAMM(23, 1.89)
Sq Error = 0.01437
Chi Square Test:
  No. of intervals = 5
  Degrees of freedom = 2
  Test Statistic = 8.61
  Corresponding p-value = 0.01493
Kolmogorov-Smirnov Test:
  Test Statistic = 0.08401
  Corresponding p-value > 0.15

Int. No.	No. of Data Pts.	x	Probability Density Data	Probability Density Function	Cumulative Distribution Data	Cumulative Distribution Function
0	8	8.300e+001	0.154	0.182	0.154	0.182
1	17	9.900e+001	0.327	0.264	0.481	0.446
2	9	1.150e+002	0.173	0.211	0.654	0.657
3	4	1.310e+002	0.077	0.142	0.731	0.799
4	7	1.470e+002	0.135	0.089	0.865	0.888
5	5	1.630e+002	0.096	0.053	0.962	0.941
6	2	1.790e+002	0.038	0.031	1.000	0.972

BEST FIT SUMMARY
Data File: PROD6.DST

Function	Sq Error
Gamma	0.01437
Erlang	0.01445
Lognormal	0.01492
Triangular	0.01626
Weibull	0.01781
Beta	0.02582
Normal	0.04405
Exponential	0.04453
Uniform	0.05241

Appendix II

Detailed Results for Product 1, One week Cycle

Product PROD1
Centre FCTRY
Archive d07

COLUMN STATISTIC

1   GOODS RECEIPT
2   ORDERS PLACED
3   TOTAL DEMAND
4   STOCK IN HAND

	1	2	3	4
31/ 5/94				70.90
1/ 6/94			2.71	68.19
2/ 6/94			2.70	65.48
3/ 6/94			2.72	62.76
4/ 6/94			2.70	60.06
5/ 6/94			5.61	54.46
6/ 6/94	10.60	10.60	4.05	61.00
7/ 6/94			2.68	58.33
8/ 6/94			2.68	55.64
9/ 6/94			2.67	52.97
10/ 6/94			2.70	50.27
11/ 6/94			2.63	47.64
12/ 6/94			5.43	42.22
13/ 6/94	26.17	26.17	3.96	64.42
14/ 6/94			2.61	61.81
15/ 6/94			2.61	59.20
16/ 6/94			2.58	56.63
17/ 6/94			2.61	54.01
18/ 6/94			2.57	51.44
19/ 6/94			5.24	46.21
20/ 6/94	13.18	13.18	3.33	56.06
21/ 6/94			2.26	53.80
22/ 6/94			2.28	51.52
23/ 6/94			2.21	49.31
24/ 6/94			2.22	47.09
25/ 6/94			2.24	44.85
26/ 6/94			4.54	40.31
27/ 6/94	26.44	26.44	5.57	61.18
28/ 6/94			3.64	57.53
29/ 6/94			3.65	53.88
30/ 6/94			3.71	50.17
1/ 7/94			3.67	46.50
2/ 7/94			3.63	42.87
3/ 7/94			7.24	35.63
4/ 7/94	38.29	38.29	3.65	70.27
5/ 7/94			2.41	67.86
6/ 7/94			2.41	65.45
7/ 7/94			2.38	63.07
8/ 7/94			2.41	60.66
9/ 7/94			2.44	58.21
10/ 7/94			4.91	53.31
11/ 7/94	10.89	10.89	2.79	61.41
12/ 7/94			1.87	59.54
13/ 7/94			1.84	57.70
14/ 7/94			1.85	55.85
15/ 7/94			1.82	54.03
16/ 7/94			1.86	52.16

	1	2	3	4
17/ 7/94			3.64	48.52
18/ 7/94	8.42	8.42	3.85	53.09
19/ 7/94			2.49	50.60
20/ 7/94			2.57	48.03
21/ 7/94			2.57	45.47
22/ 7/94			2.53	42.94
23/ 7/94			2.58	40.35
24/ 7/94			5.14	35.22
25/ 7/94	21.07	21.07	2.20	54.08
26/ 7/94			1.46	52.62
27/ 7/94			1.45	51.17
28/ 7/94			1.48	49.69
29/ 7/94			1.48	48.22
30/ 7/94			1.46	46.76
31/ 7/94			2.95	43.81
1/ 8/94	12.71	12.71	3.46	53.06
2/ 8/94			2.32	50.74
3/ 8/94			2.27	48.47
4/ 8/94			2.28	46.19
5/ 8/94			2.30	43.90
6/ 8/94			2.28	41.61
7/ 8/94			4.59	37.02
8/ 8/94	19.36	19.36	3.91	52.47
9/ 8/94			2.61	49.86
10/ 8/94			2.63	47.23
11/ 8/94			2.60	44.63
12/ 8/94			2.57	42.06
13/ 8/94			2.64	39.42
14/ 8/94			5.27	34.15
15/ 8/94	41.10	41.10	3.65	71.60
16/ 8/94			2.40	69.21
17/ 8/94			2.39	66.82
18/ 8/94			2.37	64.45
19/ 8/94			2.34	62.10
20/ 8/94			2.38	59.72
21/ 8/94			4.79	54.93
22/ 8/94	9.60	9.60	3.01	61.52
23/ 8/94			2.05	59.47
24/ 8/94			2.06	57.41
25/ 8/94			2.00	55.41
26/ 8/94			2.05	53.37
27/ 8/94			2.04	51.33
28/ 8/94			4.18	47.15
29/ 8/94	64.02	64.02	10.48	100.68
30/ 8/94			7.18	93.51
31/ 8/94			7.11	86.40
1/ 9/94			7.28	79.11
2/ 9/94			7.13	71.98
3/ 9/94			7.23	64.75
4/ 9/94			14.24	50.51
5/ 9/94	58.78	58.78	8.20	101.09
6/ 9/94			5.58	95.51
7/ 9/94			5.58	89.93
8/ 9/94			5.55	84.38
9/ 9/94			5.58	78.79
10/ 9/94			5.45	73.34
11/ 9/94			10.95	62.39

