RELIABILITY MONITORING, FEEDBACK AND IMPROVEMENT SYSTEMS: THEIR APPLICATION IN THE MACHINE TOOL INDUSTRY

Volume I

JOSIM UDDIN AHMED

MASTER OF PHILOSOPHY

THE UNIVERSITY OF ASTON IN BIRMINGHAM

January 1998

THE UNIVERSITY OF ASTON IN BIRMINGHAM

RELIABILITY MONITORING, FEEDBACK AND IMPROVEMENT SYSTEMS: THEIR APPLICATION IN THE MACHINE TOOL INDUSTRY

JOSIM UDDIN AHMED

Master of Philosophy

1998

SUMMARY

This thesis provides an overview and synthesis of the results of a major study on reliability management practices in the machine tool industry. The investigation was undertaken to provide an information base, at an operational level, of practical use for reliability management development by key decision makers in the fields of design, manufacturing, service and supplier development.

To make sense of the problems and practices found in machine tool enterprises, an integrated approach was adopted. The study addressed the principal underlying variables: the design, manufacture and supplier development aspects of reliability, the use of field performance data in design modification and improvement, and the application of reliability-based methods for reliability appraisal. The core of the project consists of longitudinal studies using methods of 'action research.' In addition to this, a survey was conducted. The combination of both these approaches provided a consistent and representative presentation of the reliability management practices in the industry.

Three points can be made concerning the findings on the most significant problems faced by manufacturers. First, it was clear that manufacturers pay insufficient attention to reliability related issues at all stages of the product design and development process. Second, little systematic and consistent use is made of field failure data in the area of reliability improvement. Companies showed a lack of interest in measuring important field reliability variables, except when major problems arise. Third, there was a marked absence of evidence that reliability-based techniques had been used among the systems for design analysis and engineering decision making. These problems illustrate the areas of deficiency regarding reliability management and determine ways in which these can be overcome.

The deficiencies identified in the approaches to the management of product reliability were addressed by the development of a generic methodology for improving machine tool reliability. This consists of a set of guidelines and techniques, which in totality provides the basis for improving the reliability management process. It is intended primarily for the machine tool industry but will have potential applications elsewhere.

Key Words: Reliability Management, Failure Data, Reliability Techniques, Design Analysis, Machine Tool Technology.

In loving memory of my father, Zia and sister, Rahana

Reliability is, after all, engineering in its most practical and innovative form

ACKNOWLEDGEMENTS

It will be apparent that the author is indebted to the many organisations, industrial and academic experts for their contributions to this research and the data and material they have made available. In this respect, the author would like to take this opportunity to thank all those people who provided input to the project, in some form or another. I am especially grateful to all those people at Cincinnati Milacron UK Ltd and Aston University who have helped in the completion of this thesis.

I would like to express my thanks to Dr. David Bennett whose continuous support, guidance and understanding were instrumental in the development of this thesis. David Bennett, who supervised this research project, has contributed in many ways. By his constant prodding, detailed questions and criticism, but also his enthusiasm, encouragement and numerous suggestions, he has been the most helpful and considerate supervisor one could possibly wish for.

I would also like to register my appreciation of the co-operation and assistance provided by some of the Managers and Directors of Cincinnati Milacron UK Ltd. In particular, I need to acknowledge the financial support provided by Cincinnati Milacron which enabled me to undertake this study. My extended thanks goes out to Graham Sexton, Ian Good and Stuart Bailey for their initial collaboration, support and understanding in the completion of this work. In addition to this, I would like to express my appreciation to Graham Sexton and Ian Good for providing me with the extra time and leave to complete the thesis at difficult times. Furthermore, I would like to thank them both for their constant drive and encouragement to complete the thesis in 'good time.'

Comments by a number of industrial organisations are gratefully acknowledged. I am grateful to The Machine Tool Technologies Association (MTTA), the Advanced Manufacturing Technology Research Institute (AMTRI) and Dr. Peter Mason for their numerous comments, suggestions and participation in the study.

In addition, I would like to acknowledge the co-operation of the many machine tool manufacturers who participated in the nation-wide survey. Especially, I would like to thank those manufacturers who had taken the courtesy of completing a series of extensive questionnaires on reliability management practices within their organisation.

Finally, I would like to thank my mother, Angura, nephew, Shahanul and my two brothers, Saley and Hashim for their patience, understanding and moral support during the latter stages of the study.

List of Contents

VOLUME I

VOLUME II

List of Figures

VOLUME I

VOLUME II

List of Tables

VOLUME I

VOLUME II

PART I

CONCEPTUAL FRAMEWORK OF RELIABILITY MANAGEMENT AND TECHNICAL GUIDELINES

1. Background and Aims of the Research Project

1.1 Introduction

Initial investigations into the subject of reliability management, in UK manufacturing industry, indicated to the low levels of research effort into this important subject area and a lack of industrial awareness of the potential benefits. This measure together with the collaboration with Cincinnati Milacron (UK) Ltd (Machine Tool Manufacturers), formed the initial basis of this research project.

Whilst many former researchers concentrated on examining the barriers to acceptance of reliability techniques [e.g. Sohal, 1986] or the organisation structure and status of reliability management in UK manufacturing industry [e.g. Abed, 1987], or the design and cost aspects of reliability during new product development [Nassar, 1988], this research is concerned with an empirical appraisal of the overall reliability management process. From a sectoral perspective, the focus of the study is the UK machine tool industry. The research attempts to determine how machine tool manufacturers are managing product reliability, particularly in response to emerging user requirements and awareness. The project also aims to identify key problem areas which face manufacturers and if there are instruments which could be developed or readily available, to support companies in the management of product reliability.

The research therefore has two specific objectives. Firstly, to conduct an analysis and evaluation of the various aspects of the reliability management process. This is carried out using machine tool products as a benchmark. Secondly, to use the core findings in developing a generic methodology for the improvement of machine tool reliability.

The purpose of this chapter is to elaborate on the framework for this research inquiry. It is intended to form the preliminary to the subsequent chapters, providing an overview of the research. Beginning with an elaboration of the research proposition, it briefly describes how the field research was undertaken and a description of the overall methodology adopted. This chapter also discusses why a decision was taken to focus on only one industry in the subsequent fieldwork. Similarly, justification is provided on the choice of the UK machine tool industry.

1.2 Product Reliability and International Competitiveness

Within the UK national economy, manufacturing industry performs a vital role, yet fierce international competition has resulted in a decline in industry in the recent past. The depth of the decline has resulted in a situation in which United Kingdom's manufacturing base now faces an uncertain future [Coutts and Godley, 1990]. Pre-occupation with short term operational issues as opposed to building long term competitive advantage has always been identified as a major reason for this failure [Banks and Wheelwright, 1979; Hayes and Abernathy, 1980; Ferdows, Miller, Nakane and Vollmann, 1986].

Competitive pressures on manufacturing organisations has greatly influenced them to look at all improvement possibilities. Reliability embodied in new products has become an important source of competitive advantage for all advanced industrial countries [see for example Collcutt, 1992; Coppola, 1994; Knight, 1991; Morrison, 1981]. In such countries manufacturers have had to put an increasing emphasis on improving product reliability in order to compete successfully in international markets. Price competition has become increasingly less attractive as manufacturers from developing countries have entered the market, supplying relatively standard products with lower manufacturing costs. This development has been particularly pronounced in the mechanical engineering sectors of the economy. However, its effects have also been felt throughout manufacturing industry.

Manufacturers are generally responsive to such market conditions. However, for high volume manufactured products, design and manufacturing activities are primarily driven by cost with reliability regarded as an add-on to product quality [Strutt, 1996]. Only for safety critical equipment (for example in the aerospace industry), design and manufacturing activities are directly driven by safety and reliability requirements. In many cases, manufacturers have the task of designing components and systems to meet often conflicting functional, quality and reliability requirements at a price that is acceptable to the customers.

It is generally agreed that the introduction and adoption of effective and economical reliability control systems (spanning from design engineering to the operation and use of the manufactured product) is a major determinant factor in achieving optimum levels of product reliability. In connection to this, previous analyses have shown an association between the attention paid to improvements in product reliability and general trading success. For example, the results reported by the Centre of Interfirm Comparison [1977] which found that the practice of using *'formal systems of quality and reliability control'* was clearly linked to obtaining better performance as measured by the operating profit: operating assets ratio.

In relation to the above, a former study [Lockyer, Oakland and Duprey, 1984] claimed that if the UK is to survive as an advanced technological based nation, it is vital that the industry provides itself with quality control and assurance systems which are both effective and economical. Further, the latest White Paper on 'Standards, Quality and International Competitiveness' [DTI, 1982] confirms the political determination to enhance the status of standards and quality assurance in the manufacturing industry, with the main objective of increasing efficiency and strengthening international competitiveness.

1.3 Manufacturer's Approach to Product Reliability

In contrast to the study of quality management in manufacturing organisations, there has been relatively few published research into reliability management. While academic knowledge is now relatively well advanced on the technical, management and organisation aspects of quality management [e.g. Eisen, Mulraney and Sohal, 1992; Lascelles and Dale, 1988; Shaw and Dale, 1987], this is not the case for reliability management. With the exception of probabilistic and risk management aspects (particularly applicable in the power, offshore, rail and aviation sectors of the manufacturing industry), the function of reliability management in the automotive and the mechanical engineering sector is relatively under researched.

However, the application, diffusion and implementation of reliability management practices in manufacturing industry has been studied to some varying degree in the quality and general operation management literature. Evidence from these studies are difficult to collate and assess. This is because they cover a broad subject areas, rather than reliability as a discipline on its own right. Broadly speaking, it would appear that British companies are not adopting 'best practice' models or methods when addressing product reliability issues during the life cycle of a product (in particular during the design, development and manufacture stage). It is also possible to conclude that many organisations may have no separate function for product reliability decisions. In that perspective, little or no consideration is given on analysing and assessing the downstream impacts of engineering decisions on product reliability. It is most likely that such decisions are taken on an ad hoc basis in general design reviews or on the responsibility and initiative of functional managers. For example, a survey carried out to establish the inter-relationships between quality and reliability assurance in UK manufacturing industry [Abed, 1987] concluded that :

> "...only a few companies have established reliability programmes and in none of the responding companies was reliability directly represented at Board level. Responsibility for the reliability function is delegated to a variety of functional managers and communication regarding reliability matters is somewhat informal, irregular and not always in writing. Managers responsible for reliability do not make adequate use of specific techniques and furthermore they are not given the responsibility to control all the activities relating to reliability management."

In context with the latter part of the above notion, there is now a considerable literature extant on the different techniques, systems and models available for assessing, analysing and improving product reliability. In particular, contemporary and antecedent material on the subject concerning the function of reliability and quality management has given considerable attention to the identification and evaluation of key components for product reliability improvement [see for example Corbett, Dooner, Meleka and Pym 1991; Sullivan, 1986; Swift and Allen, 1989].

Despite the existence of this large body of literature on systems and models to be used in reliability development, there is evidence to suggest that managers may often disregard such techniques in their actual decision making process. The work of Sohal [1986] on the usage of production management techniques and statistical methods of quality control in UK manufacturing industry reported that approximately 10% of companies in their sample make use of reliability techniques. In particular, the application of predictive techniques (e.g. Weibull analysis) to assess the reliability of products were significantly low. The main reasons for low levels of usage can be broadly classified as being:

- A lack of knowledge and understanding in the operation of the technique.
- A lack of resources and time constraints.
- A lack of senior management support.

In addition to the above, there has been relatively few studies conducted on the use, analysis and feedback of reliability performance data in UK manufacturing industry. Occasional references are made to this particular subject in the production, engineering, quality, operation management and the more specialist reliability literature. For example, a study on the 'efficiency of production systems-management' carried out by Bradford University (cited in Abed, Keller and Sohal, 1989] indicated that only 60% of British companies make use of reliability data to influence design improvements. The study also indicated that larger companies are more likely to collect, analyse and make use of reliability-related data. In conclusion, the study commented:

> "American and European-owned companies are more likely than British ones to collect data on reliability from customers and to use this data to influence product design."

Abed et al. [1989] provided further documented evidence on little use being made of reliability costs. Only one in five companies (19.6% of the sample) claimed that they collected data related to reliability costs. However, there was no evidence to suggest that such costs where used to effect reliability improvements. If, as the evidence cited above suggests, the general consensus on this aspect of the reliability management process appears to be that there is little use being made of such data to effect reliability improvements.

1.4 Previous Research into the Reliability of Machine Tools

Given that, in the view of the buyer, reliability is considered to be a significant characteristic of a machine tool product [Benchmark Research, 1994], there is little available contemporary research-based literature relating to any aspect of machine tool reliability. Reliability management of machine tool technology is a multi-faceted problem involving three major elements: (1) design and manufacture aspects (2) operational aspects and (3) application of reliability-based techniques for assessing machine tool reliability. Previous research has tended to concentrate on the operational and maintenance aspects of machine tool reliability to the exclusion of the design and manufacture factor. Similarly, no attempt has been made to evaluate the degree to which reliability-based techniques are used within the machine tool industry.

Academic knowledge is now relatively well advanced on the maintenance aspects of machine tool reliability. However, this is not the case for the design and manufacturing issues associated with machine tool reliability. There are, nonetheless, some references within a wider body of management science to this topic. Three areas of the literature offer some lessons on the reliability management of machine tool technology. These are:

1. Quality management practice in the machine tool industry (as distinct from product quality).

2. The process of new product development in the machine tool industry.
3. Structure, problems, trade and markets of the machine tool industry.

A large amount of studies of quality management practice in the machine tool industry arises from the work of Morrison [1984a, 1984b and 1985] and concentrates on the diffusion of best practice models within machine tool manufacturing organisations. Other work is more prescriptive in nature, offering ways in which companies can improve their quality management system in order to be more responsive to quality related problems. For example, having identified the need for better quality management, Morrison [1984c] developed a quality management model specifically suited to the industry. This model was developed from the context of planning (planning being the most important element), organising, directing and a controlling framework which is repeatedly used in management science circles. He demonstrated that quality and reliability operations can be managed using the basic principles that are widely accepted in the management of finance, personnel, sales and marketing. In addition, Morrison also emphasised that 'quality' should not be confined to just design and production, but stretched out to every sector of company organisation.

Similarly, a large amount of work on user and supplier interaction in new product development has been conducted by Parkinson [1980, 1982 and 1984]. These studies provided some insights into the way in which product development and design work is carried out by machine tool manufacturers. For example, the research which was later published indicated that British manufacturers in the sample should make some fundamental changes [Parkinson, 1984]. Specifically, it was recommended that manufacturers should increase the extent and quality of their involvement with domestic customers at all stages in product development work, from origination of the idea through the evaluation of alternative designs, to the testing and evaluation of prototypes.

A previous study into the buying process of machine tools concluded that manufacturers tend to place less importance to product reliability than users of machine tools [Yong, 1981]. Although manufacturers regard reliability as being the most important factor in the final evaluation of the machine tool buying process, the average weighting given by manufacturers was lower than that given by the user. From a scale of 1 to 10, users on average placed a weighted value of 9.6 where as manufacturers placed a value of 7.9 (see Table 1.1).

Furthermore, two main reasons why reliability of the machine tool was a crucial factor in the buying process were cited by users. Firstly, because of the high capital cost of machine tools, it is essential that companies try and achieve a high machine utilisation. Breakdowns are, therefore, very expensive. Secondly, where the breakdowns occur in crucial machines in a line, it can effectively shut down production and cause bottlenecks in other parts of the factory.

1.4.1 The Link Between Maintenance and Machine Tool Reliability

Early UK academic analysis and research on the reliability of machine tools have mostly been confined and developed along the following three subject areas:

1. Correlation between maintenance procedures and downtime.
2. Reasons for machine tool breakdowns.
3. Evaluation of factors which influence the reliability of a machine tool.

The Machine Tool Industry Research Association (MTIRA), which now uses the name Advanced Manufacturing Technology Research Institute (AMTRI), conducted a series of surveys on machine tool breakdowns during the 1970's [De Barr, 1973; MTIRA, 1974; MTIRA, 1967; Stewart, 1975]. These surveys represented the first of several studies initiated within the UK on machine tool reliability. A pilot survey [MTIRA, 1967] of the reasons for machine tool breakdowns was conducted by MTIRA in 1966. This survey was mainly

Table 1.1: Weighting of Machine Tool Buying Factors

Factor	User	Manufacturer
Reliability of Machine	9.6	7.9
After Sales Service	8.1	6.8
Price	7.9	7
Reputation of Manufacturer	7.4	7.7
Reliability of Delivery	7.2	6.8
Length of Delivery	6.8	6.3
Previous Experience	6.3	7.6
Special Requirements	5.3	6
Availability Ex-stock	3.4	3.3
Credit	1.6	2.1

Source: [Yong, 1981]

intended to enable an estimate to be made of the feasibility and cost of a full survey. It was restricted to machine tools in the motor industry and was based mainly on data extracted from maintenance records which were often incomplete. However, the unpublished report on this survey probably contained the first data available on this important subject, in the UK.

In July 1973, MTIRA organised a discussion meeting on 'Reliability of Machine Tools,' which was attended by 150 manufacturers and users of machine tools [De Barr, 1973]. The meeting produced a good deal of useful information and confirmed the need for authoritative data on machine tool reliability. In this respect, the discussion raised the recognition for a feedback mechanism of information on reliability between users and manufacturers of machine tools to be achieved. During the discussion with machine tool manufacturers on the subject of reliability of their products which followed this meeting, a general picture emerged. Machine tool manufacturers highlighted that they have little factual information about the reliability of their products after the warranty period is completed. It appeared from the discussion that there is very little communication between machine tool manufacturers and users on this subject. Manufacturers were informed occasionally about major failures of a machine too but, in general, they did not possess factual evidence concerning the reliability of their products such as average downtime and component life time. This general dilemma is still applicable to machine tool manufacturers of today. Use of such data can help in designing more effective warranty and spares programme.

Following on this research theme conducted by De Barr, Stewart [1975] conducted a major survey of machine tool breakdowns. A total of 15 major users of machine tools participated in the survey. A summary of the key findings of this research is provided below:

- The average downtime recorded during the breakdown survey was 2% of the available production time, with an average repair time of 9 hours.

- Mechanical breakdowns involved more downtime than electrical breakdowns. The average downtime caused by mechanical failures was 80% of the total number of hours lost. The number of mechanical failures was 57% of total number of breakdowns.
- A correlation was found to exist between the expenditure on maintenance and the average downtime. No clear correlation between the downtime and the adopted maintenance scheme was discerned.
- Most downtime was the result of failures of the drive system or the hydraulic system. The components observed to cause the highest downtime were bearings, gears, locking devices, clutches and brakes. The electrical components responsible for the highest number of breakdowns were push buttons, switches and fuses.
- The most common reason for failure was wear of parts, the next common reasons being human error and dirt. The proportion of breakdowns for which no reason was given was high. It was approximately 23%.
- The mean time between failure of conventional machine tool products was estimated to be 500 hours.

Taking up this theme, McGoldrick and Kulluk [1986] presented some significant findings on reasons for machine tool breakdowns. This particular study substantiated some of the early findings conducted by the MTIRA. Furthermore, the study also predicted the UK national cost of downtime to be in the region of 2 billion pounds (1986 figure). The link between maintenance strategies and machine tool reliability was further studied by Bennett [1978, 1979; Bennett and Jenney, 1976, 1980]. This study which presented similar findings to that of Stewart, also evaluated the impact of various maintenance strategies (i.e. planned replacement, periodic inspection and repair on breakdown) on the operational reliability of machine tools. Statistical relationships, patterns and trends of failure which exist on machine tool products were also furthered.

From a regional perspective, a substantial amount of research has been undertaken in the former Soviet Union [e.g. Vasilev and Barabanov, 1987; Zenkin, 1984; Lukinski, 1985]. However, the vast majority of the work conducted is significantly theoretical and only a limited number of publications have any importance from an industrial application perspective. Vershinin and Sharin [1987] reported on a survey relating to the analysis of failure data on 60 computer numerical control (CNC) machine tools over a five year operating period. The primary objective of this long term survey was to determine the major causes of failure of CNC machine tools and their control units. Similarly, the proportion of downtime which could be ascribed to control unit failure was also evaluated. As with early UK surveys conducted on conventional machine tools, fundamental recommendations were made for improving the reliability of CNC machine tool products.

1.4.2 Reliability Analysis of Machine Tool Products

A number of studies on the failure patterns and probability distributions of various types of CNC machine tool products have been conducted using field failure data obtained from machine tool manufacturers. A recent reliability analysis study on CNC turning centres indicated that the Weibull and Lognormal distributions provide suitable vehicles for the analysis of the failure characteristics of CNC machines [Keller, Kamath and Perera, 1982]. While the Weibull distribution was best suited to modelling the reliability characteristics of machine tools, the Lognormal was found to provide the best fit to describe repair time distributions. Similarly, the availability of CNC machine tools studied was in the range of 82% to 85% and approximately two thirds of the total system downtime was due to non-active repair times.

More recently, studies on the failure distributions of 24 CNC machining centres have shown that the failure pattern fits the exponential distribution [Yazhou, 1992; Yazhou, Molin and Zhixin, 1995]. Using the Weibull graphical analysis procedure, failure data of 24 machining centres was plotted in the Weibull probability paper. For every plot, the value of the shape parameter were all near to 1. This indicated that this type of distribution fits the special case of the Weibull distribution - the exponential failure probability model. Given that machine tool products exhibited a constant failure rate, it was possible to calculate the mean time between failure (MTBF) using the simplest steady state equation:

$$\mathrm{MTBF} = \frac{1}{r}\sum_{i=1}^{n} t_i$$

where *r* is the sum of total of failure of all machining centres, *ti* is the actual running time of the *ith* machining centre during inspection and *n* is the number of tested machining centres.

1.4.3 Reliability: A Critical Characteristic of Machine Tools

In the increasing competitive sales environment for capital equipment reliability has become an essential characteristic. Moreover, as the level of capital investment in manufacturing technology steadily increases, it has become even more desirable that reliability is maximised in order that equipment is available for production within tighter schedules.

Manufacturing industries using machine tools either totally or partially as production units cannot easily afford the cost of production downtime on high investment plant due to unreliability [Bennett et al., 1980; Nagarajah, Thompson and McFarlane, 1992; Abdul-Nour, 1993]. Product failures due to inadequate design and development considerations, latent defects prior to delivery resulting from human shortcomings and, more importantly, improper use or maintenance will all result in an increase in failure rate as the machine tool is stressed in use. The resulting early life failures and long-term random failures are not only expensive in terms of parts and labour required for restoring the machine tool back into normal operation, but are even more expensive in terms of loss of production. The cost of failure is far greater where a number of machine tools are arranged as a flow-line and the breakdown of one machine causes several others to stop due to workpiece shortages.

From the suppliers viewpoint, poor machine tool reliability, particularly during the early phases of the products useful life, will contribute to reduced customer satisfaction. Also, where manufacturers operate warranty and guarantee clauses, the consequential costs of unreliability will be superimposed on the normal associated costs of meeting warranty claims.

1.4.4 Availability and Warranty Clauses

Reliability is an aspect of engineering uncertainty and machine tool manufactures and users are accustomed to anticipating failures during the course of a machine tool's useful economic life. This simple fact is normally covered by a manufacturer's or suppliers warranty so the user may expect a machine to be repaired if it fails during the warranty period. In general, machine tool buyers expect and receive a warranty which lasts between 12 and 24 months [Benchmark Research, 1994].

The market for machine tools within the manufacturing industry largely comprises of metal cutting and metal forming equipment. In almost every case, a machine tool product will represent a major feature of a manufacturing system. Therefore it is seen as a continuing capital commitment for most manufacturing organisations. More importantly, it will serve as a vital long term asset to the company. Return on investment is therefore critical to overall productivity and, consequently, companies will demand high levels of utilisation from these products. Utilisation is normally defined as the duration a machine tool is used compared with the duration for which it could be used. It is normally expressed in hours or as a percentage.

Given this level of reliability uncertainty and the high levels of utilisation demanded by users, the provision of an availability guarantee is seen as a potentially significant factor in the selection of a new machine tool. Availability is more widely known as 'uptime' in the machine tool industry

[Granger, 1992, 1993]. In the context of this thesis, availability is defined as the proportion of total production time that the machine tool will be available for use. Availability of a machine tool is therefore influenced by its reliability and maintainability. In a recent machine tool market survey [Benchmark, 1994], users expressed the need to have a 95% availability guarantee. However, the general consensus given by users was whether machine tool manufacturers were able to fully offer such guarantees.

1.5 Research Scope

It is proposed to focus this project on reliability management. The aim is to contribute to the small body of knowledge available in this subject area. This will be achieved by means of an empirical investigation of reliability management of machine tool technology. In comparison to quality management, contemporary literature and previous studies fall far short of exploring and defining what range of business activities are encompassed in the management of product reliability at an operational level. Although there have been numerous journal papers written on reliability management and improvement techniques, a single unifying conceptualisation has not yet been proposed that encompasses their complexity and diversity. Further no research has been conducted which links reliability to the wider management of the business. It is precisely in this area that manufacturing companies require support if good practice in reliability management is to be distinguished, identified and implemented. This research project will, where possible, take this into account.

The core of the project consists of a three year longitudinal investigation of the reliability management process using methods of 'action research' [Foster, 1972]. This provided an in-depth examination of engineering and operational problems as well as the solutions found in the practice. In an inductive process, action research starts with data, generating hypotheses and a theory from the ground up. Action research allows a researcher to mould his own frameworks and hypotheses without respondent bias. In order to test the assertions made

> 'the system of methods and principles used in a particular discipline.'
> 'the branch of philosophy concerned with the science of methods and procedures.'

A more useful definition of the word methodology is given by Avison and Fitzgerald [1988] in the area of information systems development and is particularly applicable to this piece of research:

> 'a methodology is a collection of procedures, techniques, tools and documentation aids which will help the system developers in their efforts to implement a new system.'

The approach avoids the difficulties to which other empirical studies and practical implementations have fallen prey, which is to attempt to decompose the reliability management process and adopt only those elements which seem directly relevant to machine tool reliability. It is proposed that a comprehensive methodology will both provide an integrated and contextual (holistic) tool for the management of product reliability, cutting across several functional areas of a company, rather than concentrating on any particular element of a manufacturing organisation.

Within the methodology we would expect to see how the various tools and techniques for assessing, analysing and improving product reliability could be incorporated at specific stages of the product life cycle. In effect, the resulting methodology would be the basis of both an audit methodology and a mechanism whereby manufacturing organisations can formulate and implement, or improve their reliability management process. Further, if the methodology is sufficiently generic, it could be the basis of transfer of good practice from one industrial sector to another.

1.7 Sectoral Considerations

At the outset it was evident that there were a considerable number of options for the general design of the research. The one which was finally chosen represented a compromise between the need to collect information which from the case study and the literature review, a survey was conducted. This provided a consistent and representative presentation of reliability management practices in the industry. The survey design employed questionnaires [Fink and Kosecoff, 1986] as the method of data collection. This method was seen to be the most appropriate and common means of collecting the required data.

The investigation was undertaken to provide a structured information base - data, analysis, insights and recommendations, of practical use for key decision makers in the machine tool industry. The conclusion of the research aims to assist machine tool manufacturers maximise the reliability and maintainability of their products concurrently with their design and development process. Also, due to the flexibility of the research approach taken, the synthesis of this thesis has potential application more generally within the manufacturing industry.

1.6 Project Thesis

In the broadest terms, this research is concerned with the generation and evaluation of methodologies and tools for appraising and improving the reliability of machine tool technology. The objective of the research is to integrate these methodologies and tools into one generic methodology for the improvement of machine tool reliability. Given its exploratory nature the research can be defined as follows:

> a qualitative and quantitative analysis of various aspects of the reliability management process, in order to use the findings in such a way as to develop a generic methodology for the improvement of machine tool reliability.

In this way the research project seeks to assist machine tool manufacturers maximise the reliability of their products simultaneously with the design and development process.

The definition of the word methodology according to the Collins English Dictionary is:

would be useful in a broadly based comparison of UK companies and the resources available.

From a sectoral perspective, previous research carried out has been designed around examining multi-industry or individual sectors of manufacturing industry. In particular, many studies have been conducted in the automotive and allied industries regarding methods of quality management [e.g. Lascelles and Dale, 1988]. The advantage of studying more than one industry clearly lies in the broader base of information from which generalisations can be drawn. It also allows:

- A comparison to be made between different industries.
- Understanding the extent to which specific factors (e.g. market conditions, customer pressure, legislation, safety) influence a industry's approach to managing product reliability.
- Identification of reliability methods that are unique to a particular industry.

Similarly, a study between the UK and more than one overseas competitor will allow comparative views to be drawn from the study. For example, recent studies on 'total quality control' have repeatedly stated the uniqueness of the Japanese manufacturing industries in their approach to reliability improvement compared with Western companies [see Dale and Tidd, 1991; Dale, 1993].

Therefore, there would have been many potential attractions in a multi-country, multi-industry approach to the problem. However, with such an approach it proves extremely difficult to collate a detailed account of the subject of concern. Given the exploratory nature of this investigation, the approach was limited to one country, one industry study. This allowed a detailed analysis and evaluation of reliability practices, enabling more robust and applicable guidelines and tools to be generated for reliability improvement. Further, it enabled a greater examination and closer observation of the practice.

It is also important to highlight that the dis-similarity between industrial sectors and the difference in the characteristics of products and technological change means that the challenges for reliability management obviously differ between sectors. Taking this into consideration, the development of a generic methodology from a multi-industry perspective would be so general as to be of little value in application.

1.7.1 Key Factors Influencing Choice of Industry

One of the main factors which influenced the choice of the industrial sector was the collaboration with and sponsorship by Cincinnati Milacron. Cincinnati Milacron (CM) initially proposed a project, structured in specific terms and which entailed defining and measuring the reliability of their machine tool products. The scope of the CM project was defined by the company and is elaborated as follows:

1. Define a mechanism for measuring the reliability of CM's range of machine tool products.
2. Measure and evaluate the reliability of CM's current range of machine tool products at system, unit and where feasible component level.
3. Develop a method for continuously monitoring and evaluating field reliability performance of future machine tool products.

From this point, the framework of the research and overall project proposition was developed and determined by the author.

Industrial collaboration with CM also allowed the opportunity to conduct a three year longitudinal case study of reliability management. The co-operation of CM in this matter also eliminated some of the fundamental drawbacks associated with case study research [Gill and Johnson, 1991]. For example, the problem of the time needed to set up and administer a longitudinal study, both in securing the initial co-operation of managers and in making the necessary observations was eliminated. Furthermore, the researcher being physically present at CM eased the collection of data and allowed the processes of reliability management to be observed over time.