	1	2	3	4
12/ 9/94	21.14	21.14	8.33	75.21
13/ 9/94			5.55	69.65
14/ 9/94			5.48	64.17
15/ 9/94			5.46	58.71
16/ 9/94			5.50	53.21
17/ 9/94			5.44	47.78
18/ 9/94			10.77	37.01
19/ 9/94	33.31	33.31	5.15	65.17
20/ 9/94			3.46	61.71
21/ 9/94			3.48	58.23
22/ 9/94			3.51	54.72
23/ 9/94			3.42	51.30
24/ 9/94			3.44	47.87
25/ 9/94			7.01	40.86
26/ 9/94	29.37	29.37	5.50	64.73
27/ 9/94			3.69	61.04
28/ 9/94			3.66	57.38
29/ 9/94			3.64	53.74
30/ 9/94			3.63	50.11
1/10/94			3.63	46.48
2/10/94			7.41	39.07
3/10/94	45.78	45.78	4.96	79.89
4/10/94			3.28	76.61
5/10/94			3.33	73.28
6/10/94			3.29	69.99
7/10/94			3.26	66.73
8/10/94			3.26	63.47
9/10/94			6.70	56.77
10/10/94			5.58	51.19
11/10/94			3.63	47.56
12/10/94			3.64	43.92
13/10/94			3.55	40.37
14/10/94			3.71	36.66
15/10/94			3.65	33.00
16/10/94			7.30	25.70
17/10/94	34.32	34.32	4.67	55.36
18/10/94			2.98	52.38
19/10/94			3.03	49.34
20/10/94			3.04	46.30
21/10/94			3.07	43.23
22/10/94			2.99	40.24
23/10/94			6.13	34.11
24/10/94	53.78	53.78	4.76	83.12
25/10/94			3.17	79.96
26/10/94			3.17	76.79
27/10/94			3.14	73.65
28/10/94			3.16	70.49
29/10/94			3.22	67.27
30/10/94			6.43	60.84
31/10/94	27.69	27.69	4.66	83.87
1/11/94			3.12	80.75
2/11/94			3.16	77.59
3/11/94			3.15	74.44
4/11/94			3.15	71.30
5/11/94			3.15	68.14
6/11/94			6.47	61.68
7/11/94	9.29	9.29	4.39	66.57

	1	2	3	4
8/11/94			2.99	63.58
9/11/94			2.97	60.61
10/11/94			2.94	57.67
11/11/94			2.98	54.69
12/11/94			2.98	51.71
13/11/94			5.76	45.95
14/11/94	53.48	53.48	7.70	91.73
15/11/94			5.18	86.55
16/11/94			5.14	81.41
17/11/94			5.10	76.31
18/11/94			5.22	71.09
19/11/94			5.04	66.05
20/11/94			10.22	55.82
21/11/94	58.09	58.09	12.69	101.22
22/11/94			8.62	92.61
23/11/94			8.79	83.82
24/11/94			8.42	75.39
25/11/94			8.52	66.87
26/11/94			8.63	58.25
27/11/94			17.14	41.11
28/11/94	37.57	37.57	6.38	72.29
29/11/94			4.25	68.05
30/11/94			4.16	63.88
1/12/94			4.17	59.71
2/12/94			4.19	55.52
3/12/94			4.16	51.36
4/12/94			8.29	43.07
5/12/94	15.54	15.54	7.19	51.42
6/12/94			4.67	46.75
7/12/94			4.73	42.02
8/12/94			4.71	37.31
9/12/94			4.74	32.57
10/12/94			4.71	27.85
11/12/94			9.50	18.35
12/12/94	68.95	68.95	6.46	80.84
13/12/94			4.32	76.52
14/12/94			4.32	72.20
15/12/94			4.33	67.87
16/12/94			4.45	63.42
17/12/94			4.38	59.04
18/12/94			8.60	50.44
19/12/94	4.80	4.80	2.02	53.21
20/12/94			1.37	51.85
21/12/94			1.33	50.51
22/12/94			1.34	49.17
23/12/94			1.34	47.84
24/12/94			1.34	46.50
25/12/94			2.68	43.82
26/12/94	13.06	13.06		56.88
2/ 1/95			2.67	54.21
3/ 1/95			1.77	52.44
4/ 1/95			1.78	50.65
5/ 1/95			1.77	48.89
6/ 1/95			1.76	47.13
7/ 1/95			1.79	45.33
8/ 1/95			3.50	41.83
9/ 1/95	18.06	18.06	5.86	54.03