It is important to highlight that the author was not compelled to the machine tool industry as the test base for the research. Other factors entered the equation. The industry itself has a strategically important position in the national economy, since its products are used by virtually the whole manufacturing industry. A strong and progressive domestic industry is clearly important to the well-being of the whole economy. However, a pattern of decline in terms of reducing share of the international market for its products has been experienced by the UK industry. Retrospectively, the industry has also experienced a prior history of gradually reducing product quality, in terms of being increasingly less able to supply products suited to customer needs than its overseas competitors, for example Japan and German manufacturers [Parkinson, 1984].

From a product-specific perspective, the sector was chosen on the following established criterion:

- Reliability being a significant characteristic of machine tool technology. This applies to manufacturers and users alike. From a manufacturers perspective reliability can be used as a means of increasing sales revenue. Increases in warranty costs which are significantly above the allocated budget will compel manufacturers to improve the reliability of their machine tool products. With maintenance accounting for an increasing share of operational costs, users require higher availability and reliability from machinery and equipment.
- Secondly, compared with other industrial sectors, for example the automotive and motor industry, little research has been carried out on the function of reliability management of machine tool technology.

1.8 Design of the Study

The overall research methodology was designed around the many frameworks available for conducting research [e.g. Howard and Sharp, 1983]. Taking the CM project brief as a starting point, a framework was created which defined the boundaries of the research. A decision was made to adhere to an integrated approach to the research, where consideration was given to design, manufacture, supplier quality and service aspects of reliability management.

The process of developing the overall thesis of the research involved undertaking an in-depth literature review to help identify the gaps in the current body of knowledge. Discussions were also held with academic and industrial practitioners. The review of the technical literature and discussions resulted in the formulation of several hypotheses. At this point, the overall objective of the research (detailed in section 1.3 of this chapter) was also determined.

More importantly, the development of the thesis provided a substantial opportunity for making an original and useful contribution to the body of knowledge in the field of reliability engineering and management. Further, the research would benefit manufacturing organisations from the following points of view:

- Reliability being a major concern of most manufacturing organisations who produce products of high volume and high technological content [Benchmark, 1994].
- The importance of reliability as one of the key determinants of competitiveness and productivity improvement [DTI, 1982].

Following the detailed development of the research inquiry, it was recognised that the approach to the project would involve the use of a range of different research methods. A decisions was taken to adopt a combination of a longitudinal approach employing ethnographic and action type research techniques as typified by Gill and Johnson [1991] and administering of a comprehensive postal questionnaire [Fink et al., 1986]. The longitudinal approach was made possible through the researcher being physically present at all events that were of interest in recording and observing (some may take place at the same time in different places). The administering of the postal questionnaire provided the basis for broadly based generalisations to be made about the process of reliability management of machine tools. The philosophical basis for these methodical choices are detailed in relevant sections of the thesis.

1.8.1 Structure of the Research Report

This thesis has been structured largely along the same lines as the investigation on which it is reporting. To provide clarity of the overall research objective, the production of the thesis was carried out in three phases:

- In the first phase the *Conceptual Framework of Reliability Management and Technical Guidelines* (Part I) were established.
- In the second phase a series of empirical investigations (longitudinal studies and nation-wide survey) into reliability management of machine tool technology was carried out. This lead to the production of the second part of the thesis entitled *Reliability Management of Machine Tool Technology: Operation, Problems and Issues for Firms.*
- In the third phase the results of the empirical investigations were synthesised into a coherent information base for decision makers. This lead to the production of the third part of the thesis entitled *Design, Evaluation and Implementation of Reliability Monitoring, Feedback and Improvement Systems.* Using this information base, a generic methodology for product reliability improvement was developed and presented. This methodology was devised with reference to the reliability of machine tool products.

Further to the above points, Part I (Chapters 1, 2, 3 4, 5 and 6) provides a review of the relevant literature (found predominantly in Chapters 1, 2 and 4).

A critical evaluation of the current state of the art with regard to reliability management was undertaken to establish the framework for this research inquiry. In this context, it also provides an overview of the various activities that are considered part of reliability management, and discusses the various mechanisms by which these activities are carried out. Chapter 3 discusses historical and recent developments of the UK Machine Tool Industry. Chapter 5 details the research questions and hypotheses and briefly describes the statistical methods for testing these hypotheses. In ending Part I of the thesis, chapter 6 provides a discussion on the two main methodologies (descriptive survey and action research techniques) used in this research, together with the response rate of the survey.

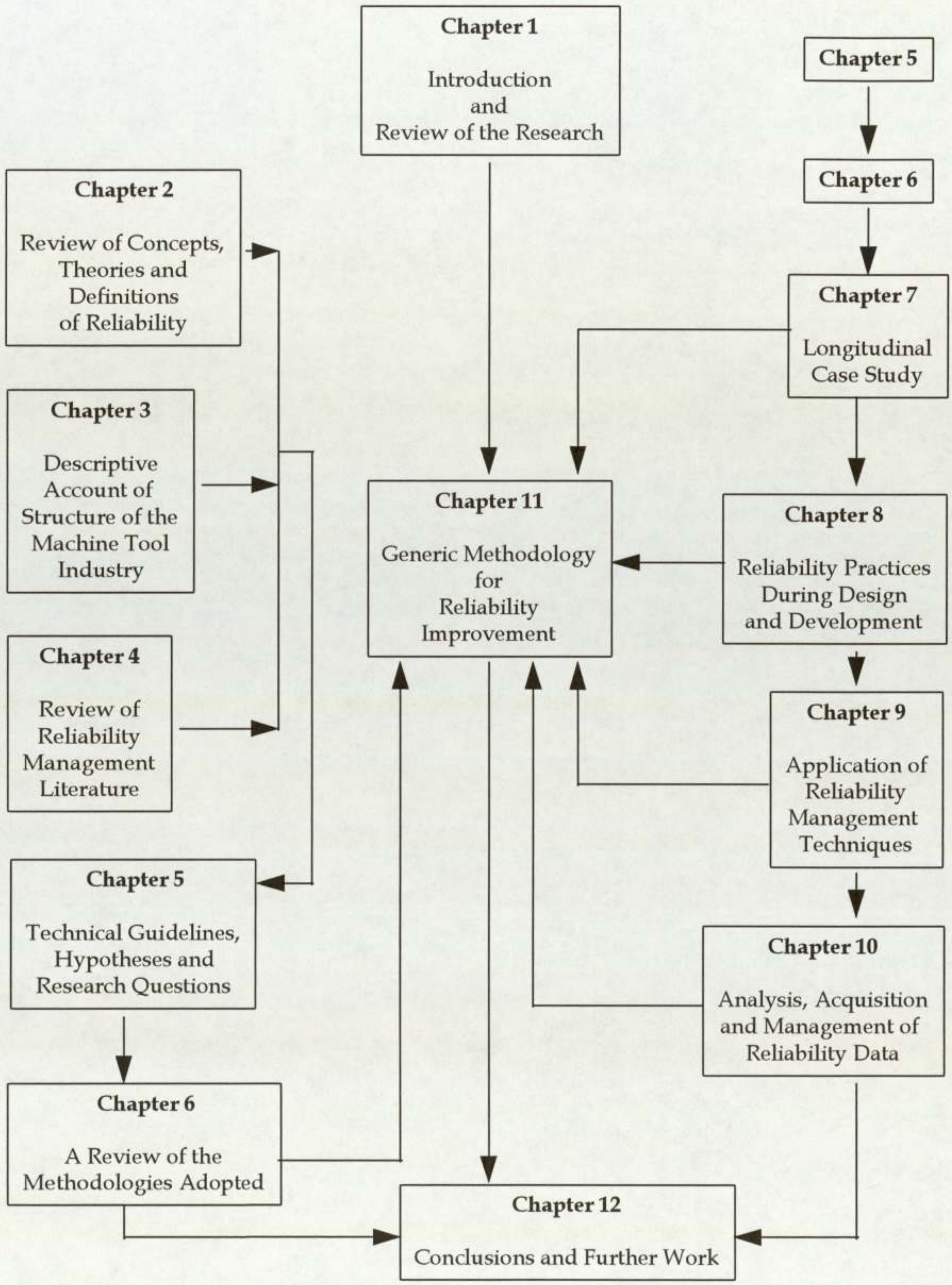
Part II (chapters 7 , 8, 9 and 10) provides detailed findings obtained from the survey and the longitudinal case study of CM. Specifically, chapter 7 provides a descriptive and qualitative overview of the longitudinal case study. In contrast to chapter 7, the other three chapters (8, 9 and 10) reports on the results of the survey. The analysis of the survey results is carried out in relation to the hypotheses and research questions formulated in chapter 6. It also provides a quantitative account on the problems, practice and operation of reliability management. This investigation yielded an interesting dilemma. Although machine tool manufacturers recognise the importance of reliability as a potential sales tool, it was not reflected in their reliability management processes. Further, the detailed analysis of the survey data concluded that no formal approach was taken in appraising and improving the reliability of machine tools during the design and development process. Virtually, no use was made of relevant reliability tools and techniques to aid in the process of assessing reliability during this process. Little use was made of field failure and spares usage data to effect design improvements. Only a few manufactures were compelled to measure reliability on a continuous basis and use such data to monitor reliability performance improvements. The definitions and descriptions given in these chapters reflect the enriched understanding of the problems and methods of reliability management of machine tool technology.

Part III (Chapters 11 and 12) presents a synthesis of the results and conclusions reported in Part II. It also focuses on the development of the generic methodology for reliability improvement of machine tools. In developing this methodology (detailed in chapter 11) , the problems and pitfalls of reliability management in the machine tool industry was taken into account (detailed in Part II). Given the nature of the research and resources available, it was not possible to fully test out the proposed methodology. Instead, a number of 'quasi-experiments were undertaken (laboratory and field type) on key aspects of the proposed methodology to demonstrate the feasibility of application. These experiments were not 'classical' tests involving the use of experimental or control groups, but provided a basis for supporting the application of the proposed methodology. The degree to which the research proposition has been supported is also discussed and recommendations for future work put forward (chapter 12).

During the course of the project, consultations were carried out with research institutions and organisations representing the machine tool industry, namely the Machine Tool Technologies Association (MTTA) and the Advanced Technology Research Institution (AMTRI). This enabled the author to take account the experience and views on the problems of reliability management faced by machine tool companies.

Figure 1.1 provides a visual overview of the structure of this thesis.

Figure 1.1: Structure of Thesis



1.9 Defining Reliability Management

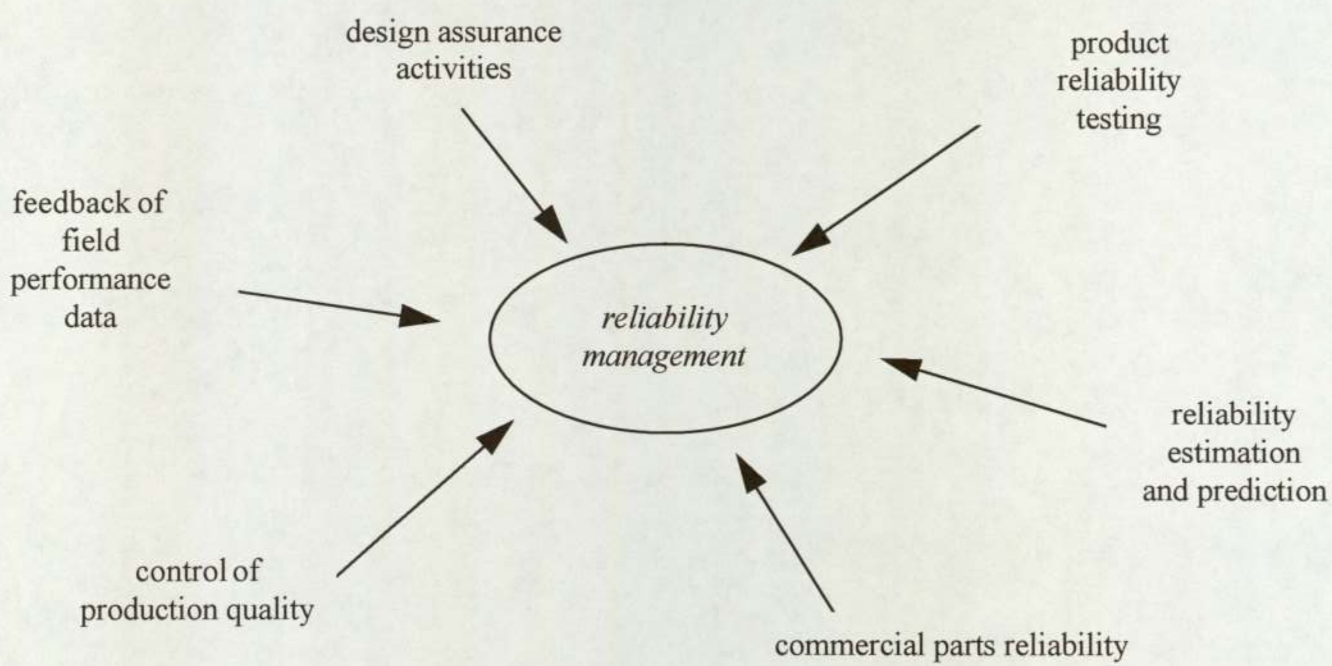
The aim of this section is to define reliability management from the context of this thesis. Given the diversity of the subject area portrayed in the relevant literature, it is important to highlight the various aspects of reliability management which will be investigated in this thesis. In this context, it defines the various aspects of an organisation's business activities that is considered to be part of reliability management.

The aim of reliability management is to sustain and improve the reliability of a manufactured product by the use of reliability assurance and control principles. This obviously covers more than the relatively well-known function of testing, obtaining quantitative measures or the application of tools and techniques. Reliability management is not so much a separate entity, but forms an essential part of these tasks. Among these things, it is also concerned with design assurance activities, use of field performance and production data to effect improvements and monitoring the reliability of commercial bought-in parts. Figure 1.2 highlights the key routines of reliability management.

A broad definition of reliability management is adopted for this project. Essentially, it encompasses those aspects of management associated with (I) supplier reliability and development, (II) design engineering and analysis, (III) product testing, (IV) effective control of manufacturing processes and (V) the statistical and technical analysis of field and warranty issues. For practical purposes, regular use will be made of the shorter expression "reliability management" to refer to these activities and processes throughout this thesis.

Reliability management therefore lies at the interface of three key engineering management areas within the firm; product engineering and design, manufacturing, and the service and support function. With reference to machine tools, a wide variety of engineering activities will form part of the reliability management process. These may include [SAE and NCMS, 1993]:

Figure 1.2: Key Routines of Reliability Management



- Measuring and monitoring reliability performance through the deployment of analytical and predictive methods.
- Analysis, evaluation and planning of reliability goals and priorities.
- Optimising the inherent reliability through feedback of field failure data.
- Effective control and management of engineering changes.
- Tracking of defective parts for technical analysis and corrective action.
- Engineering analysis of product design through design assurance techniques.
- Reduction of warranty costs.
- Design reviews from the perspective of reliability assessment and evaluation.

1.9.1 Capacity for Reliability Management

In its conceptualisation of the capacity for reliability management, the project has taken as its starting point recent contributions to reliability management theory. In particular, emphasis was placed on the concept and issues concerning the collection and analysis of field data and relevant analytical techniques concerning 'design for manufacture or reliability.' In line with the above adopted definition, the project distinguishes three key practices that together make up the capacity for reliability management of manufacturing organisation:

1. *Use of Reliability-related Data:* Collection, analysis and feedback of performance data (external and internal) as a mechanism for improving product reliability.
2. *Design Assurance Activities:* Appraisal of product reliability during the early phases of the product introduction process to reduce the likelihood of

downstream failures. Supplier selection and assessment also forms a critical part of this process.

3. *Tools and Techniques:* Mastering and making productive use of reliability methods which are of relevance to the process of reliability improvement.

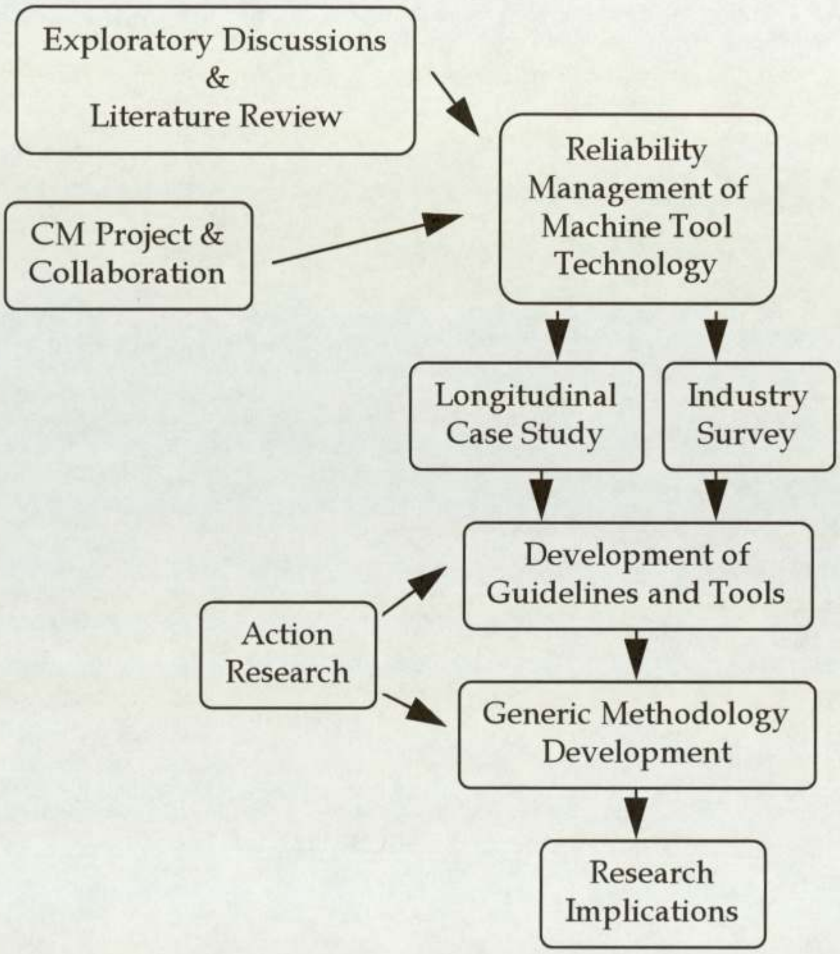
The empirical investigation will be concerned with exploring, and where possible measuring these key practices. Obviously, the three practices are interrelated, so beyond the collection of data concerning these components, the project will investigate these inter-relationships and the levels of cohesion between them.

1.10 Summary of Research Considerations

The overall research methodology is illustrated in Figure 1.3. The main objective is to conduct an analysis and evaluation of the reliability management process in the machine tool industry. Particular focus will be given to the design, supplier quality and field (service) aspects of reliability management. In doing so, this should result in a consistent and representative presentation of reliability management practices in the industry, the problems experienced as well as the solutions found. The core of the project consists of the following empirical investigations:

- A longitudinal case study of reliability management of machine tool technology, using methods of ethnographic and action type research methods. Collaboration with Cincinnati Milacron eased the overall management of the study.
- A detailed survey of reliability management in UK machine tool industry. Comprehensive questionnaires were designed for the purposes of conducting the survey.

Figure 1.3: Overview of Research



Given the lack of comprehensive and pragmatic methodologies which link reliability management to the wider management of the business, a generic methodology for improving the reliability of machine tool products is proposed. The methodology seeks to provide the basis for the operations and engineering management of product reliability.

The findings of the above empirical investigations forms the input to the development of the methodology. It is proposed that the generic methodology would be the basis of both an audit methodology and a mechanism whereby companies can improve their reliability management process.

From a sectoral perspective, the following criterion greatly influenced the selection:

- Collaboration with CM.
- Reliability being a significant characteristic of a machine tool.
- Little contemporary research based literature available relating to any aspect of machine tool reliability.
- Compared to other industrial sectors, little research has been conducted on the reliability management function in the machine tool industry.
- Strategic importance of the industry to the UK economy.

A single sectoral and product specific study was established to provide a deeper understanding of the characteristics and problems, than would be possible through a multi-industry, multi-product specific study.

Finally, this research project explicitly excluded the software reliability aspects of machine tool products for two reasons. First, CM was only interested in studying the mechanical & electrical aspects of machine tool reliability. More importantly, reliability of software is a specialist field and needs to be studied separately.

2. An Introduction to Reliability Theory and Concepts

2.1 Introduction

The purpose of this chapter is to provide an overview of the basic concepts and definitions of reliability. In addition to this, a brief is also given on the practical benefits of reliability from the perspective of machinery and equipment. The chapter concludes by providing a critique on the development of specific international and national reliability standards and their implications.

2.2 What is Product Reliability

Reliability, like quality has always been considered important. Improving the reliability of a product forms an important part of the larger picture of improving product quality. Condra [1993] emphasises that 'reliability is quality over time.' Therefore, reliability is a time-based concept of product quality and is concerned with the performance of a products' function over a stated period of time, under stated operating conditions. Whereas quality is defined always as conformance to requirements, reliability on the other hand is defined as a failure-free performance in all products provided to the customer. In reliability there are strong parallels or generalisations of important quality concepts such as process capability and control of production quality.

The reliability of a product is primarily dependent upon the design, development and manufacturing approaches which are employed within an engineering based organisation, and secondly upon the improvement of all aspects of the integrated business operation [see O'Connor, 1991, Brown, Hale and Parnaby, 1989; Hamada, 1993]. Therefore, reliability requires a sound management approach for the organisation as a whole. Improvements in reliability relies upon an organisational system which considers the dynamics of business interaction. However, reliability also goes one step further by its dependence on engineering details as a primary concern.

Hence, reliability deals with such technical issues as design methods, the physics of failure, supplier parts reliability, control of production quality and manufacturing processes (which also come within the boundaries of product quality), development testing, failure modes, causes and its effects and failure data analysis. In conclusion, the achievement and improvement of product reliability is primarily dependent on the following [Ahmed, 1996]:

- The approach taken during the design and manufacturing phase of the overall product introduction process. Considering nominal engineering activities from a reliability engineering perspective is significant to the achievement of product reliability to a satisfactory level.
- Improvement of all aspects of the concurrent engineering philosophy. With its implied concepts of 'fast to market' and streamlining of the product introduction process, reliability alongside other product characteristics must be considered and assessed up-front in the design and development cycle in order to reduce the likelihood of downstream failures.
- The level (i.e. the status and structure of the reliability function) at which reliability is considered within the hierarchical organisation domain. This will give an indication of a company's level of commitment to product reliability and the level of understanding of both the impacts of reliability and the basic concepts of reliability engineering, assurance and management.
- Intensity of the application of structured reliability tools and techniques. As reliability is regarded as an engineering uncertainty, the overall objective is to characterise this uncertainty so that it leads to an improvement in product reliability. The overall objective of these methods is to aid in the understanding and characterisation of this uncertainty.

- Depth at which retrospective reliability analysis is conducted through the utilisation of historical failure data. With due regard to this approach, it is particularly beneficial when a proposed redesign of a product is going to contain as many design features as the previous model. Reliability data analysis will not only predict a quantified measure of reliability but will also identify inhibitors to poor reliability performance for subsequent design improvement.

2.2.1 Conceptual Differences

The term reliability is not well understood, despite the fact that it has a far less ambiguous definition than does the term 'quality.' It is often confused with, or intermingled with the concept of quality.

Similar to quality, many attempts have been made to give a precise definition of the reliability concept [e.g. Brewer, 1970; Gilmore, 1964; Polovke, 1968]. Different authors and organisations have their own individual definitions. As reliability is such a multi-functional concept, nearly all of them add something to our understanding of reliability. For example, Gilmore [1964] defines reliability as being a parameter of a product or system:

> 'that product parameter that describes the probability that a device will perform its intended function under the conditions of which it was designed, for a specific period of time.'

The classical definition of reliability is 'the ability of an item to perform a required function under stated conditions for a stated period of time' [BS 4778, 1987], or as stated in US Military Standard 785 [1988] 'the duration or probability of failure-free performance under stated conditions.' An expansion of these definitions of reliability leads to a qualitative and quantitative expression:

- Qualitatively, absence of functional failure during use or service.

- Quantitatively, the probability that an item will give failure-free performance of its intended functions for the required duration of time.

These definitions have been widely accepted as a standard by both industrialists and academics working in the reliability engineering and management arena. A broader definition is given by Keller [1987] with the emphasis that the term *'guarantees fulfilment'* should be used in a probabilistic context.

> 'reliability is that property of a component or a system that guarantees fulfilment of the required task in the required time under given use conditions.'

Less formally, the Society of Automotive Engineers [1993] define reliability which is particularly applicable to manufacturing machinery and equipment:

> 'reliability is the probability that machinery/equipment can perform continuously, without failure, for a specified interval of time when operating under stated conditions. Increased reliability implies less failure of the machinery and consequently less downtime and loss of production.'

In analysing the above definitions, several conclusions can be drawn. The concept of reliability is developed along the lines of probability. The required task or function the item is designed to carry out indicates that reliability is a performance characteristic and time is a significant variable.

Reliability is, then, generally concerned with failures during the life of a product. Although there are numerous causes of failure, in general terms a common cause of failure results from the situation when the applied load exceeds the strength. This is easy to appreciate for most mechanical products, but it can be taken as a fundamental principle for all engineered products. For example, a transistor will fail if the current through it exceeds its ability to conduct without overheating to the point of failure of the substrate or of a wire bond. A bearing may seize if it has degraded to the point that the load causes local break-down of the lubricating film. Reliability is therefore an aspect of engineering uncertainty. Whether a product works for a particular period of time is a question which can be answered through the principles of probability and engineering judgement.

2.2.2 Mathematical Theory

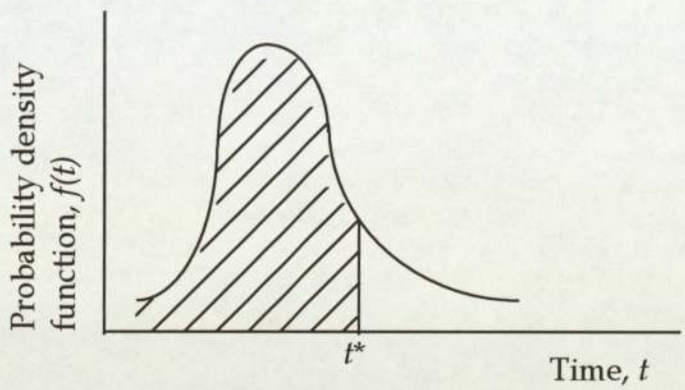
Although the mathematical aspects of reliability are well developed in the literature, it is the intention here to keep to simple concepts, lifetime distributions and notation which are sufficient in the context of this thesis.

The measure of reliability of an individual component is its 'lifetime'. This is the time elapsed between its start of life and the time at which it fails. It is denoted by the symbol t. The variable, 'time,' does not necessarily imply the passage of 'clock time.' It represents any suitable measure of component usage and is a matter of engineering judgement to choose the right one. The symbol t may, quite often, represent a straight forward elapsed time in hours. Alternatively it could represent the operating time of a machine which excludes any downtime and logistics delay, or the number of cycles before a failure. There are no absolutes in terms of selecting the right or wrong time variable for a particular product, as any sensible choices will be closely correlated. However, the use of the variable that most closely corresponds to the failure mechanism minimises the uncertainty in the reliability parameter estimation.

The value of t at which failure occurs is unknown in advance. It is a random variable that necessitates a probabilistic rather than a deterministic approach. The key to the modelling of the 'lifetimes' of a series of components of the same type is the concept of the 'lifetime probability distribution' [Lawless, 1982], as shown in Figure 2.1.

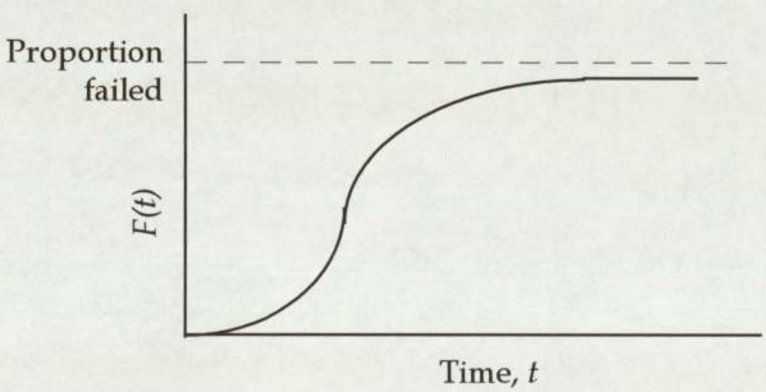
Without, ascribing any particular shape to this distribution, $f(t)$ is defined as the Probability Density Function and often referred to as the 'pdf.' The total area under the curve is equal to 1. This area is referred to as the Distribution Function denoted by $F(t)$. At any value t, the probability that the component has failed at or before this time is the area under the curve to the left. For example, the probability that the component has failed at t^* is equal to the area under the curve, shown shaded in Figure 2.1.

Figure 2.1: Lifetime Probability Distribution



The graph of the distribution function, *F(t)*, against *t* depends on the shape of the probability distribution (probability density function), but will be of the general form shown in Figure 2.2.

Figure 2.2: Distribution Function



There are three other related functions that are useful in describing component reliability and are as follows:

1. Reliability Function - *R(t)*
2. Hazard Rate Function - *z(t)*
3. Cumulative Hazard - *H(t)*

(1) Reliability Function: This is the probability that a component has survived to time t. It is simply the complement of the distribution function. It is important to highlight that $R(t)$ is the area under the curve to the right of t^*. Mathematically speaking, the reliability function is represented by the following formula:

$$R(t) = 1 - F(t)$$

(2) Hazard Rate Function: A fundamental concept in reliability engineering is the Hazard Rate Function, $z(t)$. Other terms used for this function are:

- Force of mortality.
- Age specific failure rate.
- Instantaneous failure rate.
- Conditional failure rate.
- Hazard function.

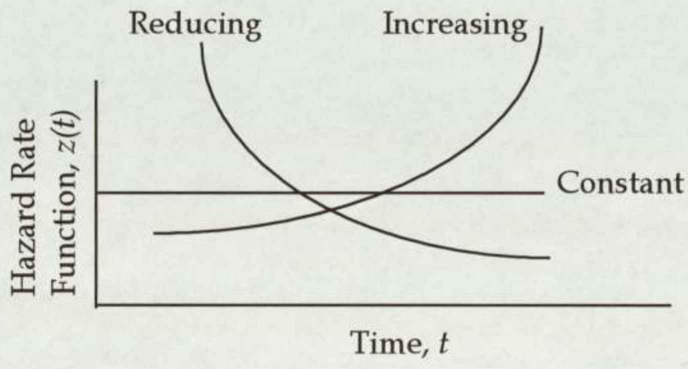
These are often incorrectly referred to as the 'Failure Rate' in reliability literature. It is essential to recognise the difference between the hazard rate function and the failure rate as they will, except in special cases, have different numerical values. This can cause great confusion in solving engineering problems. The term hazard rate function is used to describe the behaviour of non-repairable components which form part of a system. The term failure rate implicitly assumes that the time to failure distribution is exponential and is used to describe the behaviour of repairable systems.