	1	2	3	4
10/ 1/95			3.93	50.10
11/ 1/95			3.93	46.18
12/ 1/95			3.97	42.21
13/ 1/95			3.90	38.30
14/ 1/95			3.88	34.42
15/ 1/95			7.88	26.55
16/ 1/95	43.93	43.93	4.62	65.85
17/ 1/95			3.08	62.77
18/ 1/95			3.11	59.66
19/ 1/95			3.15	56.51
20/ 1/95			3.08	53.43
21/ 1/95			3.13	50.30
22/ 1/95			6.12	44.17
23/ 1/95	29.85	29.85	4.31	69.71
24/ 1/95			2.88	66.83
25/ 1/95			2.83	64.00
26/ 1/95			2.83	61.18
27/ 1/95			2.89	58.28
28/ 1/95			2.88	55.40
29/ 1/95			5.76	49.64
30/ 1/95	11.18	11.18	5.48	55.34
31/ 1/95			3.69	51.65
1/ 2/95			3.70	47.95
2/ 2/95			3.73	44.22
3/ 2/95			3.63	40.59
4/ 2/95			3.74	36.85
5/ 2/95			7.41	29.44
6/ 2/95	79.65	79.65	11.30	97.79
7/ 2/95			7.54	90.25
8/ 2/95			7.57	82.68
9/ 2/95			7.48	75.20
10/ 2/95			7.53	67.67
11/ 2/95			7.61	60.06
12/ 2/95			15.24	44.81
13/ 2/95	51.93	51.93	9.25	87.49
14/ 2/95			6.07	81.42
15/ 2/95			5.99	75.43
16/ 2/95			6.01	69.42
17/ 2/95			6.04	63.37
18/ 2/95			5.97	57.40
19/ 2/95			12.07	45.33
20/ 2/95	90.54	90.54	10.22	125.65
21/ 2/95			6.64	119.01
22/ 2/95			6.80	112.21
23/ 2/95			6.68	105.53
24/ 2/95			6.59	98.95
25/ 2/95			6.76	92.19
26/ 2/95			13.27	78.92
27/ 2/95	0.84	0.84	9.94	69.82
28/ 2/95			6.29	63.53
1/ 3/95			6.49	57.04
2/ 3/95			6.53	50.51
3/ 3/95			6.49	44.02
4/ 3/95			6.53	37.49
5/ 3/95			13.07	24.42
6/ 3/95	41.74	41.74	5.24	60.92
7/ 3/95			3.57	57.35

	1	2	3	4
8/ 3/95			3.58	53.77
9/ 3/95			3.61	50.17
10/ 3/95			3.56	46.61
11/ 3/95			3.53	43.08
12/ 3/95			7.15	35.93
13/ 3/95	23.26	23.26	4.04	55.15
14/ 3/95			2.81	52.35
15/ 3/95			2.73	49.62
16/ 3/95			2.72	46.89
17/ 3/95			2.68	44.21
18/ 3/95			2.76	41.45
19/ 3/95			5.53	35.92
20/ 3/95	33.04	33.04	4.05	64.91
21/ 3/95			2.63	62.28
22/ 3/95			2.67	59.61
23/ 3/95			2.67	56.94
24/ 3/95			2.72	54.22
25/ 3/95			2.69	51.53
26/ 3/95			5.37	46.16
27/ 3/95	16.91	16.91	3.58	59.49
28/ 3/95			2.45	57.04
29/ 3/95			2.43	54.61
30/ 3/95			2.43	52.19
31/ 3/95			2.43	49.76
1/ 4/95			2.39	47.37
2/ 4/95			4.86	42.50
3/ 4/95	18.39	18.39	3.56	57.33
4/ 4/95			2.40	54.94
5/ 4/95			2.43	52.51
6/ 4/95			2.39	50.11
7/ 4/95			2.39	47.72
8/ 4/95			2.42	45.30
9/ 4/95			4.84	40.46
10/ 4/95	28.22	28.22	3.71	64.97
11/ 4/95			2.46	62.52
12/ 4/95			2.50	60.01
13/ 4/95			2.45	57.57
14/ 4/95			2.47	55.10
15/ 4/95			2.50	52.60
16/ 4/95			4.92	47.69
17/ 4/95	22.05	22.05	3.37	66.37
18/ 4/95			2.25	64.11
19/ 4/95			2.22	61.89
20/ 4/95			2.27	59.62
21/ 4/95			2.23	57.39
22/ 4/95			2.25	55.14
23/ 4/95			4.55	50.59
24/ 4/95	3.19	3.19	4.11	49.67
25/ 4/95			2.80	46.88
26/ 4/95			2.75	44.12
27/ 4/95			2.72	41.40
28/ 4/95			2.76	38.64
29/ 4/95			2.75	35.89
30/ 4/95			5.53	30.37
1/ 5/95	34.29	34.29	3.50	61.16
2/ 5/95			2.35	58.81
3/ 5/95			2.31	56.51