The hazard rate function, then is a measure of the probability that a component will fail in the next time interval, given that it has survived up to the beginning of that time interval (that is, probability per unit time). In terms of Figure 2.1, it is the ordinate value $f(t)$ at t, divided by the area to the right of t, for any value of t. Mathematically, it is expressed by the formula:

$$z(t) = f(t) / R(t)$$

Figure 2.3 illustrates typical behaviour curves of the hazard rate function. For some components, the hazard rate function may assume a more or less constant value. In other words, the likelihood of a failure is independent of the age of the component. This is often true in the case of electronic components where failures are due to random causes unrelated to component age. Constant hazard is widely assumed when it is not appropriate as it has the attraction of being mathematically much simpler than alternatives. A constant hazard rate is characteristic of failures which are caused by the application of loads in excess of the design strength, at a constant average rate. For example, overstress failures due to accidental or transient circuit overload, or maintenance-induced failures of mechanical equipment, typically occur randomly and at a generally constant rate.

Figure 2.3: Typical Behaviour Curves for the Hazard Function

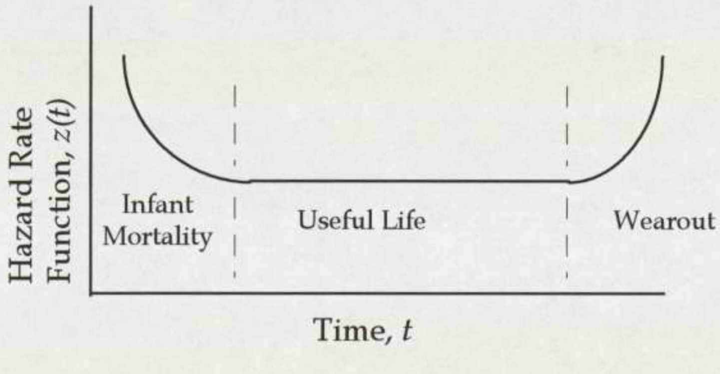


Some components may exhibit an increasing hazard rate. This is where the component is more likely to fail as it gets older. This will occur in any situation where use of the product degrades it. Examples of the increasing hazard function are corrosion, wear and fatigue. For example, material fatigue brought about by strength deterioration due to cyclic loading is a failure mode which does not occur for a finite time, and then exhibits an increasing probability of occurrence. As the increasing hazard rate applies to many engineering components it suggests that the assumption of constant hazard is, in many circumstances, at least questionable.

Circumstances also occur where a component is less likely to fail as the survival time increases. This is known as the reducing hazard rate. A common manifestation of this is the component that is initially highly stressed due to misalignment and the stress is reduced as the component 'beds-in.' Decreasing hazard rate is often observed in electronic equipment and parts. 'Burn-in' of electronic parts is a good example of the way in which knowledge of a decreasing hazard rate is used to generate an improvement in reliability. The parts are operated under failure-provoking stress conditions for a time before delivery. As substandard parts fail and are rejected the hazard rate decreases and the surviving population is more reliable.

A common reason for introducing the hazard rate function concept is that it is commonly assumed to exhibit the profile shown in Figure 2.4, which is known as the 'Bath-tub Curve [Carter, 1974]. Figure 2.4 shows the combined effect of an initial decreasing hazard rate or infant mortality period, an intermediate useful life period (constant hazard rate) and a final wearout period (decreasing hazard rate).

Figure 2.4: The 'Bath-tub' Curve



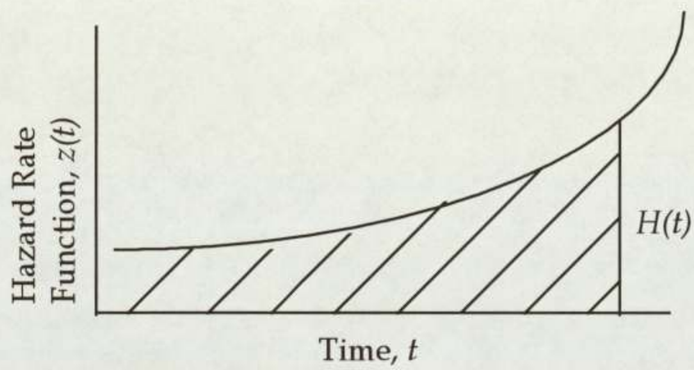
(3) Cumulative Hazard H(t): A further related conceptual function that does not have any obvious intuitive practical meaning but which will also be found useful in plotting methods for data analysis is that of Cumulative Hazard Function curve. Figure 2.5 details the cumulative hazard function (CHF). It is equal to the area under the hazard rate function, $z(t)$, curve.

As the CHF is an integral part of the hazard function *z(t)*, over the time period to *t*, it is no longer a rate and it can be shown that it is, in fact, simply related to the Distribution Function, *F(t)*, by:

$$H(t) = \log_e \left\{ \frac{1}{1 - f(t)} \right\} \text{ from which}$$

$$F(t) = 1 - e^{-H(t)}$$

Figure 2.5: Relationship Between Cumulative Hazard and Hazard Rate Functions



So far, no particular shape has been assigned to the lifetime distribution. Whilst data analysis is possible without assigning a lifetime distribution, it is usual practice to assign some specific function to f(t), thereby constraining it to a particular shape or family of shapes. Some well known functions used in reliability data analysis include the exponential distribution which describes the constant hazard case, the normal and log-normal, restricted to increasing hazard and the Weibull distribution used ascertain whether the hazard rate is constant, increasing to decreasing.

An exponential distribution was assumed in much of the early statistical literature on the analysis of product life data [e.g. Davis, 1952; Epstein and Sobel, 1954]. This implies a constant hazard rate throughout the life of the product and is reasonable when failure is due to some extraneous effect independent of product age. The exponential distribution also describes the perceived life of a product whose true hazard rate is a bath-tub curve but whose in-use hazard rate is approximately constant due to burn-in prior to shipment and replacement before wearout, leaving only the approximately constant middle of the bath-tub curve. The times between failures for a series system with many components that are replaced upon failure and which has reached equilibrium can also be represented by the exponential distribution [see Drenick, 1960].

It was soon realised that the above conditions were exceptions rather than the rule. The exponential distribution, through mathematically convenient, is not a correct model for time to failure for most products. Wrong conclusions are likely to be obtained by incorrectly assuming this distribution [see Zelen and Dannemiller, 1961]. The Weibull, lognormal, extreme value, gamma and other distributions are now being used extensively instead [see, for example, Hahn and Shapiro, 1967; Mann, Schafer and Singpurwalla, 1974; Barlow and Proschan, 1975; Gross and Clark, 1975; Nelson, 1982]. The justification for these distributions is both theoretical and empirical [Hahn and Shapiro, 1967; Nelson, 1982].

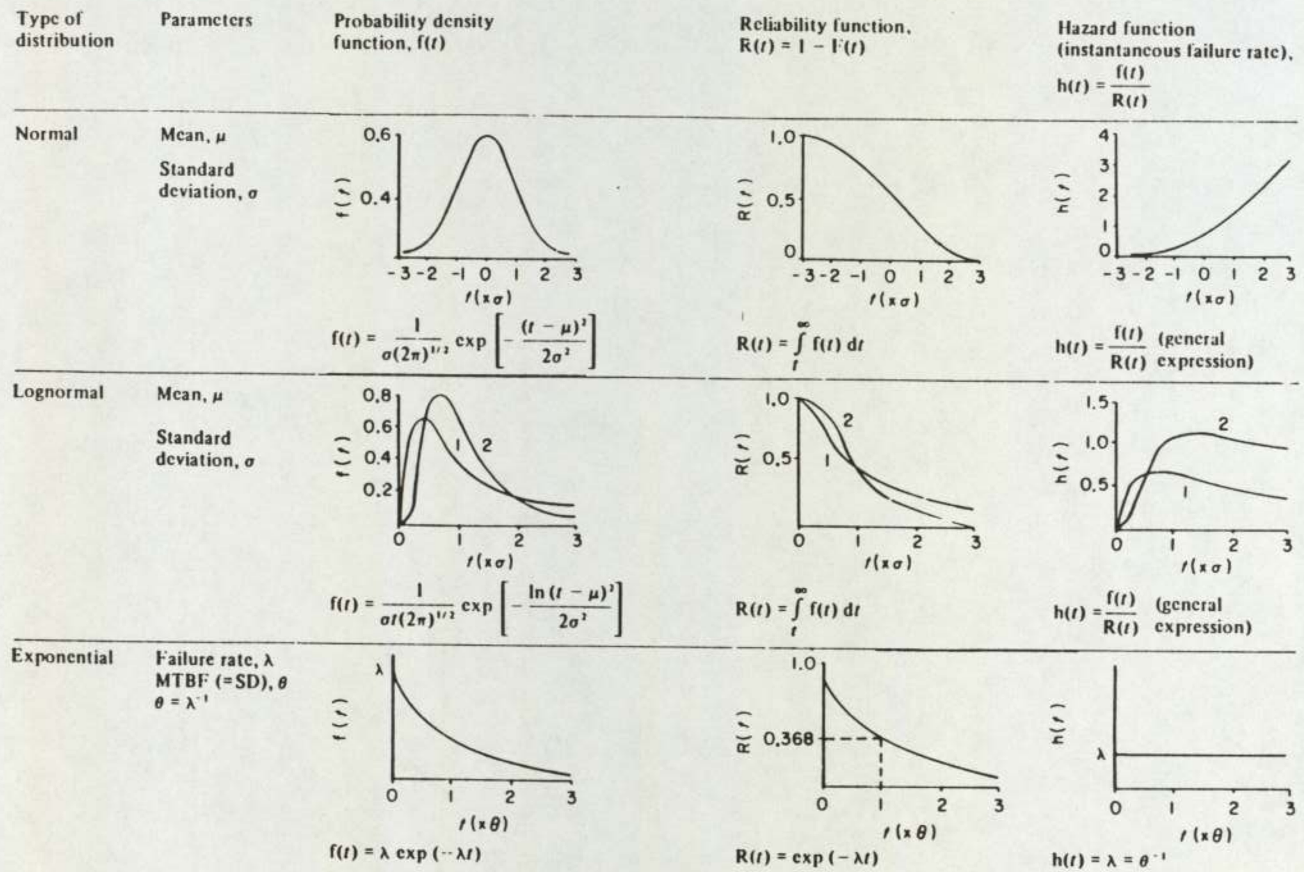
The Weibull distribution appears to be the most frequently used model for time to failure, followed perhaps by the lognormal distribution. The use of the Weibull distribution as a time to failure model arises from (1) its theoretical justification as one of three asymptotic extreme value distributions, (2) its ability to represent data with a decreasing, increasing or a constant hazard rate and (3) the fact that it has been found to fit the times to failure distribution of various types of products reasonably well [Hahn and Shapiro, 1967].

In relation to time, *t*, Figure 2.6 shows the shapes of common failure distributions, reliability and hazard rate functions.

2.2.3 Life Cycle Cost and Practical Benefits

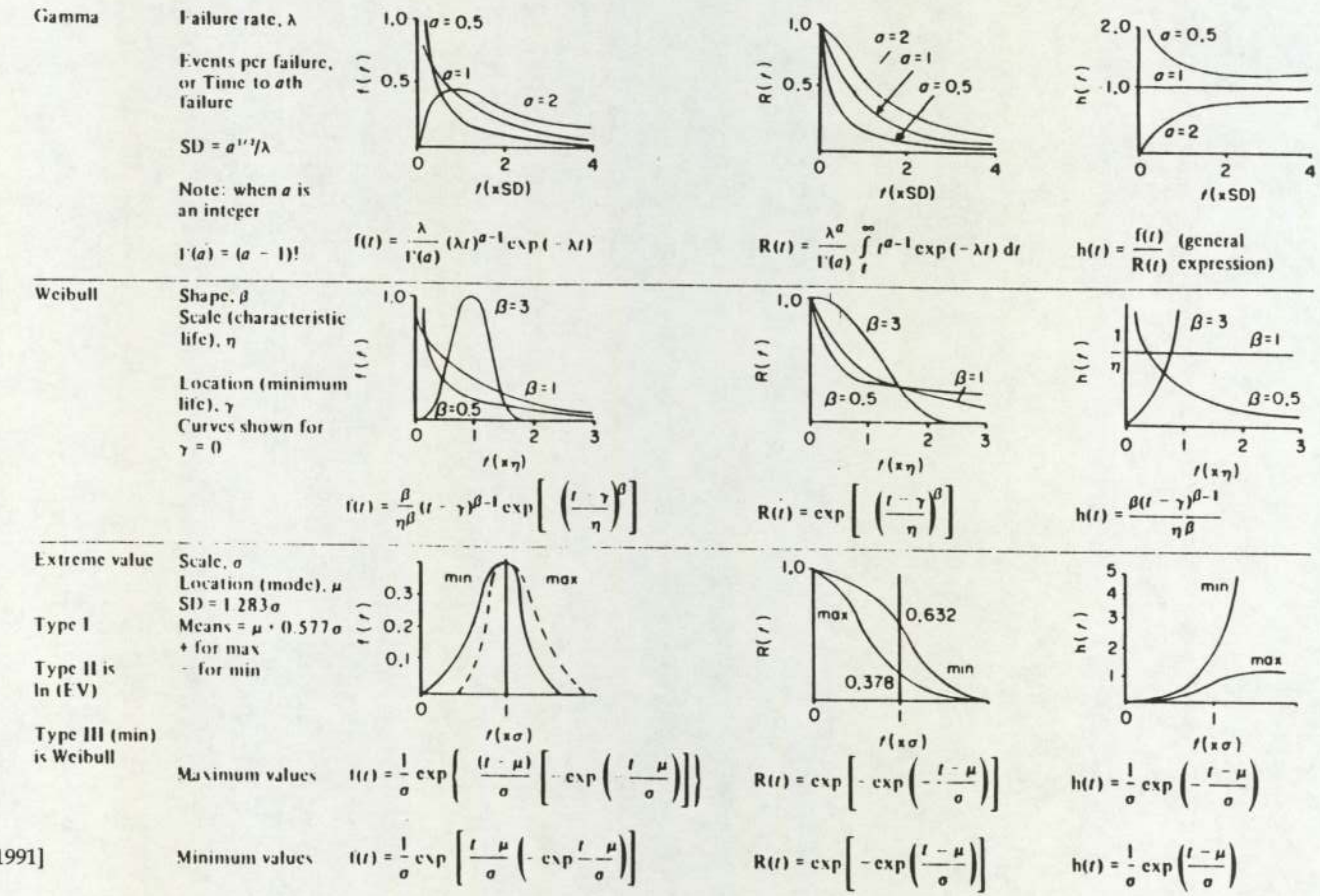
The inherent reliability of a product has a strong bearing on the overall life cycle cost (LCC). This is of particular significance to machinery and equipment. Essentially, improved reliability will lead to lower life cycle costs.

Figure 2.6: Shapes of Common Failure Distributions, Reliability and Hazard Rate Functions



Source: [O'Connor, 1991]

Figure 2.6: Shapes of Common Failure Distributions, Reliability and Hazard Rate Functions



Source: [O'Connor, 1991]

LCC refers to the total cost of a product from concept to disposal or decommission and includes both non-recurring plus operation and support costs [Omdahl, 1988]. With reference to machine tool products, the literature distinguishes two types of life cycle costs [SAE and NCMS, 1993]:

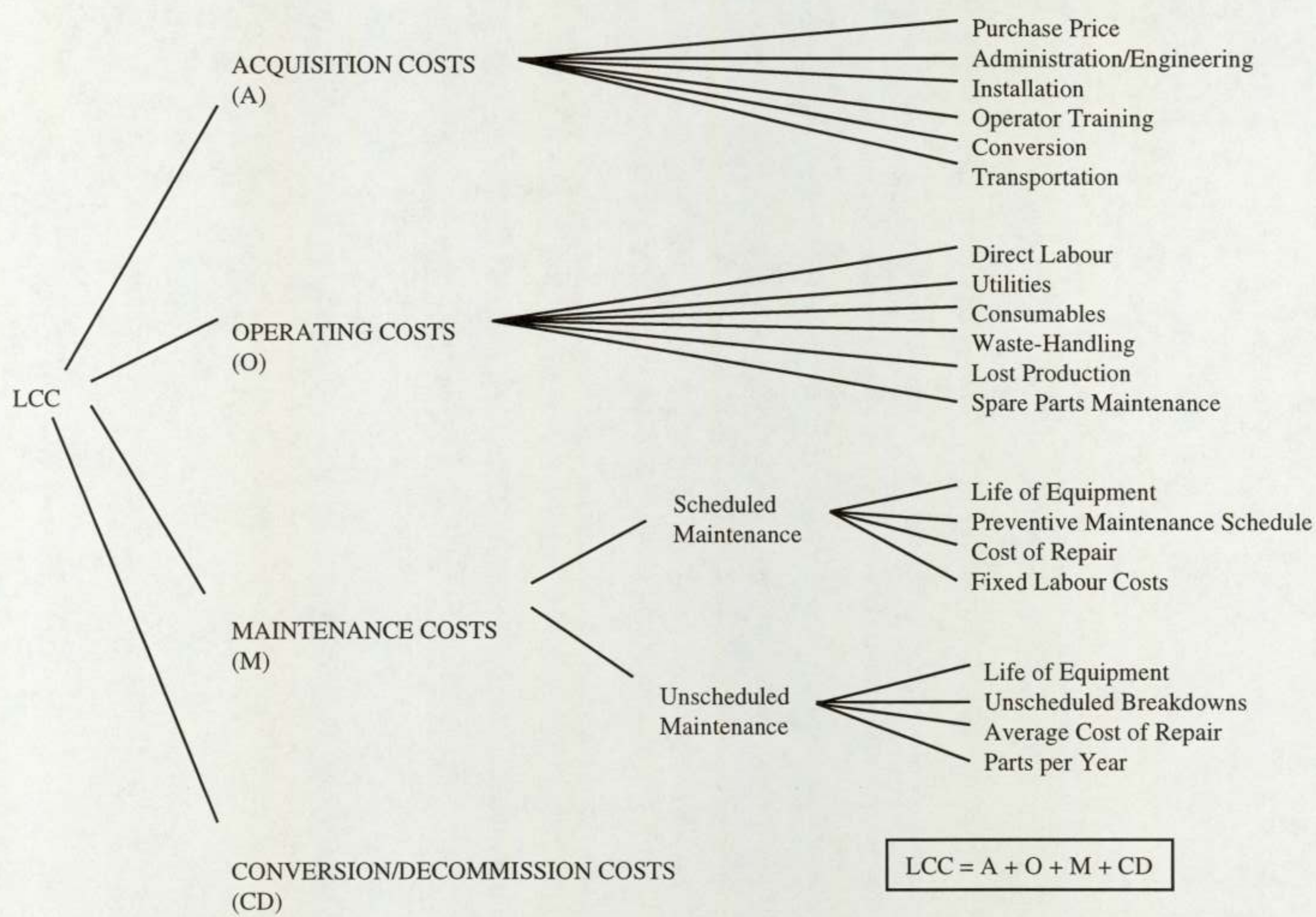
- Non-recurring Cost
- Support Cost

Non-recurring cost includes costs associated with (I) system concept and definition, (II) design and development and (III) manufacture, building and installation. These costs are usually incurred by the manufacturer. Support cost includes the costs associated with (I) acquisition, (II) operation and support of the machinery and (III) conversion or decommission costs. Support costs are usually incurred by the user of the machinery or equipment. In many cases, the user benefits from decommissioning costs by the sale of their machinery. However, in reviewing the literature, one of the fundamental flaws identified is that warranty cost is not defined as being a component of LCC. This, the author believes should be accounted for in the LCC, if a true cost of a system during its life cycle is to be obtained.

In many cases, LCC has also been defined in terms of support costs, i.e. the total cost of ownership of a system during its operational life. Figure 2.7 provides a detailed breakdown of support costs associated with machine tool products [SAE et al., 1993].

Typically, the concept and design phase of a product consume 15% of the total LCC. In contrast to consuming 15% of the LCC, industrial research studies has shown that as much as 95% of the remaining LCC (85%) is determined by engineering decisions made during the concept and design phase [Arsenault and Roberts, 1980]. It is therefore important to emphasise reliability during the concept design stages. In doing so, machinery and equipment will be less prone to failure during service and the operation and support costs that account

Figure 2.7: Breakdown of Life Cycle Costs (User Incurred)



for the bulk of total LCC will decrease. Figure 2.8 shows the breakdown of the total life cycle cost.

In addition to the reduction of LCC, improved reliability of machinery and equipment also benefits the user and manufacturer in other areas. The plethora of technical literature available on reliability engineering and management [e.g. Raheja, 1991; GMC, 1991; Henley and Kunamoto, 1981; Arsenault et al., 1980] has identified numerous benefits that can arise through the improvement of product reliability. However, no anecdotal details of such benefits are provided. Table 2.1 provides a summary of the benefits quoted by many literary writers in the area of reliability.

2.2.4 Reliability: Its Effect on Maintainability and Availability

Unspoken in such definitions is the concept of maintainability and the term availability. Maintainability is a characteristic of design and operation, usually expressed as the probability that an item can be retained in, or restored, to specified operable condition within a specified interval of time when maintenance is performed in accordance with prescribed procedures [Omdahl, 1988]. A similar definition is given by BS 4778:

> 'the ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources.'

Restore does not only mean repair, it also signifies preventive maintenance. In less probabilistic terms, the concept maintainability can be described as the ease with which maintenance work (including repair) can be carried out. Maintenance work includes both preventive and corrective.

On the other hand, availability in turn is a utilisation factor and is measured in terms of the number of hours an item is being used compared to the number for which it could be used. An alternative, however, is to make the comparison with the number of hours for which the item is available. The formal definition given by BS 4778 is 'the ability of an item (under combined aspects of its

Figure 2.8: Total Life Cycle Cost

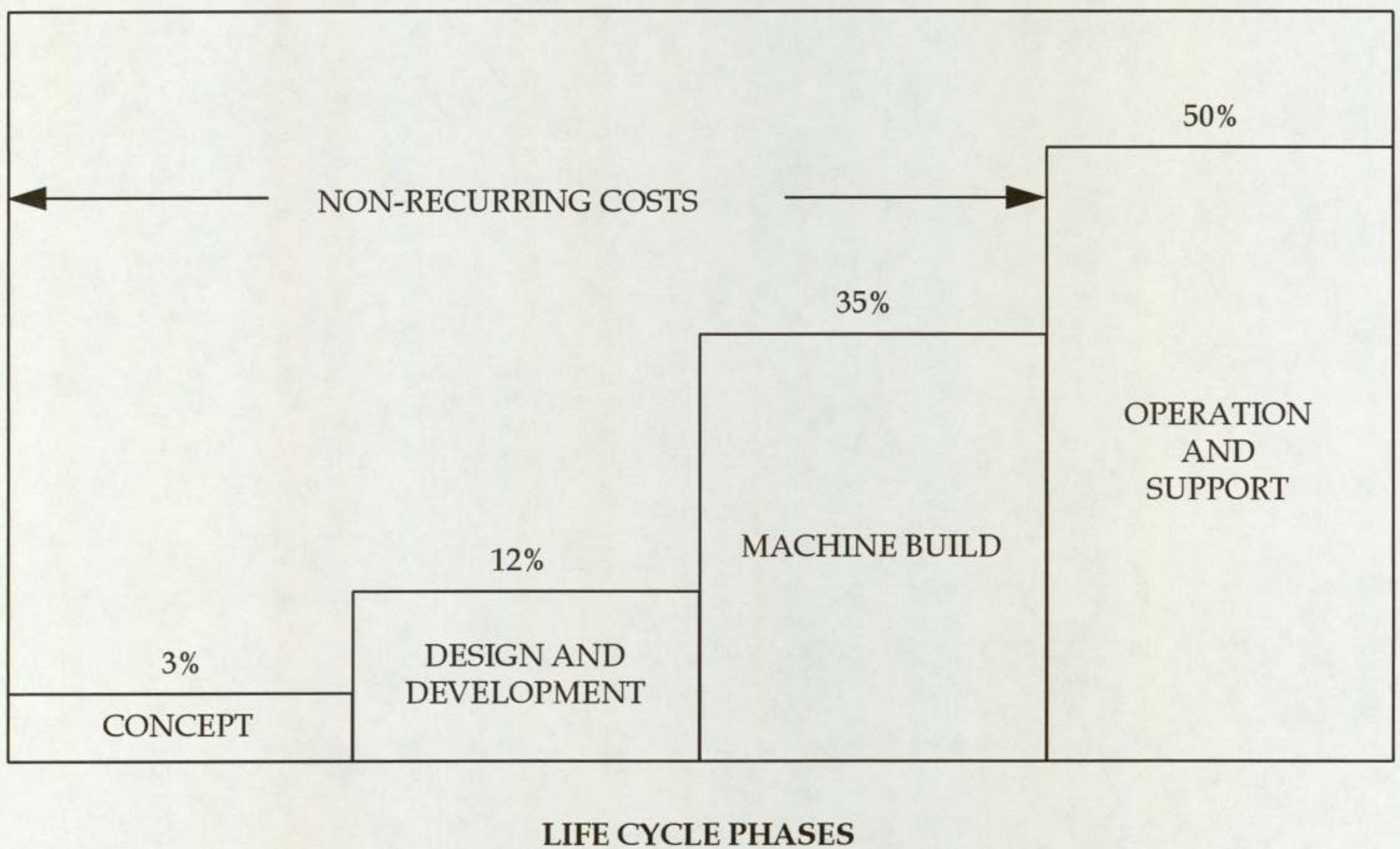


Table 2.1: Benefits of Reliability at Business and Operational Level

User Benefits	**Supplier Benefits**
Higher Machinery and Equipment Availability	Reduced Warranty Costs
Reduction of Unscheduled Downtime	Reduced Assembly Costs
Reduced Maintenance Costs	Reduced Design Costs
Lower Life Cycle Costs	Higher Customer Satisfaction
Stabilised Work Schedule	Improved Status in the Market
Improve Just in Time Capability	Reduction in Downstream Failures
Improved Profitability	Improved Profitability
Reduction in Spares Inventory for Unscheduled Maintenance	Reduction in Spares Inventory for Warranty Purposes

reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time.' These two terms are more applicable to manufacturing machinery and equipment and are directly used as a measure of manufacturing productivity.

Comparing all three concepts, it can be concluded that both reliability and maintainability affects availability directly. In mathematical terms reliability and maintainability are often related to availability by the formula:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where MTTR (mean time to repair) and MTBF (mean time between failure) are measures of maintainability and reliability. This is the simplest steady-state situation. It is evident that either an increase in the MTBF or a decrease in the MTTR figure will lead to an overall improvement in availability.

2.3 Development of Reliability Assurance and Management

Although reliability, as a separate engineering and management discipline, predominantly initiated in the United States of America (USA) during the 1950s, the origins of reliability can be traced back to 1770 BC. Edwards [1904] identifies the earliest reference to guarantee and warranty clauses. Hamoerabi, the ruler of Babylon at that time, passed a law, which when translated means:

> 'if a boat-builder has built a boat for a man and his work is not firm, and in that same year that boat is disabled in use; then the boat-builder shall overhaul that boat, and strengthen it with his own material, and he shall return the strengthened boat to the boat-owner.'

In terms of modern history, reliability theory and practice had its greatest development during the late 1950s and early 1960s. Much written work appeared on the cost-benefit of higher reliability and to show that effort and resources expended during early design and development and during product testing led to reductions in life cycle costs (LCC). Pioneers such as Bazovsky [1961], Lloyd and Lipow [1962] and Sandler [1963] and others developed modern reliability theory and techniques, partly in response to demands from the manned space programme, and partly due to encouragement from the US military establishment, which had experienced discouraging levels of reliability with many of its missiles, avionics and communications and weapon systems. These can be regarded as one of the most influential early texts to deal with reliability as it started to emerge as a field in its own right.

Following initial growth of the reliability discipline, advancements in this field were furthered through the development and revisions of standards on reliability. In the next three sections a brief discussion is provided on the development of these standards and a critical examination is given on the limitations it asserts from a practical application perspective.

2.3.1 Review of Defence Standards on Reliability and their Refinements

Developments in the field of reliability engineering and its management came as a result of increasing complexity of both military and industrial electronic systems, generating low levels of inherent reliability which resulted in reduced availability and increased costs [Dhillon, 1985; Colcutt, 1992]. Although the development of solid state technology offered the long term scope for improvement in reliability of electronic equipment and systems, the miniaturisation proportionally lead to greater complexity, which offset the reliability improvement expected [O'Connor, 1991]. Furthermore, the rate of technology advancement in this sector of engineering lead to the use of many new component types, involving new manufacturing processes and assembly methods. This consequently added to the engineering uncertainty and therefore lead to lower levels of reliability of electronic equipment. The increasing nature of complex electronic equipment were further affecting the availability during use. Problems of diagnosing, repairing the equipment, the costs of spares inventory and other logistic support issues contributed to the low levels of equipment availability.

In response to these problems, both the electronics industry and the US Department of Defence established an Advisory Group on Reliability of Electronic Equipment (AGREE) in 1952 [Knight, 1991]. A comprehensive document produced by AGREE laid down the ground rules and disciplines for achieving reliability during the design and development cycle and hence to break out of the increasing development and ownership costs due to low levels of reliability. The basic premise was that reliability optimisation could only be successful if it was operated as a formalised, rational mechanism. In particular, the report emphasised the need for new equipment to be tested for several thousand hours in high stress cyclic environments (e.g. high and low temperatures, vibration) in order to discover the majority of design weakness at an early stage. This enabled the design weakness to be rectified before initial production commenced. A large part of the report also dedicated itself to providing detailed test plans for demonstrating and proving reliability at a specified level. Various levels of statistical confidence was formally recommended for use in demonstrating reliability.

The AGREE report was accepted by the Department of Defence (DoD) and the document inevitably became a standard procedure for testing electronic equipment. Companies both investing and subsequently using these procedures soon found that they could attain levels of reliability far higher than previously. Due to its effectiveness, the DoD reissued the AGREE document on testing as US Military Standard (MIL-STD) 781, 'Reliability Qualification and Production Approval Tests.' Based on the work of AGREE, a further Military Handbook was published (MIL-HBK 217) on reliability prediction for electronic equipment.