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4/ 5/95			2.33	54.18
5/ 5/95			2.35	51.83
6/ 5/95			2.33	49.50
7/ 5/95			4.67	44.83
8/ 5/95	18.52	18.52	3.75	59.60
9/ 5/95			2.48	57.13
10/ 5/95			2.54	54.59
11/ 5/95			2.53	52.06
12/ 5/95			2.51	49.55
13/ 5/95			2.51	47.04
14/ 5/95			5.00	42.04
15/ 5/95	19.51	19.51	3.71	57.84
16/ 5/95			2.50	55.34
17/ 5/95			2.52	52.82
18/ 5/95			2.51	50.32
19/ 5/95			2.49	47.82
20/ 5/95			2.43	45.39
21/ 5/95			5.02	40.37
22/ 5/95	21.84	21.84	3.79	58.42
23/ 5/95			2.45	55.97
24/ 5/95			2.50	53.47
25/ 5/95			2.48	50.99
26/ 5/95			2.50	48.49
27/ 5/95			2.47	46.02
28/ 5/95			4.99	41.02
29/ 5/95	26.17	26.17	3.98	63.21
30/ 5/95			2.58	60.63
31/ 5/95			2.62	58.02
1/ 6/95			2.69	55.33
2/ 6/95			2.67	52.66
3/ 6/95			2.63	50.03
4/ 6/95			5.26	44.77
5/ 6/95	18.30	18.30	4.25	58.82
6/ 6/95			2.81	56.01
7/ 6/95			2.77	53.24
8/ 6/95			2.75	50.49
9/ 6/95			2.81	47.69
10/ 6/95			2.81	44.87
11/ 6/95			5.66	39.21
12/ 6/95	25.15	25.15	4.12	60.25
13/ 6/95			2.78	57.47
14/ 6/95			2.68	54.79
15/ 6/95			2.67	52.12
16/ 6/95			2.73	49.40
17/ 6/95			2.72	46.68
18/ 6/95			5.36	41.31
19/ 6/95	13.90	13.90	3.97	51.24
20/ 6/95			2.61	48.63
21/ 6/95			2.64	45.99
22/ 6/95			2.64	43.35
23/ 6/95			2.59	40.75
24/ 6/95			2.63	38.13
25/ 6/95			5.33	32.79
26/ 6/95	53.73	53.73	3.34	83.19
27/ 6/95			2.19	81.00
28/ 6/95			2.18	78.82
29/ 6/95			2.19	76.63

	1	2	3	4
30/ 6/95			2.18	74.45
1/ 7/95			2.23	72.22
2/ 7/95			4.40	67.82
3/ 7/95	0.28	0.28	5.57	62.53
4/ 7/95			3.76	58.77
5/ 7/95			3.70	55.07
6/ 7/95			3.71	51.36
7/ 7/95			3.67	47.69
8/ 7/95			3.71	43.98
9/ 7/95			7.49	36.50
10/ 7/95	26.53	26.53	3.74	59.29
11/ 7/95			2.50	56.79
12/ 7/95			2.48	54.31
13/ 7/95			2.46	51.85
14/ 7/95			2.50	49.35
15/ 7/95			2.46	46.89
16/ 7/95			4.97	41.91
17/ 7/95	3.07	3.07	2.81	42.18
18/ 7/95			1.88	40.29
19/ 7/95			1.87	38.43
20/ 7/95			1.88	36.55
21/ 7/95			1.87	34.68
22/ 7/95			1.86	32.82
23/ 7/95			3.67	29.15
24/ 7/95	24.12	24.12	3.85	49.42
25/ 7/95			2.54	46.88
26/ 7/95			2.53	44.35
27/ 7/95			2.51	41.84
28/ 7/95			2.57	39.27
29/ 7/95			2.63	36.64
30/ 7/95			5.03	31.61
31/ 7/95	34.50	34.50	2.26	63.85
1/ 8/95			1.51	62.34
2/ 8/95			1.50	60.84
3/ 8/95			1.51	59.33
4/ 8/95			1.50	57.83
5/ 8/95			1.51	56.32
6/ 8/95			3.06	53.27
7/ 8/95	5.96	5.96	3.44	55.78
8/ 8/95			2.28	53.50
9/ 8/95			2.31	51.19
10/ 8/95			2.30	48.89
11/ 8/95			2.30	46.59
12/ 8/95			2.31	44.28
13/ 8/95			4.58	39.70
14/ 8/95	27.47	27.47	3.83	63.34
15/ 8/95			2.63	60.71
16/ 8/95			2.60	58.11
17/ 8/95			2.60	55.51
18/ 8/95			2.65	52.86
19/ 8/95			2.60	50.26
20/ 8/95			5.17	45.09
21/ 8/95	22.34	22.34	3.63	63.80
22/ 8/95			2.36	61.44
23/ 8/95			2.41	59.03
24/ 8/95			2.36	56.68
25/ 8/95			2.38	54.29