Engineering reliability development progressed quickly in the United States and the AGREE document was adopted by NASA and many other major suppliers and purchasers of high technology equipment. Further to the AGREE document, the DoD issued MIL-STD-785, 'Reliability Programs for Systems and Equipment.' This document made mandatory the integration of a reliability programme of engineering activities with the traditional activities of design, development and production, to ensure that potential reliability problems would be eliminated at the earliest and therefore the cheapest stage in the development cycle. Similarly in the United Kingdom, Defence Standard 00-40

(Def Stan 00-40), 'The Management of Reliability and Maintainability was issued in 1981.

2.3.2 A Review of BS 5760 and its Refinements

To promote the use of production techniques and in order to increase productivity in all sectors of the economy, the British Productivity Council was established in 1953. Accordingly, in 1961, through the initiative of this establishment, the National Council for Quality and Reliability (NCQR) was created. Nearly 8000 companies participated in the activities of Quality and Reliability Year (1966-1967) which was organised by the National Council for Quality and Reliability [1967]. The initiative was aimed to encourage companies to reduce costs by adopting 'good' quality and reliability practices. Companies using formal quality and reliability practices (e.g. statistical quality control) found that this type of approach provided a much more structured and effective method of achieving a required quality or reliability standard, in terms of both cost and dependability.

In addition to this initiative, the British Standards Institution (BSI) has also played an important role in the development of the reliability discipline. BS 4200 was the first reliability standard to be published by the institution and consisted of two parts. Part I, entitled 'Introduction' was published in 1960 and was particularly concerned with reliability concepts and sources of information for reliability. A further revision was then carried out and published in 1967. Part II (Terminology) was published in 1968 and was concerned with the establishment of uniform criteria for reliability programmes which should be agreed between suppliers and customers.

Further to the above, a series of drafts (DD10 to DD16) was published by BSI between 1971 and 1975. The purpose of these drafts was to provide a guideline on the reliability of engineering equipment and parts. Initially, these guides were issued in draft form on a provisional basis. The objective was to collate relevant information and experience of its practical application in industry and to aid towards the development of the series for publication as a British

Standard on reliability systems. It was also suggested that potential users write to BSI giving their experience of its practical application and to supply constructive proposals for improvement.

Using the collated information, further revisions were carried out on these drafts which culminated in the publication of BS 5760, the standard dedicated to reliability systems and the replacement for BS 4200. BS 5760 [1996] is the reliability equivalent of BS 5750 (quality management systems). However, the standard is not widely known and has not received much publicity as BS 5750 (now part of the ISO 9000 series) within the industrial and academic world. Other equivalents to BS 5760 are the MIL-STD 785, NATO ARMP-1 and Def Stan 00-40. The elements of a reliability programme are outlined in these documents. Figure 2.3 (from BS 5760) indicates the cyclic nature of an effective programme and shows the range of activities involved. The activities are described fully in the various parts of the BS 5760 documents.

BS 5760 provides comprehensive guidance on many aspects of reliability management. Recently, further additions and revisions to the standard were incorporated. Currently, the standard consists of a total of seventeen parts and a list of all these parts can be obtained in Appendix A.

2.4 A Critique on Reliability Standards & Prediction Methods

There has been much criticism made by reliability practitioners (e.g. O'Connor) behind the methods described in MIL HDBK 217 and other similar standardised documents (e.g. British Telecom Handbook HRD4, Bellcore TR-TSY-000332) for the prediction of new electronic and to some extent new mechanical systems and parts. Ascher and Feingold [1984] has made an excellent critique of some of the misunderstandings of the statistical aspects of reliability theory which have been perpetuated in some of the vast academic literature developed world-wide and which have crept into military and other standards documents. Methods developed for predicting reliability characteristics (failure rate or mean time between failure - MTBF) of new systems and products are all based on the assumption that the failure rate of the system is the sum of the failure rates of its parts. Its use as a design parameter rests upon the notion that MTBF can be predicted, mainly from generic component databases.

Further to this, various other simplifying assumptions are also made, such as all failures occurring independently, have constant rates of occurrence (i.e. failures can be modelled under the exponential distribution), that every component failure causes a system failure, that there is a relationship between failure rate and operating temperature and that all system failures are the cause of component failures [O'Connor, 1993].

Many questions have been asked regarding the validity of the methods of reliability prediction (in particular the constant failure rate assumption) as a means of predicting the reliability of a new part or system. The use of this approach owes more to expediency than a scientific basis. It originated in the early days of electronics when individual devices were significantly unreliable and equipment contained large numbers of components. Data gathered during the 1950s were not accurate or integrative. Inadequate failure reporting, reporting of mixed age equipment, defective records of equipment operating times, mixed operational environmental conditions, complete neglect of thermal cycling data and many additional undesirable factors contributed to the inaccuracies.

Several authors have described the deficiencies in the technique and the weakness of the prediction techniques involved [Knowles, 1996; O'Connor, 1990; Wong, 1993; Zahid, Jones and Hayes, 1993]. Indeed, the authors of MIL-HBK 217 [Morris, 1990] state:

> 'MIL-HBK 217 is not intended to predict field reliability and, in general, does not do a very good job at it in an absolute sense.'

Furthermore, because the predictions are neither consistently optimistic nor discouraging and can vary significantly from the actual field reliability by as much as an order of magnitude, using these methods for initial assessments or trade-offs can adversely affect further product development. O'Connor [1993] states that:

> 'National telecommunications organisations such as AT&T and British Telecom maintain their own versions, which give markedly give different failure rate values for identical components.'

These methodologies based on component failure rates also suffer from the serious problem that even if it were possible to predict the unreliability caused by component failure, the vast majority of failures are caused by faults in design or assembly. A recent analysis [Pecht and Ramappan, 1992] has estimated that less than ten percent (10%) of electronic failures are caused by faults within the individual devices. Therefore, quality of design and manufacture has a far greater impact on reliability.

It is also recognised that by the time a piece of equipment has been repaired several times, its components are in a scattered state of wear because faulty components have been replaced by new ones [Davis, 1952]. Each of these components will have a different wearout characteristic governed by a time-dependent distribution and the combination of devices with different lifetimes could produce failures equally likely to occur during any period of use.

According to the literature, the constant failure rate assumption is not justifiable for the majority of cases and yet it is commonly used to specify reliability. It takes little account of individual failure mechanisms, and does not employ knowledge of the actual conditions at a potential user site. The UK Ministry of Defence has recently reversed its policy on part level and system reliability prediction techniques. Defence Standard 00-41 sets out the limitations of the prediction process [Def Stan 00-41, 1993]. It also requires that appropriate attention is paid to reliability management aspects such as management commitment, warranty requirements and production quality control. In the US, there is controversy between those who argue for the scrapping of MIL HDBK 217 and those responsible for its upkeep.

Another method which has raised questions regarding its practical application and validity is the method of reliability demonstration (US MIL-STD 781). The logic of the method is that if a product or a system has an inherent reliability, normally expressed as MTBF, then this property can be measured by a test based upon an appropriate statistical technique. Statements about the system's MTBF can be made with defined levels of statistical confidence, based upon the number of failures and the time on test. The techniques have been considerably developed over the years through international reliability standards as discussed earlier. They include guidelines on a range of test plans appropriate to different criteria such as acceptable levels of reliability. A related activity has been the development of mathematical models of reliability growth, the best known being Duanes' [Duane, 1964].

The experience of applying the techniques of reliability demonstration and growth modelling have been disappointing. Expensive tests have demonstrated one value, and in-service data have shown very different results. Attempts have been made to improve the realism of the test environments and there have been discussions on the subject. Again several authors have described similar deficiencies in these techniques [e.g. O'Connor, 1993, 1990; Knowles, 1996].

On the other hand, reliability modelling which makes up a large proportion of the reliability literature, comes mainly from academic journals and conference proceedings. These are usually based on Markov methods [e.g. Choi and Trivedi, 1993] and over usage of quantitative methods [e.g. Love and Guo, 1993; Schneeweiss, 1993]. Proponents within this field make the assumption that the reliability numbers that would have to be inserted into the complex equations are known with some exactness, but otherwise the models have interest from a theoretical perspective. It is very hard to find case evidence of the application of such methods by practising engineers and managers, yet the flow is endless. However, mathematical methods (based on regression and curve fitting techniques, proportional hazards methods) used for analysing failure data and for forecasting future behaviour are extremely useful in solving reliability related problems or for forecasting future warranty costs. Practical applications of these methods are well established in the literature [Davidson 1988].

It is also notable that other organisations are continuing to use and develop methods based upon the above techniques. The International Electrotechnical Commission (IEC) has recently decided to draft an international standard for electronics reliability prediction and a test plan for reliability demonstration.

Similarly, relevant parts of BS 5760 and other standards contain methods for predicting and demonstrating reliability. In addition to this, one of the limitations of these standards is that they tend to be rather general and lag behind known best practices. For example, all reliability standards typically require that FMEAs (failure mode and effects analysis) be produced, but most do not mention the use of design of experiments to explore design and process variation, nor the use of quality function deployment (QFD).

2.5 Summary

The objective of this chapter was to provide a preliminary to chapter 4. In examining the conceptual theory behind product reliability, it has been established that no universal definition of reliability exists. However, the definition given in BS 4778 has been widely accepted as a standard by UK industrialists and academics alike. The evolution of the reliability engineering discipline came about in the late 1950s, as a result of increasing complexity of both military and electronic systems, generating low levels of inherent reliability. Having reviewed the prediction, modelling and growth testing aspects of reliability engineering, many drawbacks have been outlined.

Before reviewing the application of the reliability engineering and management discipline in the general manufacturing industry, the next chapter provides a brief overview of the machine tool industry.

3. The Nature and Structure of the UK Machine Tool Industry

3.1 Introduction

Machine tools are used in virtually the whole of manufacturing industry, although they are concentrated in some key sectors such as the automotive and aerospace industries, the general mechanical engineering and metal goods industries. The industry as a whole only accounts for about 1% of the United Kingdom's industrial output. Its balance of payments, valuable though it may be, is unlikely to make much of an impact on the UK total. Why then do machine tools generate such a disproportionate amount of concern in government and industrial circles?

In context with the above question, this industry note describes the structure and the historical performance of the UK machine tool industry. It forms the basis for providing background material for the analysis of chapters 5 to 10. The note is divided in two sections. The first of these provides a review of the basic technologies in the industry. The second section provides a detailed study on the structural reforms that was undertaken in the UK machine tool industry. Finally, the last section describes the current market for metal-working machine tools and contrasts the relative performance of different national machine tool industries in these markets since the war.

3.2 Types of Machine Tools

The nature of manufacturing is such that different individuals and industries will view machine tools in different ways but the definition adopted here is that given in BS 4640 [1970]:

A metalworking machine tool is a power driven machine, not portable by hand while in operation, which works metal by cutting, forming, physico/chemical processing, or a combination of these techniques.

This definition has been adopted by many trading and research organisations of the machine tool industry such as the European Committee for Co-operation of Machine Tools (CECIMO), the Machine Tool Technologies Association (MTTA).

Machine tools can be spilt into two basic types:

- those which remove metal in one way or another. For example machining centres, milling machines, lathes, turning centres and grinding machines fall into this category.
- and those which shape or form metal without necessarily removing any. For example forging machines, extrusion and other presses and wire-drawing machines come under this category.

This research is predominantly focused on metal-cutting machine tools. Within this sector there are many different types of machine tool which have been used by industry for a considerable period of time. Machine tools themselves can frequently be relatively old. This is partly a function of the general applicability of a machine tool to certain basic functions. The removal of metal is a relatively basic manufacturing task and if a machine tool satisfies this need and continues to operate, then there is no obvious reason to change it.

There have been relatively few radical changes in technology in the machine tool industry, with much of the product development effort focused on minor innovation of the continuous variety. Major innovations (such as the developments in the field of computer numerical control - CNC) have come from developments outside the industry. In recent years these have included developments in electronics and control systems, notably computer software systems, microprocessors and digital elements, and the development of feed drives, particularly high powered, d.c. motors.

The main areas of continuous machine tool development are research into cutting processes, spindles and bearings, tool magazines, machine structures, modular design concepts, slideways, computer numerical control and other forms of control, physico-chemical processes, and metal-forming processes.

Research into cutting processes has contributed to the development of carbide, coated carbide and ceramic tools. This predominantly led to the improvement of tool geometry. These developments have been largely initiated by the tool manufacturers, and not by the machine tool industry itself. Improvements in the tools have led to large increases in metal removal rates despite the growing usage of 'difficult to machine' materials. Research into spindles and bearings has produced spindle/bearing assemblies of high stiffness and power handling capacity. This has lead to increased accuracy and reliability in the output of the machine tool.

The structure of the machine tool itself has also been extensively studied. This has led to improvements in structural stiffness. The trend towards modular design in machine tools has also led to greater standardisation of machine tool design. Work on the slideways of the machine tool has led to the use of more sensitive and accurate control systems. Similarly, work on the development of tool magazines has led to more sophisticated and simplistic tool changing mechanisms which are able to achieve tool change times of approximately 1 - 2 seconds.

The areas of development described thus far are areas of continuous relatively minor change. The machine tool industry has experienced a considerable change in some technologies in the last 20 years. The developments of numerical control (NC), computer numerical control (CNC) and Direct Numerical Control (DNC) technologies have allowed the user to make the best use of skilled labour and greatly increase productivity. This is particularly true for small batch production of relatively complex parts. The benefits of numerical technology in terms of improved floor-to-floor times, improvements in accuracy and enhanced reliability led to increased adoption amongst machine tool users since the 1970's.

The development of physico-chemical processes, principally electro-deposition machining (EDM) and electro-chemical machining (ECM) represents a major technical change. In the case of EDM a part is formed by depositing metal onto a piece by electrolysis. With ECM the part is formed by electrical erosion of the workpiece. Both technologies have proved to be important steps forward. EDM now makes a major contribution to productivity because in many instances it is more rapid than conventional machining technologies, and ECM enables the manufacture of components in materials that could not be economically machined in any other way.

The acceptance of technical change is ultimately influenced by economic factors, which have had a major role in determining the way in which new technologies have developed. As machine tools have become more complex and have become more productive (essentially de-skilling many machining operations), they have also become more expensive. This has led to requirements for increased reliability and easier maintenance, in order that the machines can be available for use. Emphasis has also been needed in design on increasing utilisation, particularly minimisation of time lost in setting up, in tool changing, loading and unloading of the workpiece and the inspection of manufacturing tolerances.

3.3 Structural Reforms in the UK Machine Tool Industry

For a country such as the UK which possesses few raw materials, but which requires to manufacture and export in order to prosper, the machine tool industry is of the utmost importance. Additionally, being the fundamental of the manufacturing process, it can often be an accurate guide to the condition of the UK industry and hence the economy as a whole. This importance is best summed up by an extract from the Machine Tools Economic Development Committee [MTEDC, 1970]:

"The industry accounts for about 1% of total United Kingdom manufacturing output, exports and employment. These figures do not, however, adequately reflect its importance to the economy as the supplier of equipment essential in the manufacture of other engineering and allied products."

The boring mill was probably one of the first metal-working machine tool to be made. This was developed and made by John Wilkinson in 1774 at his ironworks near Broseley in Shropshire. Initially developed for the manufacture of cannon, the machine was soon re-engineered for use in steam engine cylinders. According to Cossons [Bennett, 1978], an engine cylinder or cannon barrel had been cast in brass or iron. In order to smooth out the bore of the barrel, it was either manually rubbed with rags and sand or by running the roughly cast barrel on a trolley over a boring head mounted on a rotating pole. However, Wilkinson was able to devise a mechanical transmission to carry out this process. This was done by fixing a cutter on a rotating bar with bearings at each end. By devising a means of moving the cutter head along the bar, Wilkinson was able to bore a precise cylindrical barrel in the casting. The casting itself was bolted to the bed of the machine. This was the first time that a large diameter bore could be cut accurately without the cylinder not being further from absolute truth.

The evolution of the machine tool was fundamental to the development of better and more efficient machines. During the nineteenth century Engineers such as Maudsley, Roberts, Spencer, Nasmyth, Whitworth developed machines for carrying out the main processes of material removal, for example, turning, drilling, boring, milling, planing, shaping and grinding. In minor cases, such processes were automatically carried out. This growth of machine tools provided the basis for much of the products and services of the manufacturing industry. Users of machine tools were able to save on the number of men necessary to carry out a particular manufacturing process. More importantly, dramatic savings were acquired on the number of 'skilled' people required.

The industry itself has been the subject of not only many government inquiries and commissions [e.g. Mitchell, 1960; Way, 1970; NEDC, 1965; NEDC, 1965a; Bacon and Eltis, 1974] into its effectiveness, performance and other related problems, but also of the media [e.g. Baxter, 1992, 1994; Powley, 1996].

Perhaps the first significant governmental investigation to emerge was the Mitchell Report [1960]. The Committee was set up to consider Professor Melman's proposal as to whether mass production methods should be introduced into the machine tool industries of Western Europe to provide efficient machinery at low prices and to enable Western European industry to stand up successfully to competition from the Eastern Bloc. The proposal on mass production methods was rejected largely on the grounds that there was not sufficient evidence to justify the existence of a large enough demand for particular types of machines. The extreme standardisation of design, implicit in mass production, would fail to meet the majority of the needs of the user industries for specialised, high performance machine tools. Instead the Committee recommended further standardisation of components and a serious look into the adoption of modular design.

In considering this question, the Committee also examined a wide range of topics relevant to the industry and their recommendations have provided the background to governmental policy from 1960-70. With regards to the structure of the industry, the Mitchell report stated that there were only about 350 firms manufacturing machine tools in the United Kingdom, nearly all specialising in a limited range and some concentrating on a single type. Leaving aside the sub-contractors, it quoted that 20 firms supplied 50%, 50 firms 72% and 150 firms as much as 90% of the UK machine tool output. The remaining 200 firms were thus responsible for 10% of output. The average turnover of these 200 firms in 1959 being only £40,000 per annum. In summarising, the report concluded:

> "It is difficult to believe that small firms generally speaking are in a position to make a sustained development effort and this we believe to be the single greatest need of the industry...."

Significantly, the Mitchell report pointed out the existence of the very large number of firms in the industry whose combined output represented only a small fraction of the total. The report also questioned the viability of these firms in terms of sustained development effort. One key aspect to the survival of a small firm must be its ability to match its products against a larger competitor. This became more vital in the light of the emergence of new machine tool industries in developing countries, especially in the production of standard machines. Attention was, therefore, drawn by the Mitchell report to the possibility of structural reform.

In the 1965 National Economic Development Organisation (NEDO) inquiry [NEDC, 1965] on 'Imported Manufacturers', one of the suggestions made by the Committee to improve competitiveness by UK industry was to examine the possibilities of rationalisation and reform of structure to secure the benefits of specialisation and economies of scale. The National Plan [NEDC, 1965a] which was launched the same year made these conclusions on the machine tool industry:

"Some small companies are too weak to mount the necessary effort and so do not use the scarce labour to the best effect. Some rationalisation needs to be called for.... The action programme of the EDC (Economic Development Committee for Machine Tools) has drawn attention to the relatively fragmented nature of the industry and steps are being taken to determine the best way to approach the problem. Economic forces alone may be slow to improve the situation..."

While recognising that there was no merit in size for its own sake, three points emerged regarding government policy towards the industry by the mid 1960's:

1. recognition of the existence of a large number of small firms and their vulnerability.
2. structural reform was necessary to improve the competitive position of the industry.
3. market forces alone may not be sufficient to achieve the desired reform, implying that some form intervention may be necessary.

In the governments desire to effect the necessary structural changes within the UK industry, the Industrial Reorganisation Corporation (IRC), set up during the 1960's, actively participated with the industry. The purpose was not so much as actual involvement with financial support, but the climate the government stimulated and provided through the IRC for mergers and take-overs within the industry. Most of the merger activity in the industry took place in the 60's and resulted in the formation of industrial groups of machine tool companies. The more significant of these groups to emerge were Alfred Herbert Limited, John Brown, B. Elliot, Staveley Industries and Cohen 600.

It must be stressed that the take-over occurred during a period when the general consensus of opinion believed in economies of scale and its application to industry generally. Proponents contrasted the size of British and American companies and went on to conclude that the lower cost and efficiency of American companies were due to its size.

The Way Report [1969], published in 1969, was the most significant and far reaching investigation into the industry. It considered and made recommendations on the various aspects of the industry. These included (1) the structure, (2) capacity, (3) investment, (4) manpower, (5) marketing, (6) research and development, (7) numerical control and (8) the relationship between the government and the industry. The weakest area of activity that the Committee found was in marketing.

By the time the Way report was published, it reported that there were 200 machine tool enterprises (taking group of companies in common ownership as one enterprise). Seven of those provided 50% of the industry's output. Compared to 350 enterprises of which 20 supplied 50% of the output during the Mitchell report of 1960, the industry had undergone some structural changes over the 9 year period. The MTTA in evidence to the Committee considered that rationalisation had gone as far as it could if it was not to inhibit competition. The IRC, however, envisaged more product rationalisation with fewer competing units in smaller product areas and the Way Committee concurred with this view. In its conclusions on structure, it wrote:

> "(a) The cost of developing, manufacturing and selling advanced machines and systems of production is such that a high market share is needed to support the effort involved."

"(b) Competition in the conventional general purpose machine tool field is such that large scale production is necessary if the British industry is to remain a viable supplier at home and abroad."

In addition to the structural reforms to strengthen the industry, import penetration was recognised as a major threat to the UK machine tool industry. Import penetration in the industry increased from 18% of domestic consumption in 1975 to 40% in 1981. Germany has consistently been the principal source of supply of new machine tools to the UK. The most marked change has been the increase in the share which Japanese companies have of UK imports (rising from 4% in 1975 to 11% in 1982). The 1965 NEDC survey [NEDC, 1965] of UK machine tool users were asked their reasons for increasingly opting for imported machines: 5% said price was the main factor, 5% better aftersales service, 8% the willingness of foreign manufacturers to meet special requirements, 11% the prospect of reciprocal trading agreements, 20% quick and reliable delivery, 21% the machine specification not being available in the UK, and 30% the technical superiority of the foreign machine. If all the technical factors are combined then the technical superiority of the imported product was given as the main reason for choice by 59% of the customers. Price appeared to be a less important factor.

3.4 The Market for Machine Tools

The demand for machine tools is characterised by considerable fluctuations on a year-to-year basis, typical of an industry where the demand for its own products is derived from the demand for other products. Recessions in the industry tend to last longer than recessions in industry as a whole, and periods of expansion and high demand for its products tend to be shorter than those of industry as a whole. In recent years periods of recession have led to a considerable reduction in the number of people employed in UK machine tool industry. Periods of expansion have been accompanied by complaints that machine tool manufacturers in the United Kingdom cannot expand output as rapidly as overseas competitors can exploit the temporary market expansion.

Table 3.1 compares market shares of the top ten machine tool manufacturing countries in 1977, 1981 and 1994. In 1977, West Germany was the world's leading producer of machine tools reflecting the reputation which its products had gained in the years since the second world war. This level of performance had been sustained by a high level of exports which supported domestic production. Between 1977 and 1981 West Germany lost this lead to the United States.

Table 3.1: Shares of World Machine Tool Production (1977, 1981, 1994)

	Market Share		
	1977	**1981**	**1994**
Country	**(%)**	**(%)**	**(%)**
West Germany	17	15	-
United States	16	20	14.1
Soviet Union	15	12	-
Japan	10	18	23.5
Italy	6	5	7.7
East Germany	5	3	-
United Kingdom	5	3	3.5
France	4	3	2.2
Switzerland	4	3	6
Poland	4	-	-
Romania	-	2	-
Germany	-	-	17.9
South Korea			2.9
Taiwan			4
China			5.3

Source: [American Machinist]

The most significant development, was the rapid growth of the Japanese machine tool industry during the same period (from 10% of world machine tool production in 1977 to 18% in 1981). This continuous rapid growth, achieved particularly through exports, has taken Japan to be the leading producer of machine tools. Through the re-unification of the East and West blocks, Germany regained the lead over the United States and is currently the second largest producer of world machine tool production.

Analysis of the table also shows the emergence of new players in the machine tool industry, namely China, Taiwan and South Korea. The table also shows the significant downfall of the Russian machine tool industry. British companies continued to experience a decline in output falling from 5% of world production in 1977 to 3% in 1981. A 3.5% share of world production was measured in 1994 for the UK industry.

World-wide, the demand for machine tools increased considerably during 1994, driven by continuing growth in the United States and the Pacific Rim, particularly China. Demand for machine tools in the UK has risen about by about a fifth over the year, with an increase in demand for CNC of about 25 percent. The main demand is driven by the automotive and general engineering sectors, although the cuts in defence and aerospace sectors have badly affected the companies specialising in these areas.

A series of annual surveys carried out by Benchmark Research since 1991 show a downward decline in the overall size of the UK market [Benchmark Research, 1994]. Table 3.2 shows the trend in investment on CNC machine tool technology as recorded since 1990/91. Given the period covered by the survey it is no surprise to find a decline in the overall size of the market in value terms as the UK recession deepened during 1992 - 1994 period. Investment in the UK on CNC machine tool technology during the 1992/93 period ran at 18% less than the level recorded during the period spanning 1990/91 and reduced marginally by a further 5% during 1993/94.

Table 3.2: Trends in Investment of CNC Machine Tools

Period	Investment on CNC Machine Tools
1990/91	£500m
1991/92	£445m
1992/93	£410m
1993/94	£391m
1994/95	£410m

Source: [Benchmark Research, 1994]

Although, the overall trend in investment has shown a general reduction since the first survey in 1991, there are a number of differences when individual categories of CNC machine tools are analysed in isolation as Table 3.3 shows.

Table 3.3: Trends in Expenditure on CNC Machine Tools by Type

Category of CNC Machine Tool	Sales £m 1990/91	Sales £m 1991/92	Sales £m 1992/93	Sales £m 1993/94
Lathes	105	102	84	79
Machining Centres	160	144	142	130
Milling Machines	52	34	26	24
Turning Centres	66	57	63	66
Grinding Machines	34	28	21	19
Punch Presses	nm	20	24	28
EDM	nm	nm	10	14
Press Brakes	nm	nm	10	13
Lasers	nm	nm	6	7
Others	83	60	24	21

Source: [Benchmark Research, 1994]
nm = not measured (investment on these machines is incorporated within the general "others" grouping.

Overall revenues have declined by 18% since 1990/91, by contrast the decline in the number of new CNC machines purchased within the lathe, milling machine, machining and turning centre groups has been markedly more (a 33% decline). Clearly, there are a number of factors which combine to reconcile this apparent difference in the overall market trend. Firstly, whilst unit sales of new machines would appear to have suffered significantly since the start of the decade, the sales of second hand machines have been comparatively healthy, declining by only an estimated 13% over the entire period. As sites have closed or reduced their operations this has created an increase in the availability of relatively new second hand machines in the market which has had an impact upon the sales of new machinery. The second element stems from the fact that although budgets were clearly being limited in response to the recessionary climate, the inability to invest in new machines may in turn lead to an increase in expenditure on service and maintenance for existing installations as these become older and hence more prone to breakdowns.

The 1993 survey carried out by Benchmark Research [1994] also showed that a total of 3,767 CNC machines were purchased during the period 1992/93. This total is broken down by detailed category of machine tool in Table 3.4 to show the overall structure of the market. Since the first survey in 1991, four major categories of machine have been consistently measured. These four types also form the most significant markets, namely, lathes, turning centres, milling machines and machining centres.

Table 3.4: Breakdown of Unit Sales of CNC Machines by Type in 1992/93

Type of CNC Machine Tool	Number of Machines in Use
Machining Centres	1,001 (27%)
Lathes	965 (26%)
Turning Centres	387 (10%)
Milling Machines	318 (8%)
Punch Presses	243 (6%)
Press Brakes	196 (5%)
EDM	152 (4%)
Grinding Machines	115 (3%)
Drilling Machines	74 (2%)
Lasers	67 (2%)
Other Types	249 (7%)

Source: [Benchmark Research, 1994]

Firstly, in order to provide a more relevant analysis sales of new machines only were included by Benchmark Research. In addition allowance has been made for the sales of machines into sites with under 20 employees. The allowance is based upon the assumption that these smaller establishments will account for a similar proportion of the overall market as they do in the 1993 Survey for the period 1992/93. The results of the analysis are shown in Table 3.5.

Table 3.5: Trends in the Number of New CNC Machines Required

CNC Machine Tool Type	1990/91	1991/92	1992/93	1993/94 Planned
Lathe	913	742	591	538
Turning Centre	290	191	243	301
Combined Total	**1,203**	**933**	**834**	**839**
Milling Machines	462	333	177	202
Machining Centres	1,013	724	783	525
Combined Total	**1,475**	**1,057**	**960**	**725**

Source: [Benchmark Research, 1994]

Despite all the structural reforms and foreign competition, the UK machine tool industry is still a major player in both domestic and international markets. The current economic performance of the UK machine tool industry looks very buoyant [see Powley, 1996]. In 1996, the UK machine tool industry was ranked eighth in the world league table for machine tool production and seventh in terms of exports, with output increasing from £646 million in 1995 to an estimated £871 million in 1996 [Powley, 1997]. The average numbers employed also increased by 1400 to 14000, reversing the downward trend of recent years. There are now approximately 200 machine tool producers in the UK, making it the third largest in Europe (1990 figure).

3.5 Summary

The main objective of this industry note was to briefly examine the problems, structure, trade and performance of the UK industry on an aggregate level. This was essential to determine the true position and viability of the industry itself and also with regard to the other major machine tool producing countries. It was established that many of the problems which confront the UK industry are also prevalent in other countries. However, the performance record of the UK industry (i.e. from one of the leading nation of machine tool production), compared with most of its major competitors is poor. During the 1950s, market share was lost to foreign competition and the industry was particularly badly affected by the 1979-81 recession.

Recognising this fact, the UK industry, however, has seen significant growth in terms of exports, production, and the domestic market, during the late 1980's and early 1990's. This was helped by the need for renovation and modernisation of plant after a long period of low investment and in anticipation of the Single Market.

4. Reliability Management Issues in Practice

4.1 Introduction

In chapter 1 it was suggested that there were three key practices that together make up the capacity for reliability management of manufacturing organisations: (1) use of field data for the benefit of improving product reliability, (2) design assurance activities and (3) use of tools and techniques. Each of these three practices is based upon a different research tradition, and the purpose of this chapter is to review what is currently known about these areas as a preliminary to the fieldwork reported in subsequent chapters. This review is intended to guide the reader to the current knowledge of factors related to success in reliability management.

This activity was necessary in the overall schema of the investigation in order to establish the current theories and reported practices of reliability management. The overall aim is to outline relevant concepts in the 'textbook' approach to reliability which are of value to this piece of research.

4.2 Background to the Literature

Beale [1968] commented about the formulation of Linear Programming that:

> 'a general discussion on such topics often promises to be interesting, but in fact turns out to consist of WAFFLE'.

Being aware of such opinions it is to be hoped that this pitfall can be avoided in attempting to review the broader area of the literature related to reliability management.

A considerable body of literary information either dedicated or related to reliability management have been cited within a wider body of engineering, management science and quality management writings. Although mostly, it is theory based, a growing part is based on isolated case histories and industry studies. However, there are still pronounced gaps in both quantitative and qualitative investigations of the nature and magnitude of reliability management. Renewed interest in the application of reliability principles and practices has now began to broaden research into this field, both from an engineering management and operational context.

The literature exploring reliability management within manufacturing organisations is fragmented and has typically included aspects such as reliability data analysis, mechanisms for improving product reliability during the early phases of the design and development cycle, through to identifying the characteristics and prohibiting factors affecting the management of product reliability. For our purposes, it is perhaps appropriate and possible to categorise this into three main groups.

Practical Reliability Data Analysis: Important engineering decisions are frequently made from the analysis of product life and field data using various graphical and analytical methods (e.g. Weibull analysis). For the purposes of this research, product life and field data refers to engineering failures during service or use. A variety of graphical and analytical techniques for analysing product life data have been developed in recent years and its use from an industrial application perspective has been tested.

Methods for Reliability Improvement: These methods (e.g. Failure Mode and Effects Analysis - FMEA) primarily assist in the process of reviewing designs in order to identify and eliminate potential design, manufacture and failure related weaknesses. However, they can simply be considered to be good management and design practices, rather than tasks unique to a structured reliability programme.

Literature on the application and diffusion of these techniques in practice and their operational features has been examined through different research methods. Although these techniques provide a structured means of assessing product reliability requirements during the design and development process, one should not get the impression that their use is widespread. For example, Benchmark Research [1994] in a UK survey found a lack of knowledge and understanding regarding the application of these methods.

Design for Reliability Concepts and Techniques: The category, usually outlined as the result of an industrial case study or experience are based on what can be termed the 'systematic' approach to achieving the desired reliability at low cost during the design and development process. Systematic, here is defined as 'an orderly and well disciplined way of getting things done [Jenkins, 1969]. Generic guidelines are provided which enable up-front consideration to be given to reliability issues and therefore reducing the likelihood of downstream failures. Although, much of this research has yet to be tested in its purest form in a practical sense, it does offer some excellent guidelines to practitioners in the field of design and manufacture.

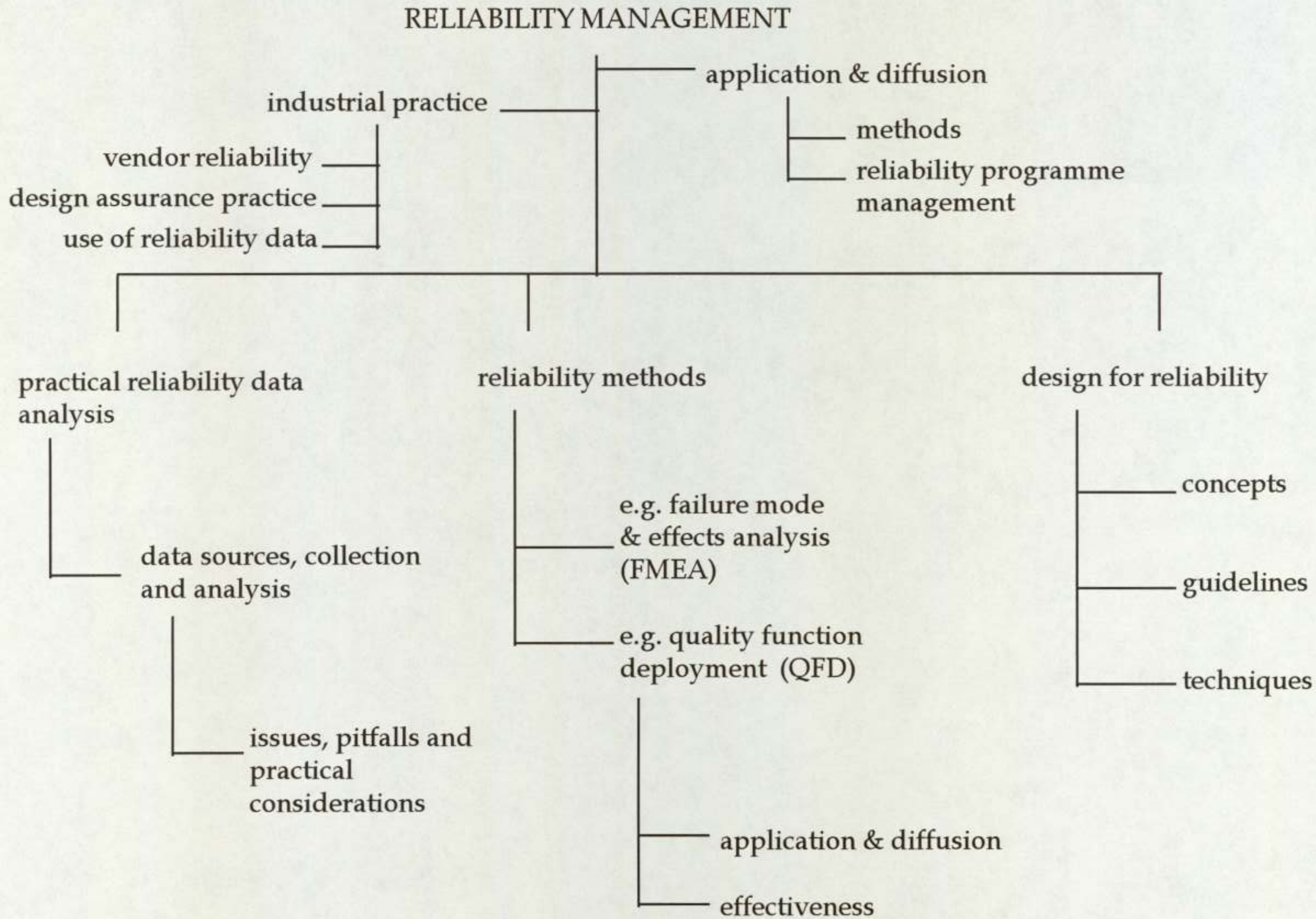
This classification is shown in Figure 4.1. Each of these broad categories relate to a particular aspect of reliability management. In one way or another, they cover all aspects of reliability management.

4.3 Importance and Diffusion of Reliability Management Practice

According to a recent UK survey, product reliability has become a major concern for most manufacturing companies. This is reflected by the fact that quality and reliability improvement programmes have become widespread in British manufacturing industry, with a 'Quality in Manufacturing' survey reporting that 89% of the survey respondents confirm they operate, or intend to operate, design and manufacturing activities to a planned quality and reliability policy [Benchmark Research, 1994]. The survey covered, the aerospace, automotive, electrical, electronic and mechanical engineering sectors.

However, the large numbers following quality and reliability policies need to be put into context. A follow-up question identified the stimulus for adhering to these policies and these reveal that external influences such as customer pressure and competitive threats play a significant part. Figure 4.2 quantifies the extent of these pressures on an industry by industry basis.

Figure 4.1: A Taxonomy of the Various Aspects of the Reliability Management Literature



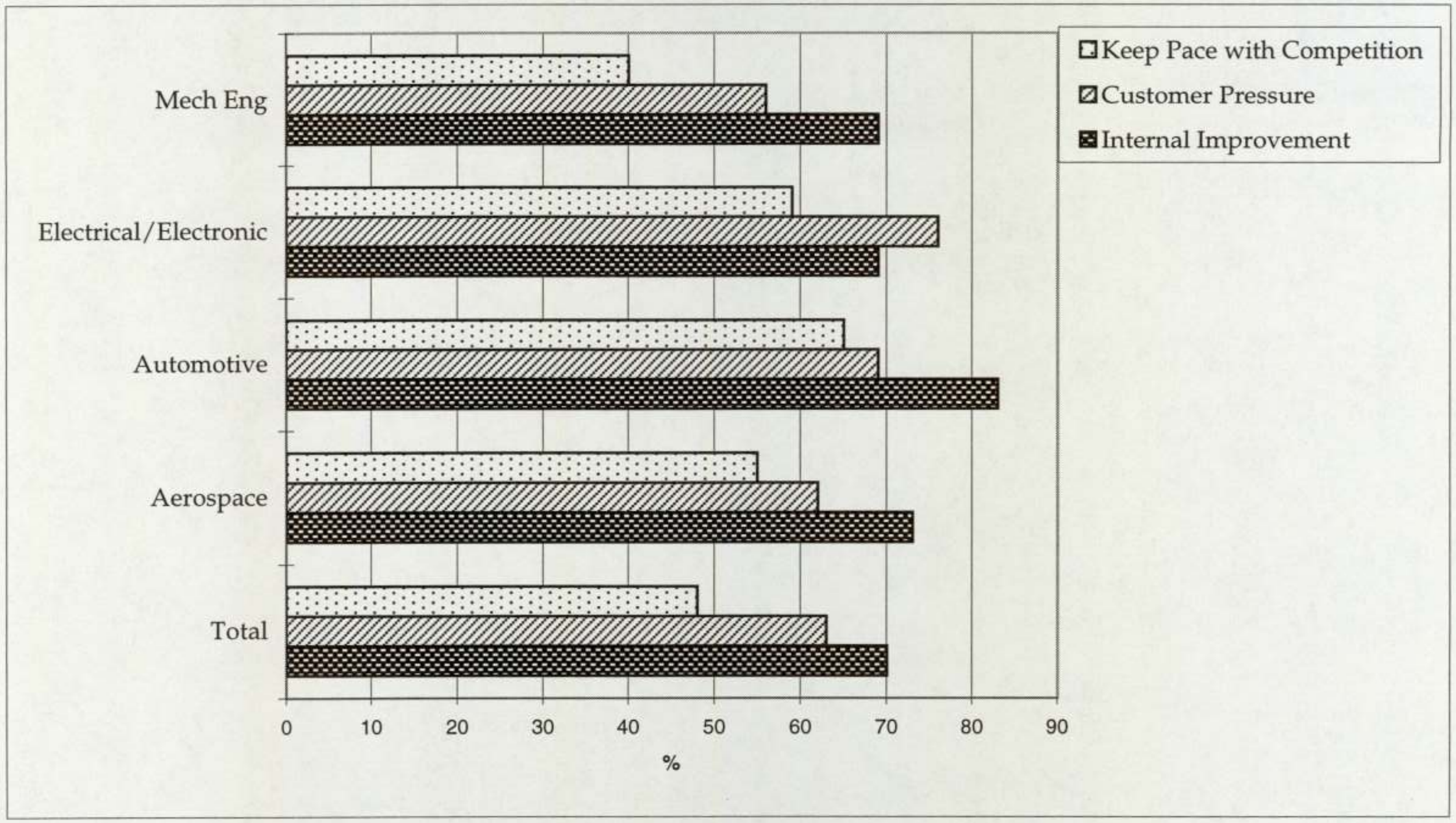
It is clear from the details presented in Figure 4.2 that automotive companies operate their policies from the perspective of internal improvement. This is consistent with the changes introduced by the Japanese and latterly adopted by most Western manufacturers. In the electrical and electronics sector, customer pressure are closely allied with an internal drive for change. This reflects an industry already highly regulated in terms of compliance to many European and World-wide Standards. Competitive threats are seen as the least significant by the mechanical engineering sector reinforcing the impression of a traditional sector resistant to change whereas the automotive companies are the most keenly aware of competitive activity.

Similarly, a survey conducted by Redman [1995] showed that customer demand for quality and reliability was the primary reason that leads to innovations in the approach to quality and reliability management. Approximately 77% of the surveyed companies held this view. Over half of the respondents said that there had been innovations due to competitive pressures. Sixty three per cent of companies reported competitive pressures to reduce cost, 55% reported competitive pressures to improve quality of products during service (i.e. reliability), while 40% of the surveyed companies reported competitive pressures to improve product design from a functional requirement perspective. Also prominent in the results reported by Redman is the effect of senior management in recent management changes. Forty per cent of organisations cited the commitment of this group as a reason for change. Again this is an encouraging sign with most writers on quality and reliability management strongly emphasising senior management commitment as a key ingredient of success.

From this review it is clear that reliability management initiatives at a business level are motivated mainly by market pressures. A recent article, published in 'Machinery and Production Engineering' [Granger, 1994], cites the general view held by UK companies on quality and reliability:

"...and from the responses, it is clear that industry recognises the importance of quality since 84 per cent of companies believe UK industry has a long-term

Figure 4.2: Reasons for Following a Quality and Reliability Policy



commitment to quality - indeed, 90 per cent of companies in the aerospace and automotive hold this conviction."

However, policies only testifies a company's commitment and importance to quality and reliability. It does not guarantee that a company has adopted, or is adopting, best practice models for ensuring overall reliability in design and production. Indeed the report itself supports this view:

> ...answers given suggest that many companies follow *some sort* of 'quality and reliability policy.'

It is indicative that the majority of UK companies recognise reliability as the first factor (alongside quality) which influence the competitiveness of the company's products. In contrast, previous studies have shown that only 26.8% place reliability first among a number of factors which affect the purchase of commercial parts and selection of vendors [Lockyer, Oakland, Duprey and Followell, 1984]. The overall position of the factors, as ranked by the respondents, are shown in Table 4.1.

Table 4.1: Ranking of Factors Affecting Purchasing and Products

Factor	**Importance to the competitiveness of the company's products**	**Importance placed by company when purchasing materials used in manufacturing**
Price/Cost	2	1
Quality/Reliability	1	2
Delivery Performance	3	4
After-sales Service	5	5
Technical Specification	4	3
1 = Highly Important	*5 = Not Important*	

Source: [Lockyer et al, 1984]

Whilst these surveys provided some positive indications of the widespread adoption of quality policies, unfortunately the findings only reflect the importance given to reliability by UK manufacturers at a business level. There is considerable evidence in the literature which indicates that many companies find difficulties in implementing reliability programmes at a functional or operational level. Recent studies of quality assurance practices of manufacturing and assembly operations from North America [Batson, 1988], United Kingdom [Sohal, Abed and Keller, 1990], Ireland [Roche and Sheil, 1986], Australia [Sohal, Ramsay and Samson, 1992] and India [Philipose and Venkateswarlu, 1980] confirm the existence of counter intuitive management behaviour and approaches towards the concepts of reliability control during manufacture. Further, there is a gap between quality control of manufacturing operations viewed as a general business strategy and the effective application of the quality assurance concept within a company. According to these studies, controlling the quality of manufacture, choosing the most relevant reliability tools and applying them in a proper way within manufacturing operations still remains a major problem in industry.

Whilst management behaviour, knowledge and understanding may have a marked impact on the adoption of reliability management practices, there is considerable evidence to suggest that other factors may be equally important. These factors include [Eisen, Mulraney and Sohal, 1992]:

- Company size, in terms of number of employees.
- Profitability - the higher the profitability the more likely it is to employ best practice models and less likely to encounter any obstacles or impediments.
- Volume of sales - companies with high gross sales volumes are more likely to be using best practice models. The findings of Eisen et al., [1992] have found a strong statistical relationship with this point.

More specifically, the work of Abed, Keller and Sohal [1989] has shown that one in five companies [18.8%] companies operate a separate reliability department and in none of the companies surveyed was reliability directly represented at board level. Of those companies who claimed to operate a reliability department, just over a fifth of the respondents claimed full responsibility for product reliability analysis and measurement, and only 14.5% claimed to have total responsibility for part evaluation and technical analysis of field failures (see Table 4.2). It is clear from the figures in Table 4.2 that many of the functions which are considered to be essential activities of a person responsible for product reliability are not under his direct control or are not being carried out.

Further review of Table 4.2 shows that the majority of the surveyed companies (over 55%) indicated that the reliability management function does not have any influence on any of the following areas:

- Product design.
- Product reliability measurement and analysis.
- New product development.
- Supplier part evaluation.
- Warranty reviews.

However, literature advocates reliability management as being an essential part of those five engineering activities [e.g. O'Connor, 1991]. It is clear from this analysis that little or no consideration is given to the various aspects of reliability assurance during the conduct of these five engineering activities. Further, since reliability management does not have any influence on these mainstream engineering activities, it raises the following question:

> "Is reliability management being practised to its full entirety in manufacturing industry?"

Table 4.2: Degree of Reliability Management Influence on Engineering Activities

Activities	Level of Responsibility (% of Respondents)			
	Complete	Partial	None	Not Applicable
Reliability Instruction	17.3	9.1	14.5	59.1
Annual Warranty Payment	3.6	5.6	29.1	61.7
Reliability Budget	8.2	12.7	19.1	60
Product Design	7.3	20.9	15.5	56.3
Product Reliability and Measurement	20.9	13.6	8.2	57.3
Maintainability Activities	11.8	20	9.1	59.1
New Product Development	6.3	21.4	12.5	59.8
Part Evaluation and Analysis	14.5	17.3	10.1	58.1
Statistical Processing	8.2	20	13.6	58.2
Annual Repair and Maintenance Costs	0.9	10	28.2	60.9

Source: [Abed, Keller & Sohal, 1989]

4.4 Impediments to the Adoption of Modern Reliability Management Techniques

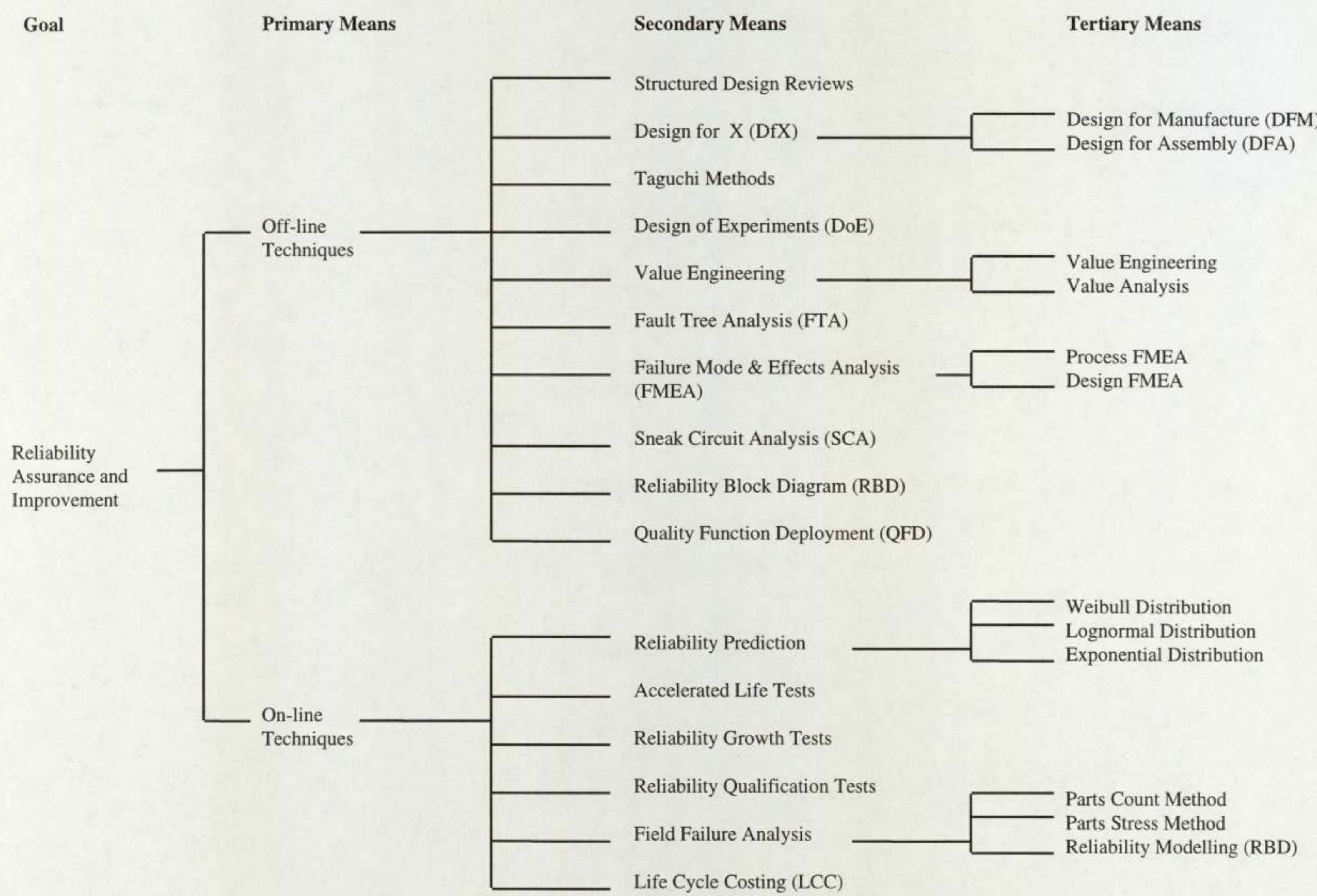
There is now a considerable literature extant describing various techniques for reliability analysis and improvement. Approximately 80 methods relating to product quality and reliability has been identified by Juran and Gryna in their

Quality Control Handbook [Juran and Gryna, 1988]. The use of these methods has been described in different ways; for example:

- As essential components of the concurrent or simultaneous engineering philosophy [Solenius, 1992; Norrell, 1993].
- Methods for quality and reliability-driven product development [Krause, Ulbrich and Woll, 1993].
- Essential techniques in support for design for X (DfX), where X can stand for quality, manufacture, reliability, assembly [Swift and Allen, 1992].
- As tools for enhancing the product development process. For example, Parvey [1994] describes the sequential integration of Quality Function Deployment, Design of Experiments and Statistical Process Control to achieve competitive advantages in product and process design.
- Methods that can be regarded as tasks for use with the more conventional approaches to reliability within the product development process. For example, development tests, failure reporting and corrective action or durability tests [Lindsley, 1994]
- Methods forming the important elements of the modern integrated approach to quality and reliability engineering [Brown, Hale and Parnaby, 1989].

The author's synthesis of these techniques is presented in Figure 4.3. The listed techniques in this illustration will be used in a later chapter of this thesis, as a

Figure 4.3: Typology of Reliability Tools and Techniques



yardstick with which to evaluate their application and perceived effectiveness in the machine tool industry.

All of the techniques detailed in Figure 4.3 are helpful in ensuring that the required degree of reliability is attained, but they can simply be considered to be good management and design practices, rather than tasks unique to a

structured reliability programme. As illustrated in Figure 4.3, these methods are categorised into two groups [Ahmed, 1996]:

Off-line Techniques : These methods are purely used for appraising product reliability requirements during the new product introduction process. In particular, these methods can be used to analyse design from a failure point of view (e.g. fault tree analysis - FTA), assess potential effects of engineering changes on the reliability of the product (e.g. FMEA), adopt a formal approach to translating customer requirements into engineering tasks (e.g. Quality Function Deployment - QFD), efficiently identify and eliminate unnecessary cost and design features which provides neither reliability, nor use, nor customer features (e.g. Value Engineering).

There are many links between these techniques because they are based upon the same set of underlying improvement philosophies which stress maximising functional performance and minimising variation. They are primarily based on the premise that upstream prevention (i.e. early in the design process) is better than detection and correction. Their use is primarily confined to the product design and manufacture process. However, these techniques have been known to be applied in process design also.

On-line Techniques : By providing the mechanism for measuring product reliability, these techniques provide the foundation for (1) monitoring reliability performance, (2) objectively identify high failure rate parts and (2) verifying and enhancing product reliability. Examples of these techniques are reliability prediction, field reliability measurement, reliability growth test.

Reliability parameters such as mean time between failure (MTBF) or mean time to failure (MTTF) are used as a mechanism for quantifying product reliability.

Despite the existence of this large body of literature on tools and techniques to be used in reliability engineering and management decisions, there is evidence to suggest that managers may often disregard such techniques in their actual decision making process. For example, having found that the larger manufacturing organisations are more likely to make use of these techniques for controlling reliability, Abed et al. [1989] commented:

> ...the study confirms the findings of previous studies that little usage is being made of the appropriate techniques (FMECA, FTA etc.) in the reliability area and the reasons given by respondents point to general lack of knowledge and understanding of the benefits to be obtained from using the techniques.

Knowledge and understanding is the most common barrier associated with the use and application of reliability-based techniques [see for example, Oakland and Sohal, 1987a]. However, there are other difficulties associated with the application of reliability-based methods. A recent technical paper outlining key factors in the successful use of tools and techniques in a process of continuous improvement, identified some common difficulties [McQuarter, Scurr, Dale and Hillman, 1995]:

- Poorly designed training and support.
- Being able to apply what has been learnt.
- Inappropriate use of tools and techniques.
- Resistance to the use of tools and techniques.
- Failure to lead by example.
- Poor measurement and data handling.
- Not sharing and communicating the benefits achieved.

The above difficulties has also been substantiated through many case studies and surveys. For example, McQuarter, Dale, Boaden and Wilcox [1996] have found difficulties associated with (1) experience of reliability-based techniques, (2) management and teamwork, (3) resources in terms cost, people, facilities, technology and time, (4) training and (5) education in terms of knowledge and understanding.

With regards to the above general difficulties associated with application of reliability-based techniques, Oakland and Sohal [1987b] have proposed a methodology for overcoming these common difficulties. The main steps of this methodology are:

1. Formalise the procedures.
2. Emphasise the need for and benefits of techniques.
3. Tackle one problem at a time.
4. The major steps in the use of techniques are (1) record ALL observed data, (2) make use of the recorded data and (3) plan for training.
5. Follow-up the implementation and training.

Whilst organisation and management difficulties are clearly significant barriers to the use of techniques, there is considerable evidence in the literature to support the view that cost-effectiveness and relevancy of application play an important role in influencing the use of reliability-based methods [Burns, 1994]. In evaluating the cost-effectiveness of any technique (particularly those of an analytical nature), the anticipated volume of production must be taken into consideration. If thousands of units are expected to be produced (e.g. high volume batch production), then the cost of using the technique (in terms resources and training) will be spread over a large number of units. Hence, the technique might be more justifiable than for low volume or one-off customer specific system or product.

As indicated in Figure 4.3, there are a number of techniques that might be considered to be relevant to product reliability development. Some of the best known include the following:

* Quality Function Deployment (QFD)
* Failure Mode and Effects Analysis (FMEA)
* Taguchi Methods and Design of Experiments (DoE)
* Value Engineering

The sequential application of the above techniques in the product design and development process have been proposed by many writers in this field [e.g. Swift, 1989; Brown et al., 1989]. For example, QFD can be used to identify key product and process features for customer satisfaction, DoE can be used to determine optimum combinations of design parameters, whereas FMEA and FTA can be used to systematically analyse the design of an engineered product to determine the effects of all possible failure modes to the functional performance of a product. Similarly value engineering principles can be used to reduce unnecessary costs and over-design of products.

The next four sections discuss the application of these techniques in the area of reliability management in more detail.

4.4.1 Quality Function Deployment

One of the most promising techniques in contemporary, customer-driven engineering is quality function deployment (QFD). It is closely related to product and process design techniques. QFD is a planning tool that allows a company to predict, through its marketing research, the performance features the customer wants and subsequently translates them into the required engineering parameters and values. Therefore, QFD ensures that what the customer wants is actually manufactured the first time around. This leads to significant reductions in engineering changes and design lead time. However, as well as ensuring that what the customer wants is actually manufactured the first time, the technique also allows a methodical way of emphasising design and process activities and control necessary to achieve reliability. Hauser and Clausing [1988] define QFD as:

> "A set of *planning and communication routines,* Quality Function Deployment focuses and co-ordinates skills within an organisation, first to design, then to manufacture and market goods that customers want to purchase and will continue to purchase. The foundation of the QFD is the belief that products should be designed to reflect customers' desires and tastes - so marketing people, design engineers, manufacturing staff must work closely together from the time a product is conceived."

There have been many other attempts to define QFD. Some of the definitions that have been widely reported in the literature are detailed in Table 4.3.

In addition to improved quality and reliability through meeting the performance requirements of the customer, QFD can also lead to a significant reduction in the lead time required to design and manufacture new products. The following example illustrates this point [McElroy, 1987]:

> "In 1977 Toyota Autobody, a Toyota subsidiary which makes bodies for small vans, began to use QFD in its design and case study development. Only two years later, Toyota Autobody was able to document a reduction in start-up costs of 20%; by 1982 the reduction was 38% and by 1984 it was 61%, while the total time needed to engineer a new van was reduced by one-third. Now it is being used throughout the company and Toyota cites QFD as one of the primary reasons why it can produce an all-new car in three years."