	1	2	3	4
26/ 8/95			2.35	51.94
27/ 8/95			4.69	47.25
28/ 8/95	44.91	44.91	3.08	89.08
29/ 8/95			2.03	87.05
30/ 8/95			2.06	85.00
31/ 8/95			2.10	82.90
1/ 9/95			2.08	80.82
2/ 9/95			2.08	78.75
3/ 9/95			4.19	74.55
4/ 9/95	9.48	9.48	10.82	73.21
5/ 9/95			7.22	65.99
6/ 9/95			7.30	58.69
7/ 9/95			7.20	51.49
8/ 9/95			7.15	44.34
9/ 9/95			7.19	37.15
10/ 9/95			14.31	22.83
11/ 9/95	57.49	57.49	8.22	72.10
12/ 9/95			5.50	66.60
13/ 9/95			5.50	61.10
14/ 9/95			5.37	55.73
15/ 9/95			5.54	50.19
16/ 9/95			5.48	44.71
17/ 9/95			10.93	33.78
18/ 9/95	63.32	63.32	8.38	88.72
19/ 9/95			5.42	83.29
20/ 9/95			5.33	77.97
21/ 9/95			5.48	72.49
22/ 9/95			5.46	67.03
23/ 9/95			5.46	61.58
24/ 9/95			10.86	50.71
25/ 9/95	7.12	7.12	5.05	52.79
26/ 9/95			3.41	49.38
27/ 9/95			3.47	45.92
28/ 9/95			3.37	42.54
29/ 9/95			3.41	39.13
30/ 9/95			3.38	35.76
1/10/95			6.84	28.92
2/10/95	30.75	30.75	5.44	54.23
3/10/95			3.66	50.58
4/10/95			3.68	46.89
5/10/95			3.60	43.29
6/10/95			3.61	39.68
7/10/95			3.58	36.11
8/10/95			7.30	28.81
9/10/95	36.78	36.78	5.00	60.59
10/10/95			3.32	57.27
11/10/95			3.32	53.95
12/10/95			3.37	50.58
13/10/95			3.27	47.31
14/10/95			3.33	43.98
15/10/95			6.65	37.33
16/10/95	34.72	34.72	5.41	66.64
17/10/95			3.58	63.06
18/10/95			3.67	59.40
19/10/95			3.62	55.78
20/10/95			3.67	52.11
21/10/95			3.62	48.49

	1	2	3	4
22/10/95			7.23	41.26
23/10/95	17.91	17.91	4.55	54.63
24/10/95			3.02	51.61
25/10/95			3.07	48.54
26/10/95			2.99	45.55
27/10/95			3.05	42.50
28/10/95			3.02	39.48
29/10/95			5.92	33.56
30/10/95	30.09	30.09	4.71	58.94
31/10/95			3.16	55.78
1/11/95			3.17	52.61
2/11/95			3.21	49.41
3/11/95			3.13	46.28
4/11/95			3.21	43.07
5/11/95			6.29	36.78
6/11/95	33.28	33.28	4.86	65.20
7/11/95			3.25	61.95
8/11/95			3.27	58.68
9/11/95			3.22	55.46
10/11/95			3.27	52.20
11/11/95			3.26	48.93
12/11/95			6.44	42.49
13/11/95	60.67	60.67	4.29	98.86
14/11/95			2.92	95.94
15/11/95			2.86	93.08
16/11/95			2.93	90.16
17/11/95			2.89	87.26
18/11/95			2.91	84.35
19/11/95			5.82	78.53
20/11/95			7.73	70.81
21/11/95			5.20	65.61
22/11/95			5.14	60.47
23/11/95			5.13	55.34
24/11/95			5.20	50.14
25/11/95			5.19	44.94
26/11/95			10.34	34.60
27/11/95	52.18	52.18	12.80	73.98
28/11/95			8.48	65.51
29/11/95			8.58	56.93
30/11/95			8.45	48.48
1/12/95			8.57	39.91
2/12/95			8.70	31.22
3/12/95			16.89	14.32
4/12/95	68.58	68.58	6.19	76.71
5/12/95			4.04	72.66
6/12/95			4.05	68.62
7/12/95			4.07	64.55
8/12/95			4.06	60.48
9/12/95			4.11	56.37
10/12/95			8.33	48.04
11/12/95	36.06	36.06	7.20	76.91
12/12/95			4.84	72.06
13/12/95			4.82	67.25
14/12/95			4.68	62.56
15/12/95			4.75	57.81
16/12/95			4.74	53.07
17/12/95			9.65	43.42