QFD comprises a system of highly traceable engineering procedures in a cross-functional team framework that use graphical displays to drive all phases of product development without stifling the voice of the customer. QFD-based product realisation yields clear competitive advantages over more traditional processes by promoting greater customer satisfaction, shorter time to market, and improved product performance. The power of QFD is in its effectiveness in re-examining customer defined requirements in order to establish optimum design parameters and values of a product. The key to QFD's competitive advantage is its structured application of four strategic concepts [Brown, 1991]:

- *Preservation of the voice of the customer* ensures that customer needs won't be translated or distorted in the development process.
- A *cross-functional team* provides input to product realisation from all areas of the business. Thus, the concerns of marketing, design,

Table 4.3: Definitions of Quality Function Deployment (QFD)

Definition	Reference
QFD is a system for designing a product or a service based on customer wants, involving all members of the supplying organisation. As such, it is a conceptual map for inferfunctional planning and communication.	Lynch and Cross [1991]
QFD may be defined as elaborate charts to translate perceptions of quality into product characteristics and product characteristics into fabrication and assembly requirements. In this way "the voice of the customer" is deployed throughout the company.	Garvin [1988]
QFD is a process that provides structure to the development cycle where the primary focus is the customer requirement.	Bossert [1991]
Quality Function Deployment can be defined as a system for designing a product or service based on customer demands and involving all members of the organisation.	Maddux, Amos and Wyskid [1991]
A systematic means of ensuring that customer or marketplace demands (requirements, needs, wants) are accurately translated into relevant technical requirements and actions throughout each stage of product development.	Fortuna [1988]
A detailed planning and design support technique applicable to any design process whether for services or products aimed at translating "the voice of the customer" into company specifications at every stage of the product introduction process.	Adams and Gavoor [1990]

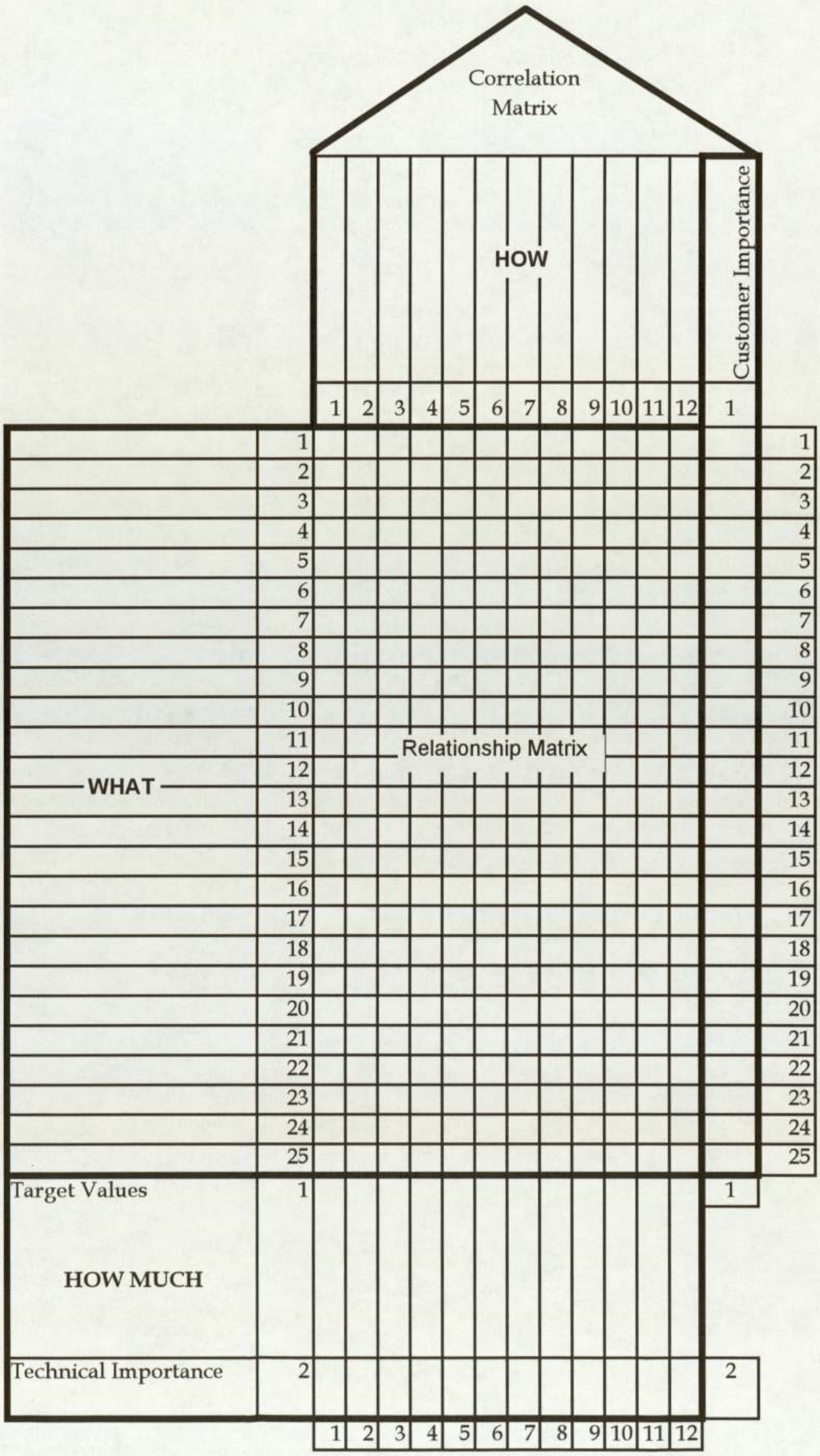
development, and support organisations are brought to the surface and dealt with early in the process.

- *Concurrent engineering* allows those parties, such as manufacturing, who have traditionally participated later in the product-realisation
- Cycle to begin planning earlier, using more accurate information. This shorten time-to-market.
- A concise *graphical display* presents a picture of the product that clearly links explicit customer needs to product realisation decisions. In the literature this graphical display is termed the House of Quality (HoQ) [Zucchelli, 1992]. It displays customer wants versus the design requirements necessary to meet them. Related product definition information (for example, customer importance, competitive position) is also displayed.

The graphical display is called the HoQ because of its shape [Wasserman, 1993]. This provides the framework that guides the product introduction team through the QFD process. The HoQ is a matrix that contains information about customer values, mechanisms to address these values in the product, and criteria for deciding which of these values in the product will provide the greatest customer satisfaction. Figure 4.4 provides a detailed illustration of the House of Quality. The areas of this HoQ [Brown, 1991] are:

1. WHAT: Identifies customer needs, which are grouped into topic areas.
    - *Customer Importance*: Contains the customer-priority rating for each of the whats'.
2. HOW: Identifies the mechanisms to fulfil the whats'. These mechanisms are best stated as design requirements or as technical characteristics of solutions, rather than a specific solution.
    - *Relationship Matrix:* Shows the relationship between the 'whats' and the 'hows.'
3. HOW MUCH: Contains target values for the 'hows.'

Figure 4.4: Schematic View of a House of Quality (HoQ)



- *Technical Importance*: Shows the customer-satisfaction effect of each 'how.' Typically, the strength of each relationship is multiplied by the customer-importance rating. Then each cell values in a given column is summed.

- *Correlation Matrix*: Shows the interaction among the 'hows.'

Using the concept of HoQ, detailed above, customer requirements, or the 'voice of the customer' as they are sometimes called, are cascaded down through the product introduction process in four separate phases [Brown et al., 1989; Swift et al., 1989]. Figure 4.5 illustrates this cascade effect of QFD. In phase 1 of QFD, customer requirements or attributes (inputs) form the rows of the matrix structure where the columns are represented by product design features and functions. The need is then to transfer the important features and functions to the rows of the next matrix where the columns are the component characteristics (see Figure 4.5). In this way, customer requirements are cascaded down through the product introduction process keeping the effort on the important issues and thus a direct link is formed from the 'voice of the customer' (design requirements inputs in phase 1) to actual shop-floor operations. (outputs from phase 4).

A further development of QFD [Clausing, 1986] relates to the inclusion of a number of enhancements, namely as follows:

- The analysis of complex products on different levels such as system, sub-system and component;

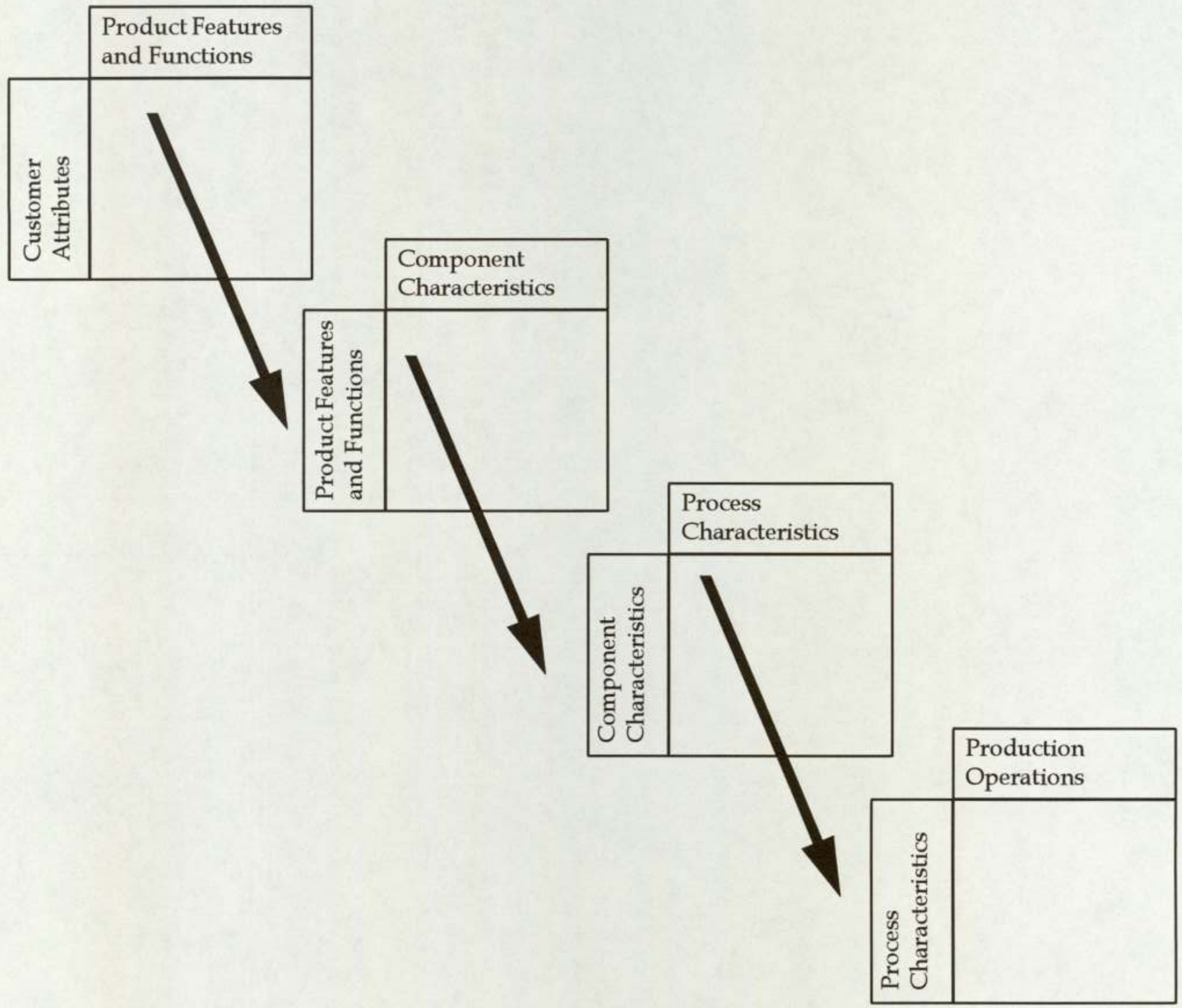
- The introduction of a design concept selection technique;

- A status evaluation method, which indicates whether a design concept is static or dynamic;

- Where benchmarking techniques such as parameter analysis can be used to plot two characteristics against one another;

- The use of a generic structure of requirements, to help with the compilation of the needs.

Figure 4.5: The Cascade Effect of QFD



The QFD process facilitates the definition, documentation and ranking of customer requirements and as such provides a sound basis for design concept selection. QFD is best suited to teamwork, having valuable team building qualities, and represents a significant contribution beyond the more traditional design methods [Lockamy and Khurana, 1995; Zairi and Youssef, 1995]. Theoretically, the use of QFD can lead to a wide variety of benefits [Sullivan, 1986], it can help:

- Better customer satisfaction resulting from improved quality and reliability of design.
- Shorter lead times due to fewer and earlier engineering changes.
- Better linkages between various design and manufacturing stages.
- A reduction in the number of product components.
- An improved work atmosphere through the horizontal integration of functions.

The QFD technique was born in Japan as a strategy for assuring that reliability and quality is built into new products. QFD was first used in 1972 by Kobe Shipyard of Mitsubishi Heavy Industries Ltd [Akao, 1990] and was then referred to as quality tables. Japanese companies attribute tangible benefits to the QFD process such as low product cost, high quality and reliability and shorter development lead times. More specifically, recent surveys conducted on the spread of QFD in Japanese industry reported numerous design-related and organisational benefits [Hauser and Clausing, 1988; McElroy, 1987]. Table 4.4 details the benefits identified by this survey.

While the use of QFD in Japan has increased over years, its extension to the West, was, however, very slow. The first examples of using QFD in the USA did not emerge until 1986 when companies such as Ford, Rank Xerox Chrysler first introduced it [Griffin, 1992; Eureka, 1987]. Subsequently other companies started to introduce it, for example; AT&T Bell Labs, Digital Equipment, Procter and Gamble and Hewlett-Packard. In the UK the uptake of QFD is

Table 4.4: Design and Organisational Benefits of QFD

Design Benefits	Organisational Benefits
Fewer and Early Design Changes	Encourages Teamwork
Less Time in Development	Encourages Documentation of Marketing, Design and Manufacturing Knowledge in a Consistent and Objective Manner
Fewer Start-up Problems	
Lower Start-up Cost	
Fewer Field Problems	

Source: [Hauser and Clausing, 1988]

very recent and there are only a few isolated cases of companies trying to experiment with it, for example Lucas Industries plc [Brown et al., 1989].

4.4.2 Failure Mode and Effects Analysis

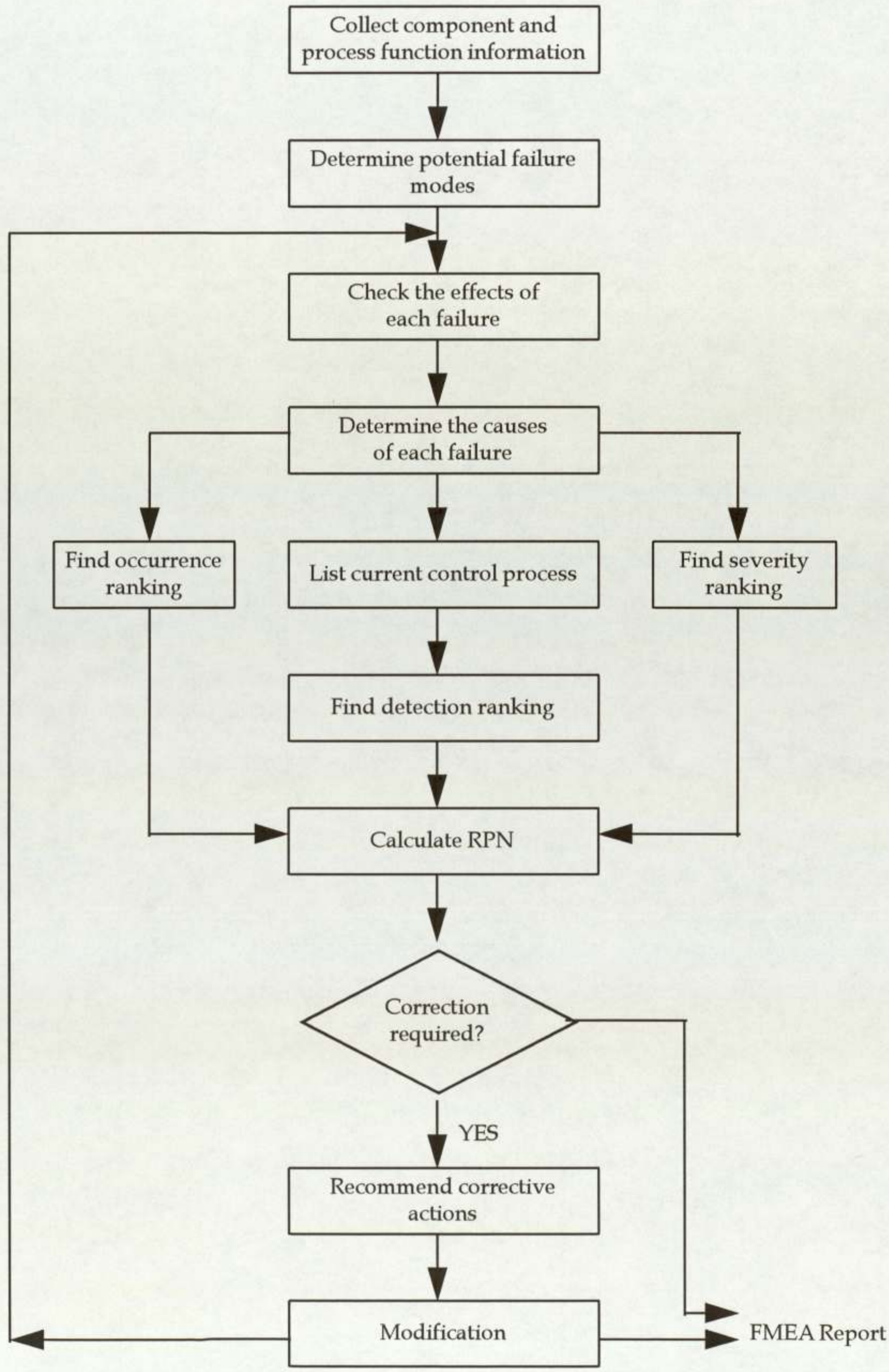
Failure Mode and Effects Analysis (FMEA) is now a very familiar tool which is extensively used in both design and process activities. This section primarily discusses Design FMEA. QFD and FMEA are complimentary as the first is targeted at satisfying customer expectations, the second at preventing failure to satisfy. FMEA from a product design point of view can be defined as: [Ahmed and Bates, 1996]

> "an extremely objective method of analysing designs in order to identify modes of failures (i.e. the way in which the product could fail), the effect of failure and to identify priorities for eliminating or reducing the scope of failure."

Therefore, the main objective of FMEA is to assist in the design process by identifying the effects of component or sub-system failures on the system operation [MIL-STD-1629A, 1980]. Essentially, the technique is a cross-functional activity that sets out to capitalise on the advantages of concurrent engineering. Where FMEA is carried out, it forms an essential part of the design and manufacturing process and should be integrated with all other design and manufacturing activities. Outputs from FMEAs can be used as inputs to formal design reviews leading to improvement of the design, spare parts planning for high risk components identified by the FMEA, or identification of areas for specific attention during assembly [Ahmed et al., 1996].

Figure 4.6 reveals the general procedure of the FMEA process. There are three stages that are very critical in the FMEA process to ensure the success of the analysis [Teng and Ho, 1996]. The first stage is to determine the potential failure modes, their effects and root causes. The second stage is to find the data for occurrence, detection and severity rankings and calculate the risk priority numbers (RPN) for each failure mode. RPN is the product of the occurrence,

Figure 4.6: A Typical FMEA Procedure



detection and severity rankings. A ranking of 1 - 10 is normally used. The third stage is the modification of the current product design to reduce the

RPNs. Figure 4.7 illustrates a typical FMEA worksheet used to document the analysis [SMMT, 1989].

A total understanding of the product and process functions and careful gathering of data ensure the correctness of the FMEA report. The usefulness of the FMEA depends on the stage of the process. To modify the design to eliminate the failure modes and to develop the process control plan to reduce the occurrence of failures to a minimum, are the major goals for the implementation of FMEA.

A step by step guide to the use of the FMEA technique is described in Part 5 of BS 5760 [BS 5760, 1991] and Military Standards [MIL-STD-1629A, 1980]. Similarly major engineering organisations [e.g. Ford, 1988; Jaguar, 1986; Lucas, 1986] have published their guidelines on FMEA, as have the Society of Motor Manufacturers and Traders [SMMT, 1989]. However, there appears to be little published research on how organisations use FMEA and its effectiveness as a tool for product reliability improvement during design and manufacture.

Compared to other reliability-based techniques (e.g. QFD and DoE), the application of FMEA is generally well established in the manufacturing industry [Balachandra, 1983; Brown et al., 1989]. In particular, the use of FMEA is fairly widespread in the UK automotive industry [Lieberman, 1990; Dale and Shaw, 1989; Aldridge, Taylor, and Dale, 1991]. However, the widespread use of FMEA needs to be put into context. It appears that the implementation and use of the FMEA process is primarily driven by demanding customers, rather than being internally driven by the company using it. A recent survey conducted by Dale and Shaw [1990] on the use of FMEA by Ford Motor Company's UK suppliers concluded that the primary reason for using the technique was to conform to the contractual requirement of Ford's Q-101 [Ford, 1987] quality system. Indeed, Ford now require all first-line suppliers to provide evidence of the use of Design and Process FMEAs.

Figure 4.7: A Typical FMEA Worksheet

DESIGN/PROCESS FMEA WORKSHEET

FMEA No. ____________
Sheet ______ Of ______

Part or Assembly Name ____________________
Part or Assembly Number ____________________
Drawing Issue ____________________

Amendments	1	2	3	4	5	6	7	8	9	10
Date	Original									

FMEA Committee	
FMEA Approved	Date
Name	Signature

ITEM	Part No.	Function	Failure mode	Effect of failure	Cause of Failure	Current Controls	Current Status				Recommended Corrective Action	Action by	Action Taken	Revised Status			
							OCC	SEV	DET	RPN				OCC	SEV	DET	RPN

Source: [SMMT, 1989]

However, from this survey it was clear that the technique stipulated as a contractual requirement by a major customer on its supplier community goes through a maturity effect, as Dale et al. [1990] commented:

"... the first phase is for the supplier to do the minimum in application of a particular technique in order to pass the customer's assessment of its quality assurance system. During this phase the supplier resorts to a number of camouflage measures in a bid to convince the customer that they are serious about application of the technique. The theme of this phase is satisfying the paperwork requirements. The second observable phase is where the supplier starts to question how they might use the technique to their own advantage in order to advance the process of quality improvement...."

Although this evidence indicates that the majority of organisations are preparing FMEA because of contractual requirements, other reasons given by respondents were to improve product reliability, quality, design and customer satisfaction. Reduction of warranty claims and concerns about the regulations governing product liability were also mentioned by respondents.

Empirical evidence suggests that in the current applications of FMEA, many companies terminate their FMEA process whenever their FMEA report is done [Raheja, 1981; Rudy and Wang, 1990]. In such circumstances, companies waste a great deal of effort, time and resources in the FMEA process. The main purpose of FMEA is to reduce the scope of potential failures upstream in the design and manufacture cycle. Problems associated with FMEA implementation include the timing of the process at the product design stage, the establishment of a well trained and balanced FMEA team, the co-ordination of individual departments in generating an accurate FMEA report and agreement by all relevant functional areas to use FMEA reports as a cornerstone to solving product design problems.

The feasibility of integrating FMEA with other reliability-based techniques has also been examined by writers. For example, the combining of sneak circuit analysis (SCA) and FMEA as a comprehensive reliability analysis technique for electronic systems and circuitry design have been proposed [Jackson, 1986; Savakoor, Bowles and Bonnell, 1993]. Whereas FMEA examines the ways in which a system fails, SCA looks for latent circuit conditions which may lead to unexpected modes of operation. SCA can be implemented by applying operational clues to the functional block diagram of an electronic system. Some of them are:

1. Do functions perform as intended?
2. Are all the functions and grounds compatible with the power sources?
3. Is power available when required to activate a function?
4. Are connected grounds compatible?
5. Are connected power sources from different power buses (i.e. is there a potential power to power tie)?
6. Can any functions be activated inadvertently or at incorrect times?
7. Are there undesired effects when a current or energy path is unintentionally opened or closed?
8. Can any combination of functions be activated by an unintended current or energy path?

SCA is combined with FMEA by using the SCA sneak circuit detection rules to identify sneak conditions, design weaknesses and improper system operations resulting from a device failure. The Rome Air Development Centre (RADC) have developed various sneak circuit detection rules for use during electrical and electronic system design [cited in Savakoor et al., 1993]. Table 4.5 illustrates an example of a SCA rule base for use in early design phase, whereas Table 4.6 details the rule base for use with functional system design. Conversely, the effects of sneak conditions that cause failures by over stressing components or causing incorrect or prohibited operations can be identified by the FMEA. Similarly, Lieberman [1990] discusses the use of FMEA in transforming each failure mode into a mathematical model. The model and the available statistical data then can be employed in Fault Tree Analysis (FTA) to uncover single-point failures in complex system operations.

Table 4.5: SCA Rules Base for Use In Early Design Phase

Rules related to circuit structure and orientation are used during early design phase for conceptual validation and to help avoid many common causes of sneak circuits.

Circuits involving multiple power sources and/or multiple ground returns:

Circuits should be structured so that all current for a given load flows from one power source to one ground return.

If this is not possible, power sources should be isolated using diodes for DC power or relays for AC and DC power.

Returns should be isolated by separating high and low current loads.

Ground side switching:

Current interrupting elements (switches, relays, circuit breakers, fuses) should not be placed in ground return paths.

In case connectors are required on the ground side of the load then supply and ground return paths should be kept symmetrical.

This precaution avoids the 'H' topological pattern which is a common source of reverse current flow.

Power and ground connectors:

Separate connectors for power and ground return lines should be avoided.

The Redstone mishap would have been prevented if power and return lines had been routed through the same connector.

Wired-OR circuits:

Sneak paths are caused by selecting alternate paths in wired-OR circuits.

They should be used only where the effect produced by the alternate conditions are exactly the same.

When an alternate condition causes additional or modified effect, isolation should be provided.

Memory power switching:

Momentary loss of power to volatile computer memory and other essential loads during switch-over to an alternate source causes sneak timing.

For small memories, break-before-make switching with sufficient capacitance to maintain voltage during switch-over will avoid this problem.

For large memories or to protect against a short on the main supply, make-before-break switching along with diode isolation should be used.

This prevents partial or complete loss of data.

Switch labelling:

Switches should be labelled clearly about the action performed in addition to the object being controlled.

Table 4.6: SCA Rules Base for Use with Functional System Design

Rules used when functional diagrams at the sub-system level are available to identify functional networks commonly associated with sneak conditions. These rules are applicable to power distribution circuits, switching circuits, sneak timing and sneak labels and indications.
Asymmetrical pattern of connection for power distribution and ground return circuitry:
The same circuit connection topology should be used for both the supply side and ground side of the load.
The same connector should be used for symmetrical power and ground connections.
Power-to-power ties between supplies providing power to a common load:
Diodes should be used to isolate DC power supplies.
Double-throw relays or break-before-make switches can be used for either AC or DC power to elect supply.
Adequate capacitance should be provided at the load to hold up the voltage during switch-over.
Multiple supplies unintentionally enabling a shared load:
The logic and timing of the power control circuitry should be thoroughly analysed to ensure that all power sources sharing a common load are switched off when the load must be disabled.
Power-to-power path between supplies providing power loads sharing a common, independently switchable ground:
Switching elements other than those associated with circuit connections should not be placed on the ground side of a load.
For circuit connections, power and ground connections should be combined in the same connector.
Difference in ground potential between two interfacing assemblies (e.g. two PC boards):
Interfacing circuitry should share a common ground. Voltage differences caused by IR drop should be minimised by keeping ground return paths between assemblies as short as possible and by using adequate wire gauges or bus bars.
Mixing high and low current grounds within a circuit:
Separate ground return paths should be provided for high current and low current loads

Table 4.6: SCA Rules Base for Use with Functional System Design

Rules used when functional diagrams at the sub-system level are available to identify functional networks commonly associated with sneak conditions. These rules are applicable to power distribution circuits, switching circuits, sneak timing and sneak labels and indications.

Switching devices controlling shared loads:

Unintentionally enabling of a load connected to more than one switch by the closing of a switch can be avoided by placing a diode or relay between the load and the switch in question.

Similarly, unintentionally disabling of a load by a switch being opened is prevented by connecting the load in question to a switch directly tied to the power source or by adding a switch dedicated to controlling the load in question.

Sneak timing in digital circuitry:

Logic and timing errors can be caused by a digital signal that splits and later recombines which could result in sneak timing.

The signal path through a complete cycle (e.g. ON-OFF-ON) should be analysed to ensure correct logic and timing.

Timing skew problems can be corrected by providing a clocked data buffer (e.g. a latch) to sample stable data at the point where they recombine.

False data can be caused by interfacing digital devices powered by different supplies.

This can be prevented by ensuring that interconnected digital devices share a common power supply.

If this is not possible, circuit outputs must be considered invalid until all supplies are powered up and all registers reset to their initial states.

Sneak labels and indications:

Signal labels: Interface signals can be routed to unintended places.

Signal names on both sides of an interface should be checked.

In an indicator circuit that depends upon the function it monitors for proper operation, ensure that indicator power and drive signals are present even when the monitored function has been turned off, disconnected or is inoperative due to a failure.

This prevents inhibition of indicator circuitry when the function operates in an improper or an unexpected manner.

Given the iterative nature of the FMEA process, there is considerable need for improved computerised aids to reduce the effort in preparing and analysing FMEAs. In this context, the automation of FMEA has recently received much attention. Attempts to automate FMEA have progressed from commercially available packages which assist with clerical functions, data collection, database manipulations, and automatic report generation, to prototype packages incorporating Artificial Intelligence (AI) techniques [Luthra, 1991; Russomanno, Bonnell and Bowles, 1993]. The more sophisticated computer-aided techniques emphasise system simulations that predict the effects of item failures. These simulations utilise numerical models [Lehtela, 1990], rules of device behaviour [Kamhieh, Cutts and Purves, 1988] and even qualitative equations representing the causal behaviour of components [Bell, Cox, Jackson and Schaefer, 1992]. Table 4.7 highlights the advantages of automating FMEA in terms of a simple computerised database are [Kukkal, Bowles and Bonnell, 1993].

Table 4.7: Advantages of Using a Database for FMEA

Meaningful Division and Manipulation of Data
Faster Access of Data of Complex Systems
More Specific Help Facilities Makes the FMEA Less Time Consuming
Promotes the Use of Consistent Terminology within the Organisation
Validity Checks Enable Incompleteness of Data to be Identified
Easy Maintenance of FMEA Worksheets Since Data is Divided into Groups
Promotes Generation of Transportable and Re-usable Data
Ease in Forming Custom Libraries in terms of components, failure modes etc.
Fast, Easy and Specific Browsing of Similar Projects
Data Can be Used as Input for other Reliability Techniques

The overall methodology of the FMEA process and the problems associated with has also been discussed and better methods have been proposed. For example, a recent paper identified that existing published guidelines on FMEA do not address themselves to the computation of RPN's for all modes of failure for each item and module of the system of interest to the analyst [Zaitri, Keller, Barody and Fleming, 1991]. The following fundamental problems were identified:

- General problems with the tabular method of recording the FMEA analysis. For example, there is an argument to list all failure modes, effects and causes on a modular basis (natural grouping of components or sub-systems) rather than on a component or sub-system basis for complex systems.
- Problems with FMEA terminology in terms of ambiguity. For example a failure mode can be a cause, a cause can be an effect and vice versa.
- Confusion with occurrence, severity and detection rankings. For example are detection rankings related to failure modes or to failure cause?
- Computation of RPNs. Published guidelines on FMEA either define RPN as the sum of occurrence, severity and detection rankings or sometimes the product of all three rankings.
- Computation of RPNs for a failure mode. In many cases, RPN is calculated by summing all RPNs of a particular failure mode which defeats the objectivity of the FMEA exercise.
- Presentation of results. With ordinary tabular form, it is difficult to trace or cross reference a particular failure mode, cause or effect.

In view to this, a methodology based on probability theory was proposed to calculate RPN's for every recorded failure cause. The probabilistic approach presented is extended to calculate Priority Indices for every recorded failure mode (FMPI), component (CPI) and finally for the total system (SPI). These recorded qualitative and quantitative information is stored in an ordered matrix format. Similar representation of FMEA information in matrix forms have also been previously explored by Barbour [1977] and Legg [1978].

More recent literature on alternative methods for preparing FMEAs advocate functions to be treated as virtual components at a more abstract level in analysis [Sexton, 1991]. In Figure 4.8, virtual components (i.e. functionality from Level 3) and real components from Level 2, along with other functional components at Level 2, make up an overall assembly at Level 1.