	1	2	3	4
18/12/95	13.92	13.92	6.19	51.14
19/12/95			4.17	46.97
20/12/95			4.20	42.77
21/12/95			4.08	38.69
22/12/95			4.14	34.55
23/12/95			4.10	30.45
24/12/95			8.26	22.19
25/12/95	25.83	25.83	2.01	46.01
26/12/95			1.35	44.66
27/12/95			1.34	43.32
28/12/95			1.35	41.97
29/12/95			1.36	40.61
30/12/95			1.35	39.25
31/12/95			2.67	36.58
1/ 1/96	29.42	29.42	2.68	63.32
2/ 1/96			1.74	61.59
3/ 1/96			1.74	59.85
4/ 1/96			1.75	58.10
5/ 1/96			1.75	56.35
6/ 1/96			1.73	54.62
7/ 1/96			3.39	51.23
8/ 1/96	16.18	16.18	5.85	61.56
9/ 1/96			3.85	57.70
10/ 1/96			3.89	53.81
11/ 1/96			3.91	49.90
12/ 1/96			3.88	46.02
13/ 1/96			3.89	42.13
14/ 1/96			7.62	34.51
15/ 1/96	36.51	36.51	4.64	66.38
16/ 1/96			3.03	63.36
17/ 1/96			3.09	60.27
18/ 1/96			3.07	57.20
19/ 1/96			3.10	54.09
20/ 1/96			3.04	51.06
21/ 1/96			6.28	44.78
22/ 1/96	30.90	30.90	4.27	71.41
23/ 1/96			2.79	68.62
24/ 1/96			2.82	65.79
25/ 1/96			2.79	63.00
26/ 1/96			2.83	60.17
27/ 1/96			2.85	57.32
28/ 1/96			5.70	51.62
29/ 1/96	74.47	74.47	5.30	120.78
30/ 1/96			3.52	117.27
31/ 1/96			3.50	113.77
1/ 2/96			3.58	110.19
2/ 2/96			3.43	106.77
3/ 2/96			3.54	103.23
4/ 2/96			7.08	96.15
5/ 2/96			11.47	84.68
6/ 2/96			7.49	77.20
7/ 2/96			7.54	69.65
8/ 2/96			7.60	62.06
9/ 2/96			7.43	54.63
10/ 2/96			7.57	47.06
11/ 2/96			15.03	32.02
12/ 2/96	52.72	52.72	9.06	75.68

	1	2	3	4
13/ 2/96			6.22	69.46
14/ 2/96			6.19	63.28
15/ 2/96			6.16	57.11
16/ 2/96			6.14	50.98
17/ 2/96			6.19	44.79
18/ 2/96			12.10	32.69
19/ 2/96	63.66	63.66	10.26	86.09
20/ 2/96			6.83	79.26
21/ 2/96			6.81	72.45
22/ 2/96			6.78	65.67
23/ 2/96			6.74	58.93
24/ 2/96			6.84	52.09
25/ 2/96			13.58	38.51
26/ 2/96	39.89	39.89	9.58	68.82
27/ 2/96			6.38	62.44
28/ 2/96			6.45	55.98
29/ 2/96			6.52	49.46
1/ 3/96			6.55	42.91
2/ 3/96			6.39	36.52
3/ 3/96			13.03	23.49
4/ 3/96	31.89	31.89	5.09	50.29
5/ 3/96			3.38	46.92
6/ 3/96			3.40	43.52
7/ 3/96			3.38	40.13
8/ 3/96			3.37	36.76
9/ 3/96			3.43	33.34
10/ 3/96			6.78	26.55
11/ 3/96	29.41	29.41	4.01	51.95
12/ 3/96			2.73	49.22
13/ 3/96			2.72	46.50
14/ 3/96			2.68	43.82
15/ 3/96			2.70	41.12
16/ 3/96			2.72	38.39
17/ 3/96			5.45	32.95
18/ 3/96	30.57	30.57	3.98	59.54
19/ 3/96			2.64	56.90
20/ 3/96			2.63	54.27
21/ 3/96			2.61	51.66
22/ 3/96			2.63	49.03
23/ 3/96			2.67	46.36
24/ 3/96			5.37	40.99
25/ 3/96	21.80	21.80	3.48	59.31
26/ 3/96			2.31	57.00
27/ 3/96			2.32	54.69
28/ 3/96			2.31	52.38
29/ 3/96			2.27	50.10
30/ 3/96			2.28	47.83
31/ 3/96			4.62	43.20
1/ 4/96	32.57	32.57	3.55	72.22
2/ 4/96			2.40	69.82
3/ 4/96			2.38	67.45
4/ 4/96			2.38	65.07
5/ 4/96			2.41	62.66
6/ 4/96			2.38	60.28
7/ 4/96			4.87	55.41
8/ 4/96	12.30	12.30	3.66	64.05
9/ 4/96			2.43	61.61