Typically, a FMEA considers each physical component of a product, system or unit based on a structural taxonomic decomposition. Hence, any model of the system bases its relationships on physical parts (i.e. the system's topology). However, the functional decomposition, reveals more about the system's operation and functions. For example, an organisation of the device around functions does not limit the knowledge base to a physical-functional match (i.e. a function coincides with a physical component or subsystem). Rather, high level concepts can be considered. Figure 4.9a and 4.9b illustrates this principle of structural and functional decomposition of FMEA, using a portable communications gear as an example [Russomanno et al., 1993].

In particular, the author himself identified a fundamental flaw in the use of the term FMEA. Invariably, some writers use the term 'failure *mode* and effects analysis,' while others use the term 'failure *modes* and effects analysis. The correct terminology as defined in BS 5760 is 'failure *mode* and effects analysis [BS5760, 1991] and should be referred to when writing about any aspect of FMEA.

4.4.3 Value Engineering

Unlike, other reliability-based techniques value engineering (VE) has been accepted and practised continuously by manufacturing industry. For example, a recent 'Quality in Manufacturing Survey' [Benchmark, 1994] found that

Figure 4.8: A Functional FMEA Methodology

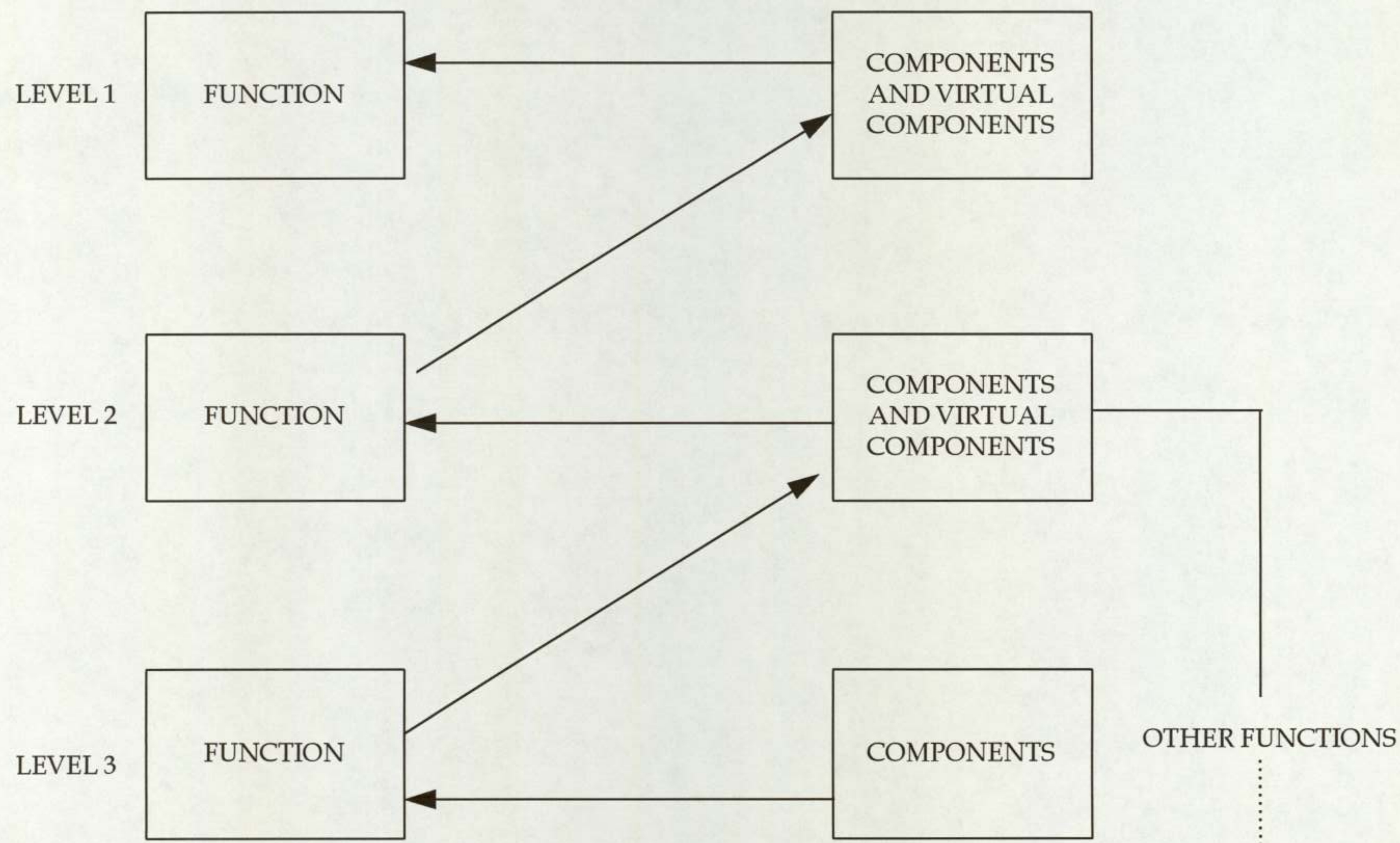


Figure 4.9a: Structural Decomposition of FMEA

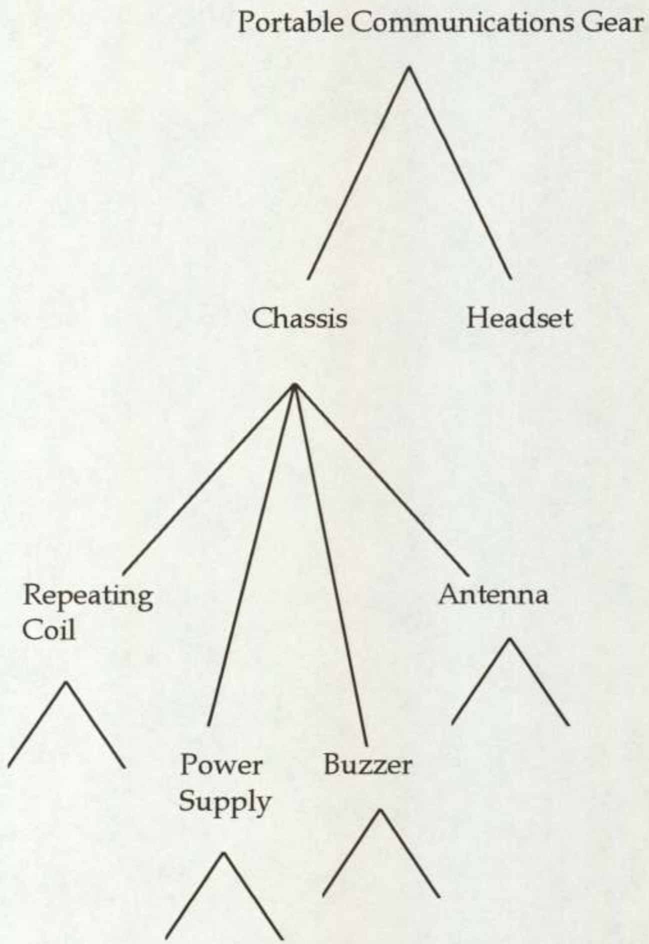
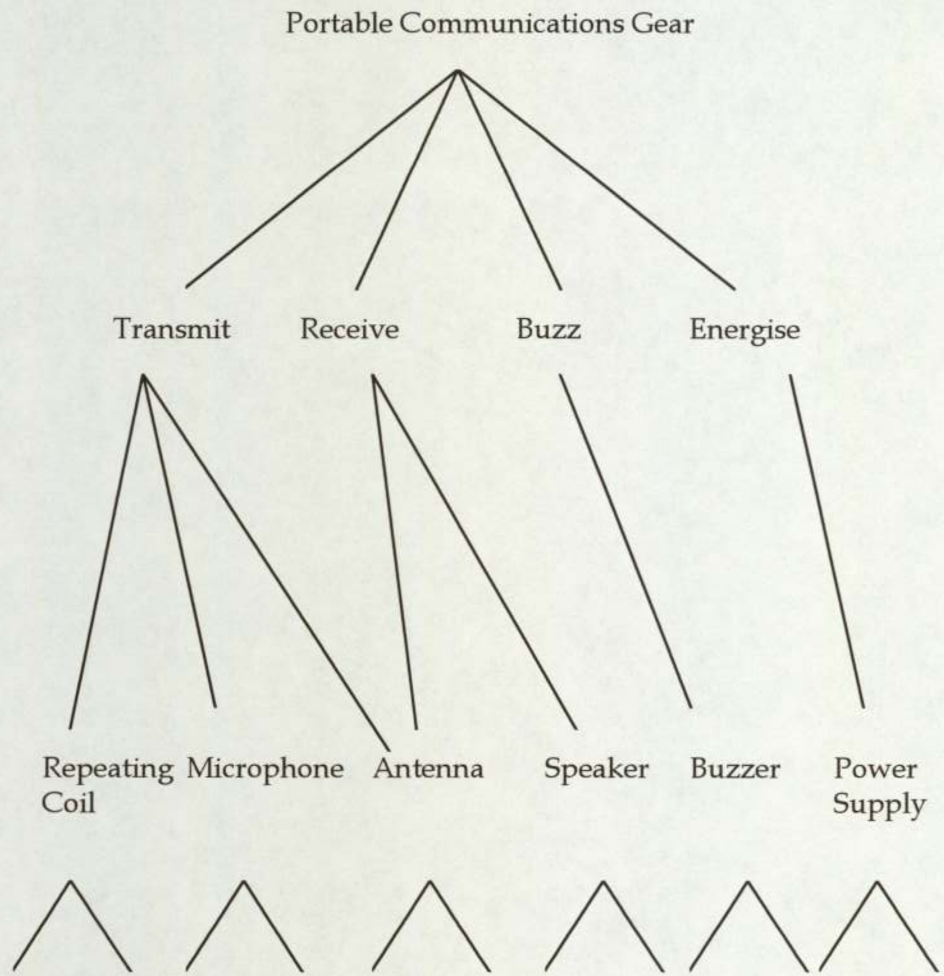


Figure 4.9b: Functional Decomposition of FMEA



approximately 50% of the respondents were practising VE for reasons of reducing product design and manufacturing costs without lowering the functional requirements of the product (see Figure 4.10). This is primarily because VE has no formal methodology associated with it and does not require any documentation to record the results of the analysis.

In the literature, value engineering is divided into two categories [Fowler, 1990]. However, the term VE is used for both categories;

Value Analysis: This is an organised functional approach which has for its purpose the efficient identification and elimination of unnecessary cost, i.e. cost which provides neither quality or reliability, nor use, nor life, nor appearance, nor customer features.

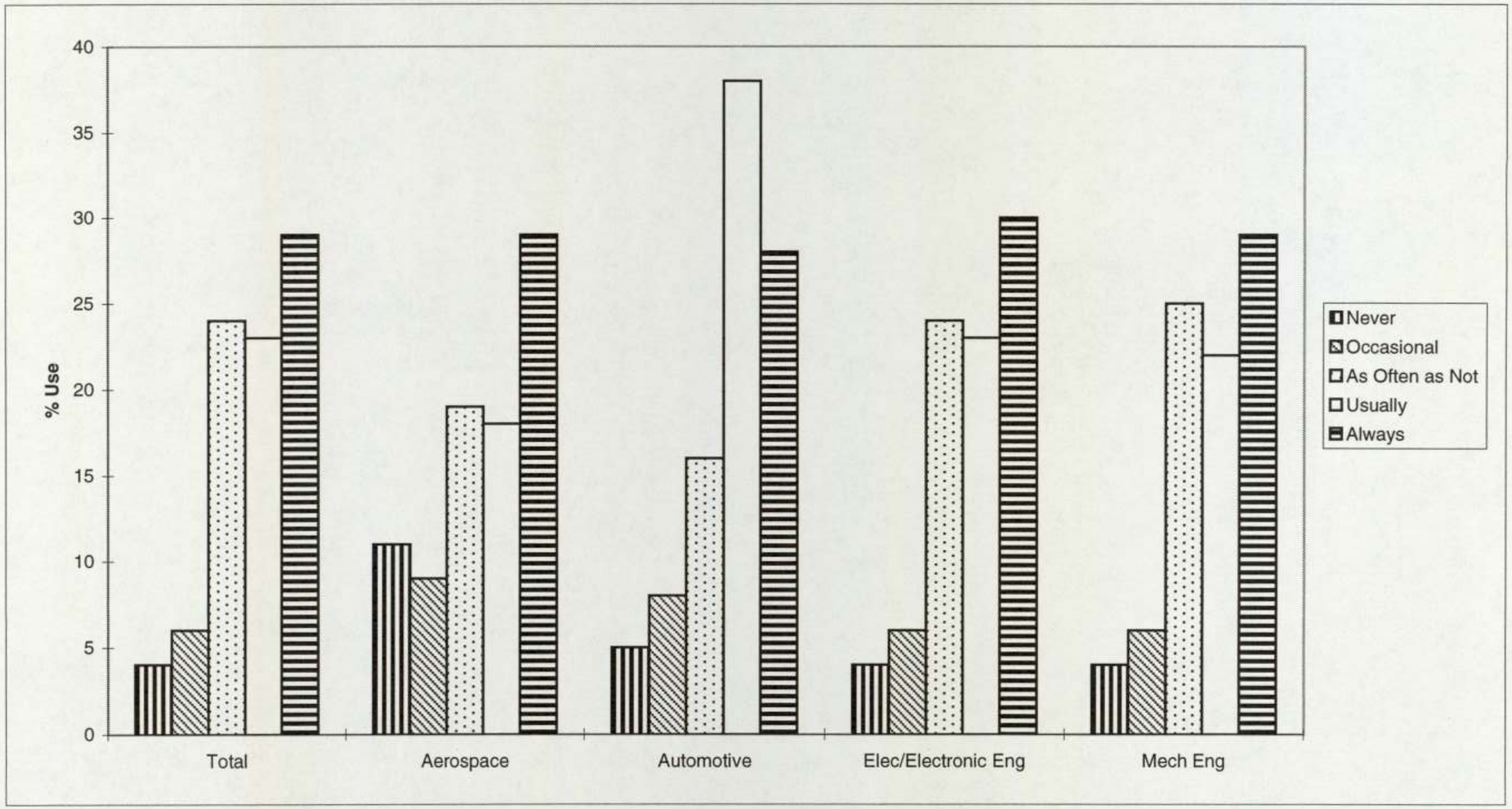
Value Engineering: This is in principle the same as value analysis but whereas value analysis is applied to a product that is in production, value engineering is applied at the design stage.

Below are listed some of the basic questions which will be asked of any component in value engineering exercise:

1. Does it use contribute Value?
2. Is its Cost proportionate to its usefulness?
3. Are all its features necessary? (i.e. does it contribute to use or life?)
4. Is there anything Better for the intended use?
5. Can a part be made by lower Cost Method?

Therefore, value engineering is an organised effort directed to analysing the functions of each product, component by component, for the purpose of achieving the required function at the lowest cost, consistency with quality, performance, reliability and maintainability requirements. It is important to understand that VE is rather more than that which is normally regarded as cost-cutting. To many people, cost-cutting means a review of things as they

Figure 4.10: Frequency of Use of Value Engineering



Source: [Benchmark Research, 1994]

are, whereas value engineering is a systematic examination of each component, assembly or sub-assembly, including bought-out parts. It covers design, materials, engineering, manufacturing, purchasing and even packaging. After considering all these factors, step by step, then ways of performing the same function at a reduced cost without lowering reliability, performance or appearance are investigated.

4.4.4 Taguchi Methods

Genichi Taguchi's [Taguchi, 1986] strategy of designing a product so that its performance is insensitive to noise factors, i.e. manufacturing factors that cannot easily be controlled or factors over which one has little control, such as the environmental conditions in which the product is used, has attracted much attention in recent years [Phadke, 1993; Bisgaard, 1993; Coleman and Montgomery, 1993; Barker, 1986; Ross, 1988]. Table 4.8 provides a comparison of Taguchi methods against the traditional quality and reliability approach to design. As with many innovative approaches to quality and reliability improvement, Taguchi methods were originally implemented in Japan. In an interview [Ealey, 1993] Taguchi stated:

> "Because quality gets neglected upstream in the process, Western companies have been forced down the expensive route of inspecting products, scrapping them that do not fall within specifications limits, reworking those that are close, and spending heavily on warranty. In effect they have not attached a cost to quality. Among Japanese managers, by contrast, attention to quality is usually driven by the need to slash costs."

Taguchi developed a framework for statistical design of experiments adapted to the particular requirements of engineering design. He suggested that the design process consists of three phases:

- System Design
- Parameter Design
- Tolerance Design

Table 4.8: Comparison of Taguchi Methods and the Traditional Quality Approach

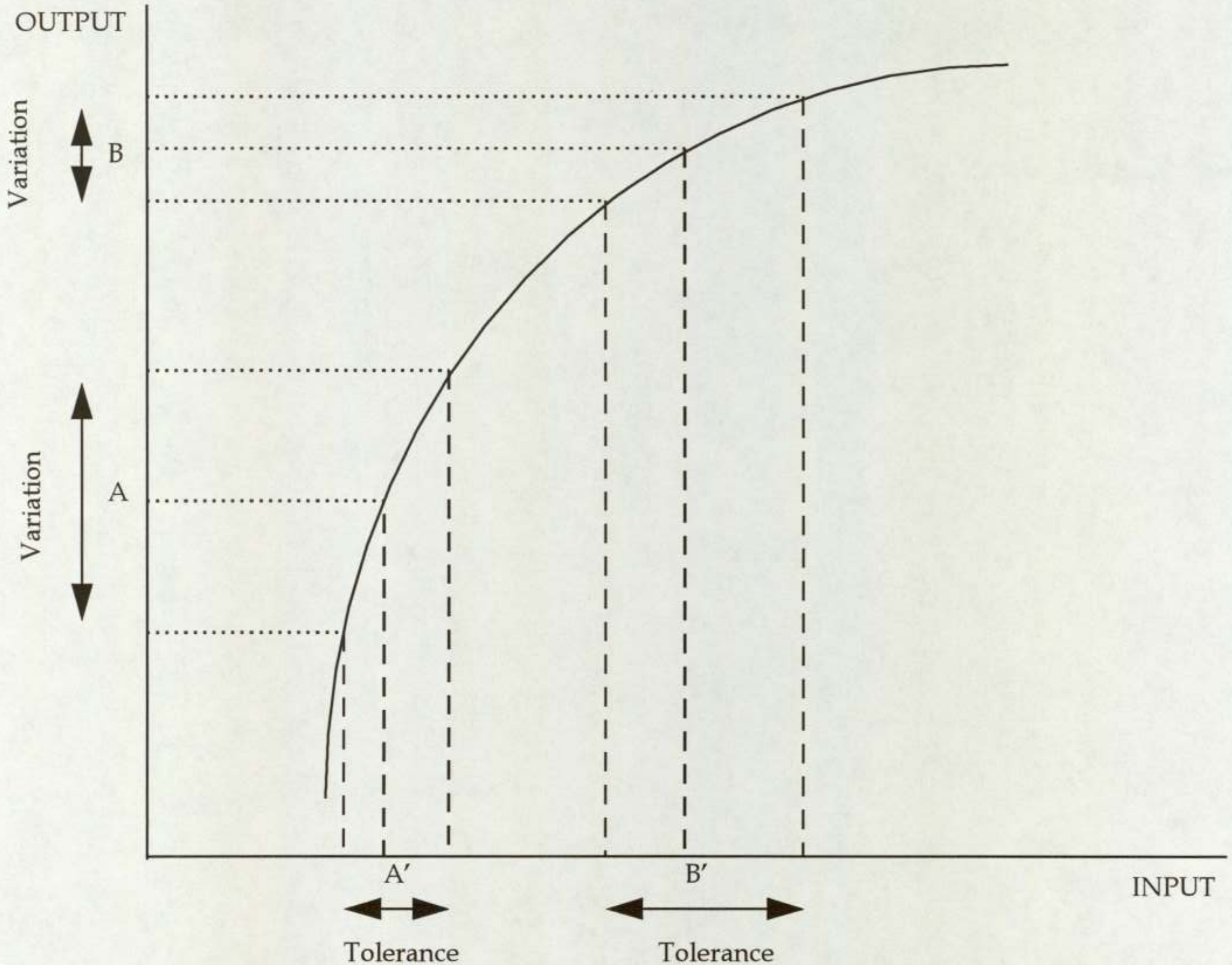
	Traditional	Taguchi
Stage of Study	After drawings and specifications are finalised.	Before drawings and specifications are finalised
Content	To meet specifications; to adjust means.	To dampen environmental effects; to reduce variability.
Method	Tolerance design.	Parameter Design.
Cost	High (factorial style experiments).	Starts from low-cost material and component parts.
Continuation	Stops when the problems are solved and specifications are met.	Quality process continues to optimise process.
Attitude	Problem solving, failure analysis, study of existing problems.	Optimisation to avoid future problems.
Philosophy	Mathematical models are important.	Discovery of control factors whose effects are consistent. Such effects may be reproducible for unknown factors. Adjust control factors to optimise results with minimum variability.

In the *system design* phase the basic concept and calculation of the parameter values to provide the performance required are decided upon by using theoretical knowledge and experience. In *parameter design*, these values are refined in order to optimise the performance in relation to factors and variation which are not under the effective control of the designer. This ensures that the design is 'robust' in relation to these factors and variation. The final phase of Taguchi's design framework is *tolerance design*. In this phase, the effects of random variation of manufacturing processes and environments (i.e. field operation) are evaluated, to determine whether the design of the product and the production process can be further optimised, particularly in relation to cost of the product and the production processes. In proposing the framework, Taguchi assumes that the design process includes the design of the production methods and their control. Parameter and tolerance design are based on statistical design of experiments.

Taguchi separates variables into two types. Control factors are those variables which can be practically and economically controlled, such as a controlled dimensional or electrical parameter. Noise factors are the variables which are difficult or expensive to control in practice, though they can be controlled in an experiment, e.g. ambient temperature, or parameter variation within a tolerance range. the objective is then to determine the combination of control factors settings (design and process variables) which will make the product have the maximum 'robustness' to the expected variation in the noise factors. The measure of robustness is the 'signal-to-noise' ratio, which is analogous to the term as used in control engineering.

Figure 4.11 illustrates the approach [O'Connor, 1991]. This shows the response of an output parameter to a variable. This could be the operating characteristic of a transistor or of a hydraulic valve, for example. If the desired output parameter value is A, setting the input parameter at A', with the tolerance shown, will result in an output centred on A, with variation as shown. However, the design would be much better, i.e. more robust to variation of the input parameter, if this were centred at B', since the output would be much less

Figure 4.11: Taguchi Method - Response of an Output Parameter to a Variable



variable with the same variation of the input parameter. The fact that the output value is now too high can be adjusted by adding another component to the system, with a linear or other less sensitive form of operating characteristic. This is a simple case for illustration, involving only one variable and its effect. For a multi-dimensional picture, with relationships which are not known empirically, the statistical experimental approach must be used. Figure 4.12, illustrates the concept when multiple variations, control and noise factors affect the output of interest.

The case where multiple variations and their effects is best illustrated by an example [O'Connor, 1991]. Table 4.9 shows the results of a Taguchi experiment on a fuel control system, with only the variation in components A, B and C being considered to be significant. These are then selected as control factors. The effects of two noise factors, X and Y, are to be investigated. The design must be robust in terms of the central value of the output parameter, fuel flow, i.e. minimal variation about the nominal value. Figure 4.13 shows graphically the effects of varying the control factors on the mean response and signal-to-noise ratio. The variation of C has the largest effect on the mean response, with A and B also having effects. However, variation of B and C have negligible effects on the signal-to-noise ratio, but the low value of A provides a much more robust design than the higher value. This is a rather simple experimental design, to illustrate the principles. Typical experiments may utilise rather larger arrays for both the control and noise factors.

The experimental framework uses fractional factorial designs. Taguchi argued [Taguchi, 1986] that in most engineering situations, interactions do not have significant effects, so that much reduced, and there therefore more economical, fractional factorial designs can be applied. When necessary, subsidiary or confirmatory experiments can be run to ensure that this assumption is correct. Taguchi developed a range of such design matrices, or orthogonal arrays, from which the appropriate one for a particular experiment can be selected. For example, the 'L8' array is a sixteenth fractional factorial design for seven variables, each at two levels. The L refers to the Latin square derivation.

Figure 4.12: Taguchi Method - The Effect of Multiple Variations, Control and Noise Factors to the Output Parameter

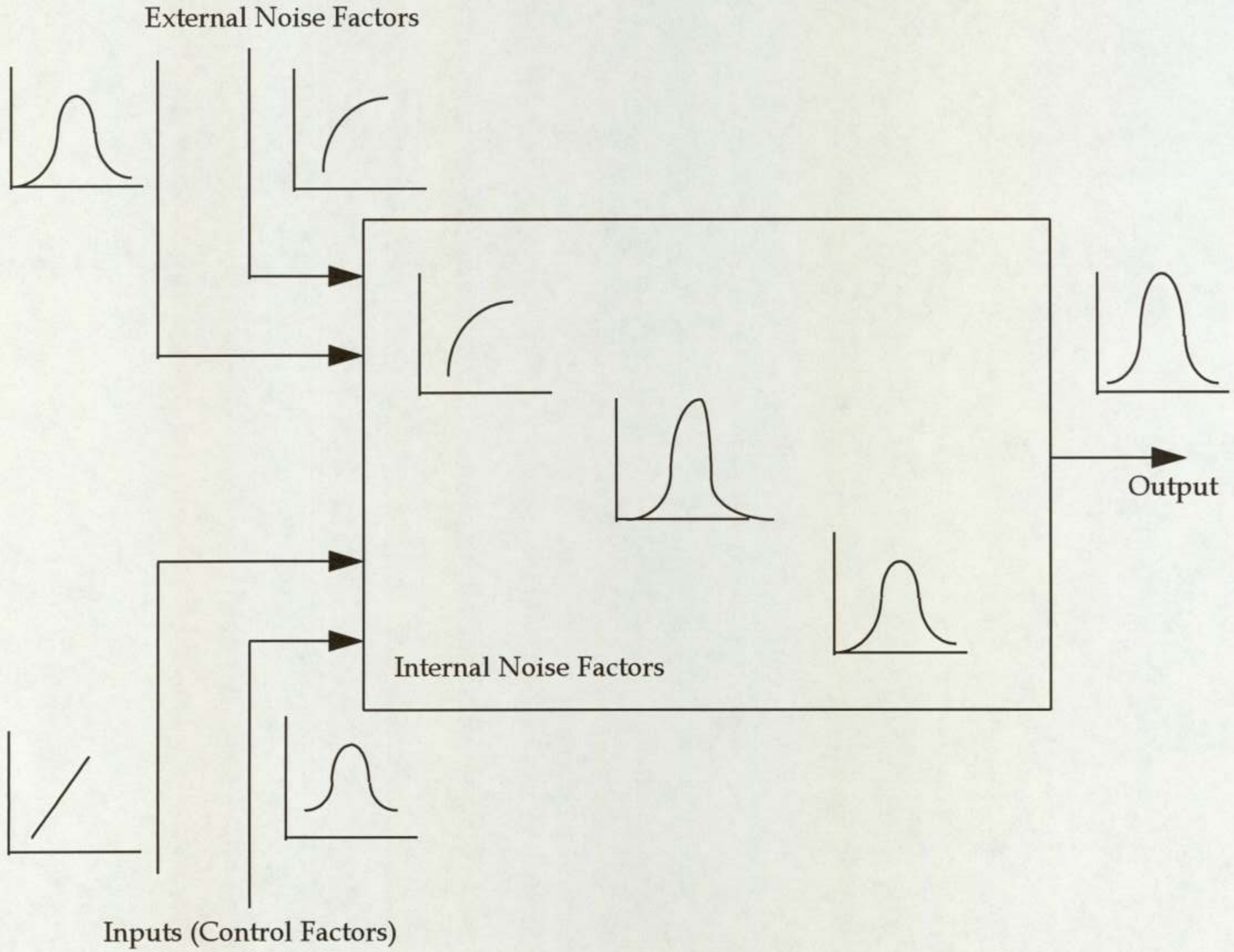
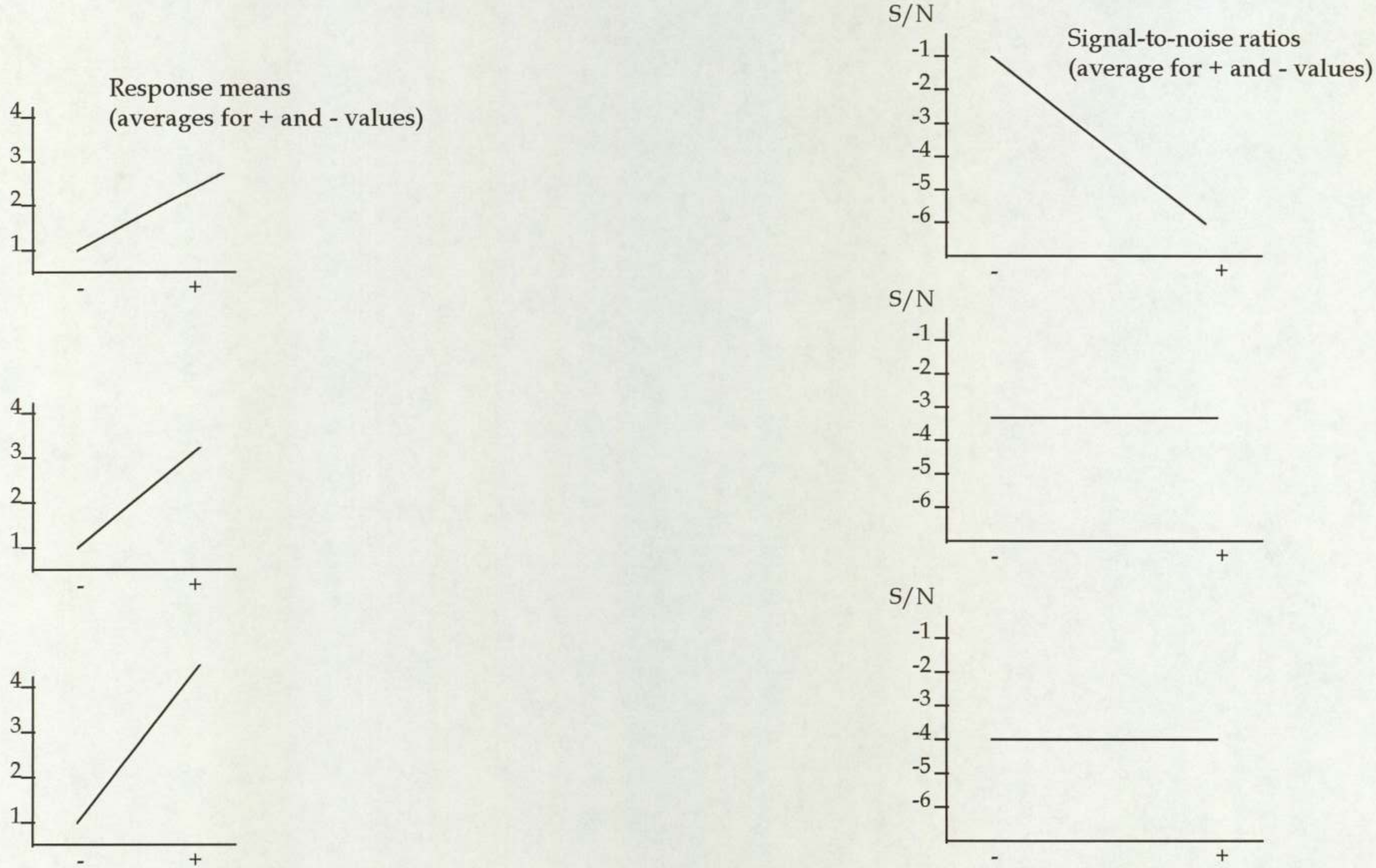


Table 4.9: Results of Taguchi Experiment on Fuel System Components

				OUTER ARRAY (2*2)							
			INNER ARRAY (L4:3*2)	X	+	+	-	-			
				Y	+	-	+	-			
	A	B	C		RESPONSE (-30)				mean	standard deviation	S/N
1	+	+	+		8	6	4	4	5.5	1.91	-5.63
2	+	-	-		0	0	-2	-4	-1.5	1.91	-5.63
3	-	+	-		0	-2	0	-2	-1	1.15	-1.12
4	-	-	+		4	2	4	2	-3	1.15	-1.12

Figure 4.13: Results of Taguchi Experiment



Further examples of orthogonal arrays are given by Taguchi [1978], Ross [1988] and Logothetis and Wynn [1990].

The arrays can be combined, to give an inner and outer array, as shown in Table 4.9. The inner array contains the control factors and the outer array the noise factors. The signal-to-noise (S/N) ratio is calculated for the combination of control factors being considered, using the outer array, the formula depending on whether the desired output parameter must be maximised, minimised or centralised. The expression are as follows:

Maximum output, S/N ratio = $-10\log\left[\frac{\sum 1/\chi^2}{n}\right]$

Minimum output, S/N ratio = $-\log\left[\frac{\sum \chi^2}{n}\right]$

Centralised output, S/N ratio = $-10\log\left[\hat{\sigma}^2\right]$

X is the mean response for the range of control factor settings, and $\hat{\sigma}$ is the estimate of the standard deviation. Analysis of Variance (ANOVA) is performed using the S/N ratio calculated for each row of the inner array. Figure 4.14 illustrates the basic steps to applying Taguchi Methods [Noori, 1989]. Similar steps have also been proposed by Antony and Kaye [1995] in the form of a methodology for conducting Taguchi design of experiments.

The Taguchi methods have been widely applied to industrial situations, particularly within US multi-national organisations [Bendell, Diney and Pridmore, 1989; Taguchi, 1984]. In particular, the Taguchi methods have recently received much attention in the reliability field [Hamada, 1993; Byrne and Quinlan, 1993]. This is not surprising when one considers that the Taguchi philosophy is an increasingly important design paradigm aimed at reducing the overall variability of the product to achieve maximum reliability at low cost.

Figure 4.14: The Basic Steps to Taguchi Methods

Select the desired outcome; the control, signal, scaling noise factors for the process/product under study	Step 1
Choose an appropriate range for both the external and internal factors involved	Step 2
Select an appropriate orthogonal array to study the effect of the above factors, including the interaction	Step 3
Conduct the necessary experiments as defined by the orthogonal array - do each experiment more than once and take the average results to increase the accuracy	Step 4
Calculate the signal-to-noise ratio for each of the factors for each level selected	Step 5
Perform a variance analysis (ANOVA) to determine which factors contribute to the variability of the final product	Step 6
Select the level of each factor that maximises the signal-to-noise ratio and hence reduces variability and optimises the noise	Step 7
Use the factors that don't increase the variability to adjust the mean to the desired output	Step 8
Perform an conformation experiment using the factor levels selected in step 7 and 8	Step 9
If the results are satisfactory terminate the analysis. If not re-analyse the data to pick different factors or range of levels for each factor and start again	Step 10

Table 4.10 provides a collation of experiences of several US based firms using Taguchi methods and the operational and business benefits achieved. As can be seen from the Table, the methods have met with overwhelming success. As a comparison to the US, Taguchi methods have received little attention by UK firms. Rare case examples of Taguchi Applications in UK firms have been cited [e.g. Graham and Grigg, 1989; Brown et al., 1989].

Despite the overwhelming success of the Taguchi Methods, critics still express concern over their validity. Some critics such as Ryan [1988], question the logic of Taguchi's optimisation techniques. He believes that Taguchi's tactic of varying process variables one at a time to maximise a particular variable neglects the effects of their interactions. The resulting marginal averages, Ryan claims, can at best provide only workable approximations. Other critics also find weakness in the use of Taguchi's measure of performance (i.e. minimisation of loss). Pignatiello [1988], for example, found that some combinations of expected loss function and related process models provide spurious results using the Taguchi methods and therefore must be used with caution. Pignatiello goes on to conclude:

> "There are distinctive differences between the Taguchi strategy and the Taguchi tactics. Most of the controversy and mystique which surrounds the Taguchi methods centre on the Taguchi tactics and not on the basic strategy.... The Taguchi tactics are the specific techniques recommended by Taguchi to implement this strategy. Such things as signal-noise ratios and the so-called Taguchi designs are all part of the tactics of Taguchi. Other performance statistics can be used. Other designs can be used. It appears that other designs and performance measures *should* be used if one wishes to find *the best* process and/or product design."

Durrant [1988] states that the Taguchi methods are based on the original concepts of Design of Experiments (DoE) developed half a century ago by Fisher [1935]. The concepts have been developed and applied by Taguchi to such effect that they are now re-exported to the United States and Britain. However, Durrant highlights the success of Taguchi in applying such methods in industrial applications:

Table 4.10: Case Examples of Taguchi Applications

Company	Objective	Analysis Methods	Results
Doehler/Jarvis Farley Ind. (Toledo, OH)	Improve breakage strength Decrease porosity of diecast components	Accumulation analysis	30% strength increase 40% porosity decrease
United Technologies Essex Group (Lafayette)	Improve high tension ignition cable	S/N Ratio	Improved die-electric strength Maintain processability
Eaton Yale Ltd. (Wallaceburg)	Reduce leaf spring free height variability	S/N Ratio	Variability reduced by 82% (Cpk)
ITT Supernant (Boston, MA)	Insulated wire strip force	S/N Ratio	\$100, 000 per savings
ITT Thermotech Division (Hopkins, MN)	Reduce variability of shrinkage Minimum gas burn and flash conditions	S/N Ratio Accumulation analysis	Shrinkage reduced to 1/100th Flash: 100% moved to best class Burn: 90% moved to best class 7% to acceptable
ITT Bell & Gossett (Morton Grove, IL)	Maximum spot welding integrity	S/N Ratio	Cpk increased from 2 to 6 Time per weld decreased by 33%
Flex Products (Romulus, MI)	Emission control Harness Durability	S/N Ratio	Inspection savings of \$100, 000/month

Table 4.10: Case Examples of Taguchi Applications

Company	Objective	Analysis Methods	Results
MACLO (Montgomeryville)	Cruise control valve study	S/N Ratio	Push out force increased 17% Standard deviation decreased by 50% Productivity increased by 21% $17,000 annual savings
3M Co. (Minneapolis, MN)	Injection moulding study	Accumulation analysis	Cycle time reduced 20% $2 million annual savings
Davidson Rubber Co. (Athens, TN)	Improve component fit	Accumulation analysis	Reject rate reduced from 15% to 5%
Automotive Industries	Arm rest assembly study	Accumulation analysis	Average shrinkage reduced to target
Baylock Manufacturing Co. (Leonard, MI)	Nylon tube assembly	S/N Ratio	Tool cost reduced by 75% Productivity increase of 20%
McGraw-Edison Co. Wagner Division (Severeville, TN)	Grey iron casting study	Accumulation analysis	45% defect reduction $100, 000 annual savings

> "Taguchi's major achievement has been to obtain management recognition of the importance of these experimental techniques and to introduce them into areas where they have hitherto been ignored. In this respect, he has done more than all the books and articles written on the subject since Fisher's great initiative half a century ago."

The strength of simplifying Design of Experiments techniques is also highlighted by the following quote from an industrial quality control manager in the United States [Sprow, 1992]:

> "I think highly of Taguchi methods. Prior to him you had to be a statistician to do DoE; there weren't easily accessible cookbook recipes. His simplifying it, bringing it into the hands of the masses was a tremendous contribution."

4.5 The Impacts of Concurrent Engineering

Considerable research has been undertaken in the area of product design and development in the context of achieving reliability and quality upstream in the design process [e.g. Morup, 1991; Lewis and Samuel, 1991; Chen and Morris, 1989]. A decision concerning product design tends to have a number of significant impacts upon the life cycle of the product. The following examples signify such an importance:

- A study revealed that the product design is responsible for only 5% of a production cost of 2000 components [Corbett, 1986].
- According General Motors executives, 70% of the cost of manufacturing truck transmissions is determined in the design stage [Whitney, 1988].
- Ford Motor Company has estimated that among the four manufacturing elements of design, material, labour and overhead, 70% of all production savings stem from improvements in design [Cohodas, 1988].
- A study revealed that the product design is responsible for only 5% of a product's cost: it can however, determine 75% or more of all

manufacturing costs and 80% of a product's reliability performance [Huthwaite, 1988].

- Managing engineering changes is a significant aspect the reliability improvement process [Joyce, Ayres and Cruickshank, 1991; Nichols, 1990].

- Yet another study shows that 70% of the life cycle cost of a product is determined at the design stage. The life cycle cost here refers to cost of materials, manufacture, use, repair and disposal of a product (Neville and Whitney, 1989].

The concept of concurrent engineering (CE) has received much attention from the perspective of reducing development lead time for new products and improving quality and manufacturability by removing design flaws at an early stage in the product introduction process. The most widely accepted definition of CE, developed by the Institute for Defence Analyses in 1988 [cited in Carter and Baker, 1992]:

> "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule and user requirements."

Therefore CE, as it is defined, calls for consideration and inclusion of such design attributes as manufacturability, reliability, maintainability and the like in the early phases of the design process. As well as life cycle phases of a product mentioned in the above definition, Ishii [1993], considers maintainability or serviceability (aspects of product reliability) to be of major concern during the design phase of a new product.

CE is widely used as a common term for new approaches towards the design of new products. Immediately visible results of successful CE implementation are improved quality and reliability, reduced time to market and reduced life cycle costs. Both Japanese and American industry have devoted considerable resources to CE and have had long-term government funding through the Ministry of Trade and Industry [Kuo and Hsu, 1991] in Japan and the Concurrent Engineering Resource Centre (CERC) in the US. As a comparison to the intake of CE in Japan and the US, Europe is lagging behind according to recent research [Driva and Pawar, 1995]. There are well documented success cases of CE which highlight the importance of improved quality and reliability, reduced time to market and reduced costs [Trygg, 1992; Shina, 1993; Ettlie and Stoll, 1990].

A recent UK survey [Benchmark Research, 1994] evaluated that more than half of all companies surveyed implemented the principles underlying the philosophy of CE. As illustrated in Figure 4.15, CE is more prevalent in the automotive industry. In analysing by company size, the results are somewhat ambiguous (Figure 4.16). The expectation that CE is the domain of the larger sized companies is not supported in the survey results which recorded approximately two thirds of the smallest companies claiming to undertake CE.

An explanation may be that in small sized enterprises communication between relevant business functions are quicker and easier. In many cases, an individual may be performing several of the design, quality, production and marketing functions usually associated with CE because of the size of the establishment. Therefore, while it is true to say that the functions are integrated, this may not be the result of a deliberate policy to implement CE. The additional demand made by customers forced half the companies to adopt CE according to the survey. The pressure was particularly acute for respondents in the aerospace and electrical/electronic sectors (71% and 73% respectively).

On closer examination of the survey methods and questions, it is evident that the approach to the survey are far from ideal and there are inherent weaknesses. The question of the survey was specifically worded to describe the activity rather than to name it. The exact question was *"Are the design, production and quality engineering functions integrated or do they operate*

Figure 4.15: The Extent of Concurrent Engineering Implementation in UK Manufacturing Industry

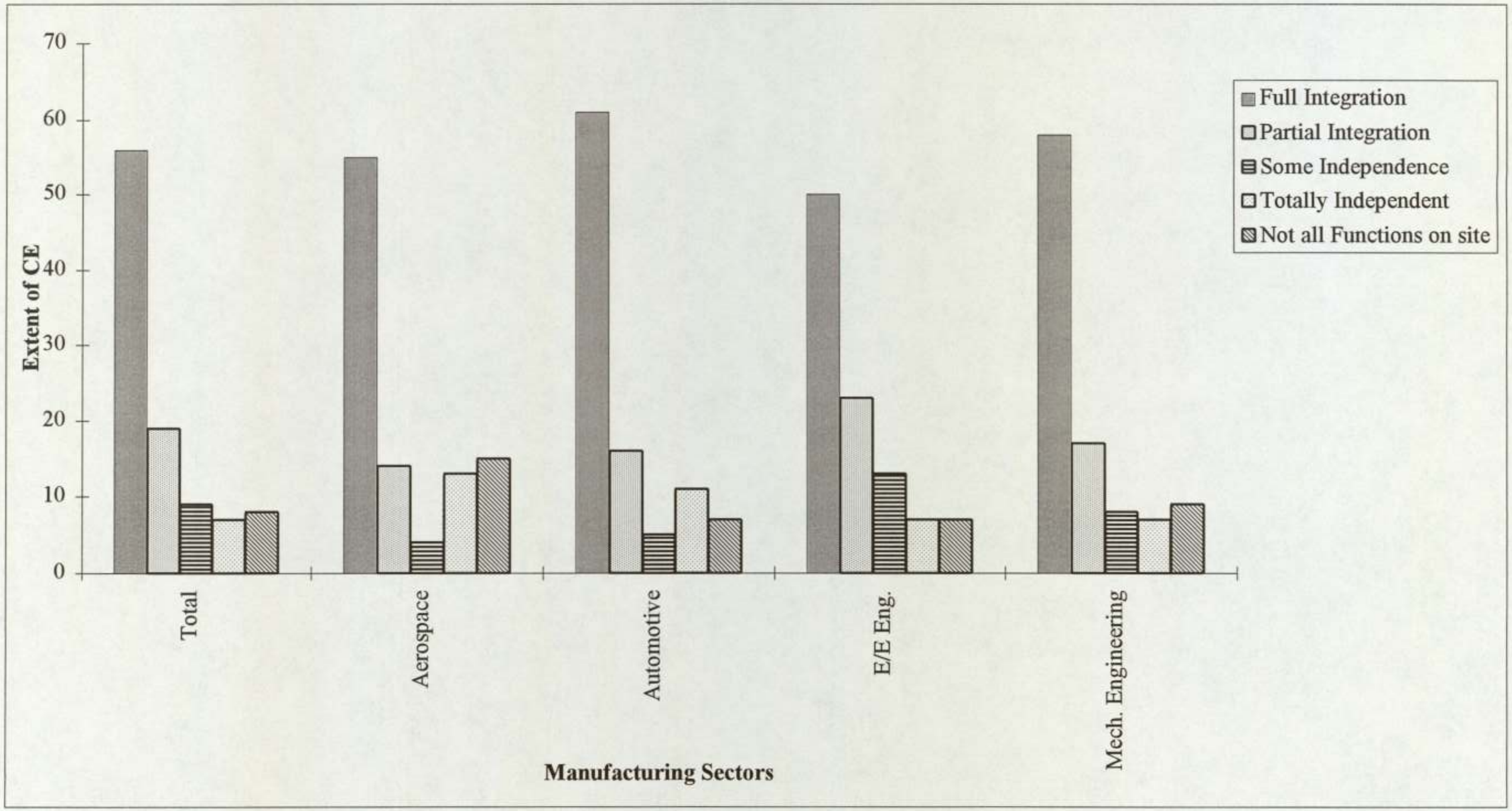
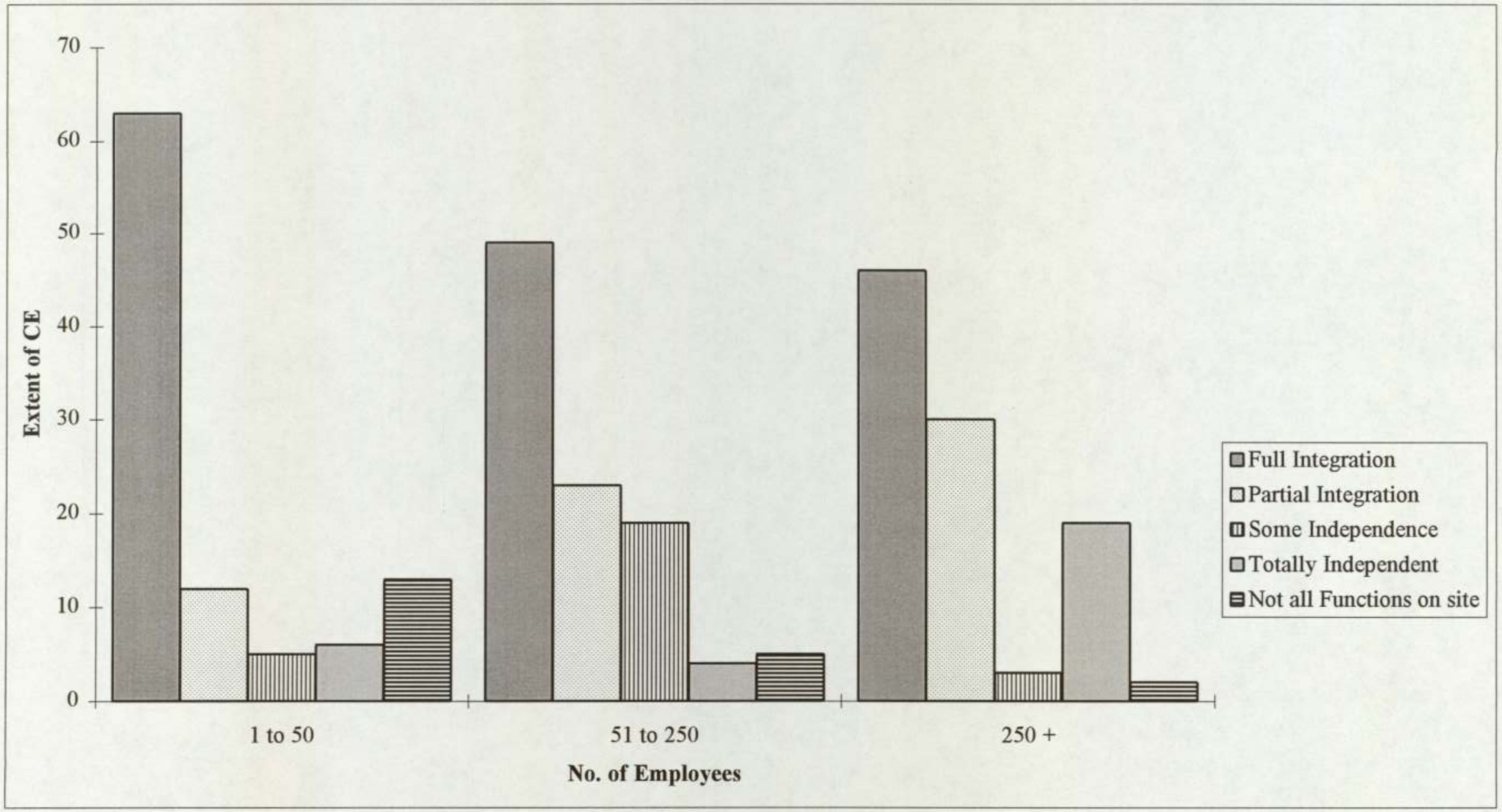


Figure 4.16: Concurrent Engineering Implementation by Company Size



independently of each other (this is sometimes referred to as CE? This is a highly simplistic view which assumes the purist form of CE. On closer examination of the survey results it is evident that:

- CE is not practised to its full entirety.
- The integration of design, production and quality functions is not a indicator to the implementation of CE.
- Their is a lack of awareness of tools and techniques and their integration within CE.
- Their is lack of methodology or consistent approaches to the implementation of CE.

There are many varying descriptions of CE in the literature. These include CE principles, practices, implementation and company assessment. From the perspective of this thesis, it is possible to categorise this into three groups:

1. Models that describe what CE is and why it should be adopted.
2. Models which can be used during CE projects.
3. Models that is used as a benchmark to assessing the application of CE in a company.

4.5.1 Models that Describe What CE Is

There is a considerable literature extant on the models describing the principles of CE and frameworks for successful implementation [e.g. Solenius,1992; Carter and Baker, 1992]. A comprehensive review of the concepts and principles of CE is given by Zangwill [1992]. He elaborates that the key to CE is that the entire development process is managed by a cross-functional team of experts from all relevant departments, including marketing, design and manufacturing. The central notion is that the team is responsible for conceptualising the product correctly up-front in the design process. Each expert ensures that the problems that could later develop in his department are, to the greatest extent possible, avoided, thereby dramatically reducing engineering changes and chances of failures during operation.

With all the important areas represented right at the start, the cross-functional team conceives the product correctly, manages parallel processing and cuts delays and waste. By contrast, the traditional sequential approach to product design and manufacture kept the marketing, engineering design and manufacturing phases separate and performed them sequentially [Carter and Baker, 1992].

However, the use of multi-functional teams only forms an element of CE. Other elements enter the equation. Figure 4.17 illustrates a 2 dimensional representation of CE methods and technology [Rawcliffe and Randall, 1989]. It states and classifies constituent parts of CE and is divided into three subsections:

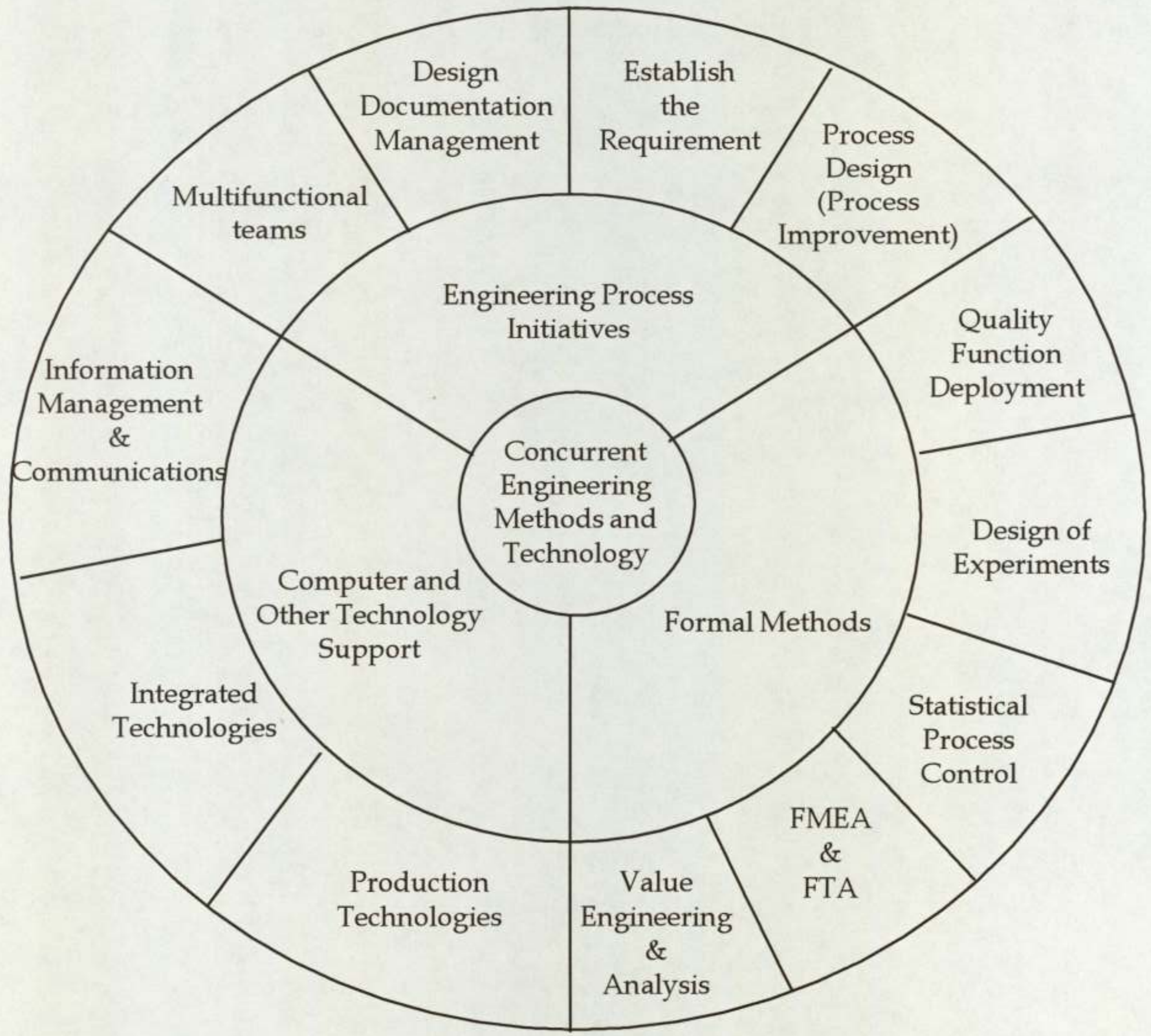
1. Computer and other technology support.
2. Engineering process initiatives.
3. Formal methods.

This model is perhaps the most well-known and often quoted CE classification system. It makes it possible to pick and choose which parts the user want to follow. However, it focuses on what CE is and there is no 'how' to follow for a practical implementation. A somewhat different yet complimentary approach is adopted in a model developed by Hurst [1994] which shows CE as containing hard sides (tools and hardware) and soft sides (people and organisational change). According to Hurst, soft elements are more difficult to come to terms with.

4.5.2 Models which can be used During CE Projects

There are many models developed for use during CE projects and each have been developed to cater for individual design circumstances. For example, a model which firms can actually apply to the product introduction process is

Figure 4.17: Concentric Wheel Model of CE



developed by Lucas Engineering and Systems Ltd in the UK [Brown et al., 1989]. It is primarily developed for use on a specific product rather than the whole organisation. The Lucas approach is based around the 'Integrated Design and Manufacture' methodology. This methodology consists of three elements:

1. Multi-disciplinary teams.
2. Concurrent engineering which uses structured approaches and design methodologies to maximise use of resources.
3. Tools and techniques.

These key elements are supported by a professionally managed design process, with phase reviews and design audits. This is underpinned by the integrated product introduction process which highlights the use of QFD and other techniques in the design process. It is a general, broad approach making it widely applicable in different circumstances.

Design reviews forms an important element of the CE process. The need for a design review to be conducted on a structured basis is significant. The design review should consider maintainability and reliability issues which contribute to the total performance of a product. Thompson [1993] provides a framework for conducting design reviews from the perspective of reliability and maintainability. It consists of 4 principle stages:

Specification review: This ensures that the significance of all points in the design specification are understood. It is carried out prior to the commencement of any design activity.

System review: Here there are two distinct activities. At the conceptual design stage, when functional requirements have been specified, critical areas should be identified to which special attention is required. These may be areas which significantly affect reliability and maintainability or perhaps functional requirements which involve high-risk design. A second system review may be carried out after functional units have been designed. Here the objective is to examine the character of the design with respect to many variables in order to identify weak points. Also the reliability of the design can be checked using quantitative assessments based on a detailed analysis of the proposed functional units and system failure studies may be carried out.

Functional unit evaluation: The objective here is to maximise the usefulness of a functional unit. The analysis considers all relevant design variables. it can only be carried out properly after the function units have been designed or selected.

Component analysis: On completion of the detail design, certain important sets of components can be examined in detail. Clearly it is not possible to embark upon a general review of all components. Such a task would be so great as to become meaningless. The objective is to complement functional unit evaluation by identifying sets of components, such as seals on a particular process line and then to undertake an in-depth study.

Therefore, the theme of the design review is to identify carefully specific areas of a design for in-depth study rather than to carry out a broad, shallow overview. The design review procedure detailed above is not put forward as a rigid procedure. A company can adapt it or use certain parts as appropriate to its own circumstances.

A number of researchers have attempted to develop instruments to enable design teams to assess and trade off various design concepts in relation to the reliability and maintainability requirements placed upon them [e.g. Gardner, Jackson and Sheldon, 1994]. These instruments help design teams focus effort upon reliability and maintainability issues early in the product introduction process. This ultimately lead to the enhancement of product reliability and quality. Key benefits can be attained through the use of such tools:

- Co-ordinate team activity by identifying problem areas early in the design stage for future design effort;

- Enable the technique to mould and interact within the design process providing an integrated product introduction process;
- Enable teams to co-ordinate other existing design tools at specific staging points.

However, no details of these benefits are provided. In many cases, a matrix type of instrument is developed by researchers (similar to the QFD matrix) which provides the backbone to any design 'analysis.' By predetermining a set of criteria and expectations to which the design must perform, design teams can condition the multitude of reliability issues in relation to the product concept. This provides the design team with a ranked action list of reliability concerns with which they can focus design effort. These matrices also provides the basis for documentation which is both simple and revisable.

One of the most widely used and publicised approach to reliability-based design is the concept of design for simplicity (DFS) [Watson, Theis and Janek, 1990]. This method of utilising concurrent engineering techniques aims to reduce the number of parts in an assembly and eliminate unnecessary design features. The method is primarily for use in mechanical equipment design. Evidence seems to suggest that the application of this method yields higher reliability products at lower cost, through reducing the number of mechanical parts. Field service personnel have also found that products designed through the DFS methodology are far more easier to service. Figure 4.18 details the DFS methodology. The basic mechanics of the method is elaborated below:

Measure the design: This step establishes a basis for comparing alternative designs. First, determine the part motions and assembly processes necessary to assemble the product. This is carried out by following a set of assembly operation elements and penalty points procedure. An example of this is detailed in Table 4.11 [General Electric, 1982]. Penalty points are charged for each part movement or joining processes, except for the straight-down movement of one part onto a connecting part. This movement is the simplest and quickest way to assemble. The penalty points for other motions such as

Figure 4.18: The Design for Simplicity (DFS) Methodology