	1	2	3	4
10/ 4/96			2.45	59.17
11/ 4/96			2.41	56.76
12/ 4/96			2.47	54.29
13/ 4/96			2.44	51.85
14/ 4/96			4.84	47.01
15/ 4/96	27.52	27.52	3.58	70.95
16/ 4/96			2.40	68.55
17/ 4/96			2.37	66.19
18/ 4/96			2.39	63.80
19/ 4/96			2.39	61.41
20/ 4/96			2.35	59.07
21/ 4/96			4.73	54.34
22/ 4/96	5.68	5.68	4.33	55.69
23/ 4/96			2.86	52.82
24/ 4/96			2.86	49.96
25/ 4/96			2.89	47.07
26/ 4/96			2.87	44.20
27/ 4/96			2.85	41.35
28/ 4/96			5.81	35.54
29/ 4/96	26.57	26.57	3.40	58.72
30/ 4/96			2.29	56.43
1/ 5/96			2.28	54.15
2/ 5/96			2.32	51.82
3/ 5/96			2.25	49.57
4/ 5/96			2.27	47.30
5/ 5/96			4.55	42.75
6/ 5/96	29.69	29.69	3.72	68.72
7/ 5/96			2.46	66.27
8/ 5/96			2.52	63.74
9/ 5/96			2.43	61.31
10/ 5/96			2.42	58.90
11/ 5/96			2.48	56.41
12/ 5/96			4.93	51.49
13/ 5/96	5.44	5.44	3.88	53.05
14/ 5/96			2.62	50.43
15/ 5/96			2.57	47.86
16/ 5/96			2.57	45.29
17/ 5/96			2.58	42.71
18/ 5/96			2.61	40.10
19/ 5/96			5.14	34.96
20/ 5/96	11.91	11.91	3.86	43.01
21/ 5/96			2.56	40.45
22/ 5/96			2.60	37.86
23/ 5/96			2.57	35.28
24/ 5/96			2.55	32.73
25/ 5/96			2.62	30.11
26/ 5/96			5.12	25.00
27/ 5/96	49.33	49.33	4.02	70.31
28/ 5/96			2.67	67.63
29/ 5/96			2.65	64.98
30/ 5/96			2.67	62.31
31/ 5/96			2.64	59.66
1/ 6/96			2.62	57.04
2/ 6/96			5.24	51.80
3/ 6/96	9.83	9.83	4.01	57.62
4/ 6/96			2.70	54.92
5/ 6/96			2.67	52.25

	1	2	3	4
6/ 6/96			2.70	49.55
7/ 6/96			2.71	46.84
8/ 6/96			2.70	44.14
9/ 6/96			5.37	38.76
10/ 6/96	30.71	30.71	4.00	65.47
11/ 6/96			2.64	62.83
12/ 6/96			2.67	60.16
13/ 6/96			2.66	57.50
14/ 6/96			2.61	54.88
15/ 6/96			2.63	52.26
16/ 6/96			5.29	46.97
17/ 6/96	10.77	10.77	3.78	53.95
18/ 6/96			2.56	51.39
19/ 6/96			2.58	48.81
20/ 6/96			2.57	46.24
21/ 6/96			2.57	43.67
22/ 6/96			2.56	41.11
23/ 6/96			5.10	36.01
24/ 6/96	49.89	49.89	3.33	82.57
25/ 6/96			2.21	80.36
26/ 6/96			2.22	78.13
27/ 6/96			2.20	75.94
28/ 6/96			2.21	73.73
29/ 6/96			2.21	71.52
30/ 6/96			4.43	67.09
1/ 7/96			5.75	61.34
2/ 7/96			3.80	57.54
3/ 7/96			3.76	53.78
4/ 7/96			3.80	49.98
5/ 7/96			3.83	46.15
6/ 7/96			3.81	42.34
7/ 7/96			7.67	34.68
8/ 7/96	23.90	23.90	3.72	54.86
9/ 7/96			2.47	52.39
10/ 7/96			2.44	49.95
11/ 7/96			2.46	47.49
12/ 7/96			2.54	44.95
13/ 7/96			2.49	42.46
14/ 7/96			4.95	37.51
15/ 7/96	6.18	6.18	2.74	40.95
16/ 7/96			1.80	39.15
17/ 7/96			1.84	37.30
18/ 7/96			1.82	35.48
19/ 7/96			1.82	33.66
20/ 7/96			1.82	31.83
21/ 7/96			3.66	28.18
22/ 7/96	33.76	33.76	3.88	58.06
23/ 7/96			2.61	55.45
24/ 7/96			2.53	52.92
25/ 7/96			2.56	50.36
26/ 7/96			2.53	47.83
27/ 7/96			2.56	45.27
28/ 7/96			5.15	40.12
29/ 7/96	23.10	23.10	2.23	60.99
30/ 7/96			1.43	59.56
31/ 7/96			1.44	58.12
1/ 8/96			1.48	56.64

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2/ 8/96			1.50	55.13
3/ 8/96			1.44	53.69
4/ 8/96			2.93	50.76
5/ 8/96	30.19	30.19	3.25	77.70
6/ 8/96			2.21	75.49
7/ 8/96			2.22	73.27
8/ 8/96			2.22	71.05
9/ 8/96			2.23	68.82
10/ 8/96			2.18	66.64
11/ 8/96			4.43	62.22
12/ 8/96	5.73	5.73	3.95	64.00
13/ 8/96			2.63	61.37
14/ 8/96			2.65	58.72
15/ 8/96			2.64	56.08
16/ 8/96			2.59	53.49
17/ 8/96			2.63	50.86
18/ 8/96			5.19	45.67
19/ 8/96	16.89	16.89	3.55	59.01
20/ 8/96			2.39	56.62
21/ 8/96			2.34	54.28
22/ 8/96			2.32	51.96
23/ 8/96			2.38	49.58
24/ 8/96			2.40	47.18
25/ 8/96			4.76	42.42
26/ 8/96	45.07	45.07	3.11	84.38
27/ 8/96			2.07	82.31
28/ 8/96			2.08	80.23
29/ 8/96			2.09	78.14
30/ 8/96			2.07	76.06
31/ 8/96			2.05	74.01
1/ 9/96			4.16	69.85
2/ 9/96			10.49	59.37
3/ 9/96			7.00	52.37
4/ 9/96			6.94	45.42
5/ 9/96			6.86	38.56
6/ 9/96			7.06	31.50
7/ 9/96			6.89	24.61
8/ 9/96			13.96	10.65
9/ 9/96	85.63	85.63	8.25	88.02
10/ 9/96			5.47	82.55
11/ 9/96			5.50	77.05
12/ 9/96			5.56	71.49
13/ 9/96			5.57	65.92
14/ 9/96			5.47	60.45
15/ 9/96			11.17	49.28
16/ 9/96	16.78	16.78	8.44	57.62
17/ 9/96			5.64	51.97
18/ 9/96			5.63	46.35
19/ 9/96			5.74	40.61
20/ 9/96			5.66	34.95
21/ 9/96			5.69	29.26
22/ 9/96			11.34	17.92
23/ 9/96	85.37	85.37	5.23	98.06
24/ 9/96			3.52	94.54
25/ 9/96			3.55	90.99
26/ 9/96			3.52	87.46
27/ 9/96			3.51	83.95

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28/ 9/96			3.54	80.42
29/ 9/96			7.19	73.22
30/ 9/96	3.11	3.11	5.52	70.81
1/10/96			3.63	67.18
2/10/96			3.60	63.58
3/10/96			3.64	59.93
4/10/96			3.76	56.18
5/10/96			3.69	52.49
6/10/96			7.29	45.20
7/10/96	23.99	23.99	4.89	64.30
8/10/96			3.38	60.92
9/10/96			3.37	57.55
10/10/96			3.37	54.18
11/10/96			3.33	50.85
12/10/96			3.30	47.56
13/10/96			6.63	40.93
14/10/96	30.21	30.21	5.34	65.80
15/10/96			3.57	62.23
16/10/96			3.54	58.70
17/10/96			3.62	55.08
18/10/96			3.57	51.50
19/10/96			3.58	47.93
20/10/96			7.08	40.85
21/10/96	20.87	20.87	4.64	57.08
22/10/96			3.06	54.01
23/10/96			3.03	50.98
24/10/96			3.05	47.93
25/10/96			3.04	44.89
26/10/96			3.03	41.86
27/10/96			6.20	35.66
28/10/96	26.58	26.58	4.78	57.46
29/10/96			3.16	54.30
30/10/96			3.19	51.10
31/10/96			3.23	47.87
1/11/96			3.18	44.70
2/11/96			3.18	41.52
3/11/96			6.40	35.12
4/11/96	44.30	44.30	4.72	74.70
5/11/96			3.15	71.55
6/11/96			3.10	68.45
7/11/96			3.18	65.27
8/11/96			3.14	62.12
9/11/96			3.12	59.01
10/11/96			6.34	52.67
11/11/96	41.69	41.69	4.32	90.04
12/11/96			2.83	87.21
13/11/96			2.90	84.31
14/11/96			2.90	81.41
15/11/96			2.92	78.49
16/11/96			2.94	75.56
17/11/96			5.72	69.84
18/11/96	53.60	53.60	7.80	115.63
19/11/96			5.26	110.38
20/11/96			5.19	105.19
21/11/96			5.18	100.01
22/11/96			5.21	94.80
23/11/96			5.24	89.56

	1	2	3	4
24/11/96			10.58	78.99
25/11/96	21.30	21.30	12.76	87.53
26/11/96			8.52	79.01
27/11/96			8.52	70.49
28/11/96			8.50	62.00
29/11/96			8.44	53.56
30/11/96			8.42	45.14
1/12/96			16.84	28.30
2/12/96	86.88	86.88	6.43	108.75
3/12/96			4.24	104.51
4/12/96			4.33	100.18
5/12/96			4.37	95.82
6/12/96			4.30	91.52
7/12/96			4.33	87.19
8/12/96			8.60	78.59
9/12/96	12.36	12.36	7.08	83.86
10/12/96			4.87	78.99
11/12/96			4.84	74.15
12/12/96			4.96	69.19
13/12/96			4.72	64.48
14/12/96			4.83	59.65
15/12/96			9.64	50.01
16/12/96	2.13	2.13	6.47	45.67
17/12/96			4.20	41.47
18/12/96			4.27	37.21
19/12/96			4.24	32.97
20/12/96			4.16	28.81
21/12/96			4.32	24.49
22/12/96			8.43	16.06
23/12/96	26.76	26.76	1.95	40.86
24/12/96			1.32	39.55
25/12/96			1.30	38.25
26/12/96			1.33	36.92
27/12/96			1.32	35.60
28/12/96			1.30	34.30
29/12/96			2.59	31.71
30/12/96	9.16	9.16		40.87

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SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCE

PhD THESIS

Academic Year 1990-94

NEWTON B MATUPI

Prediction of Manufacturing Flexibility by the Use of Simulation Modelling

Supervisor: J M Kay

January 1997

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy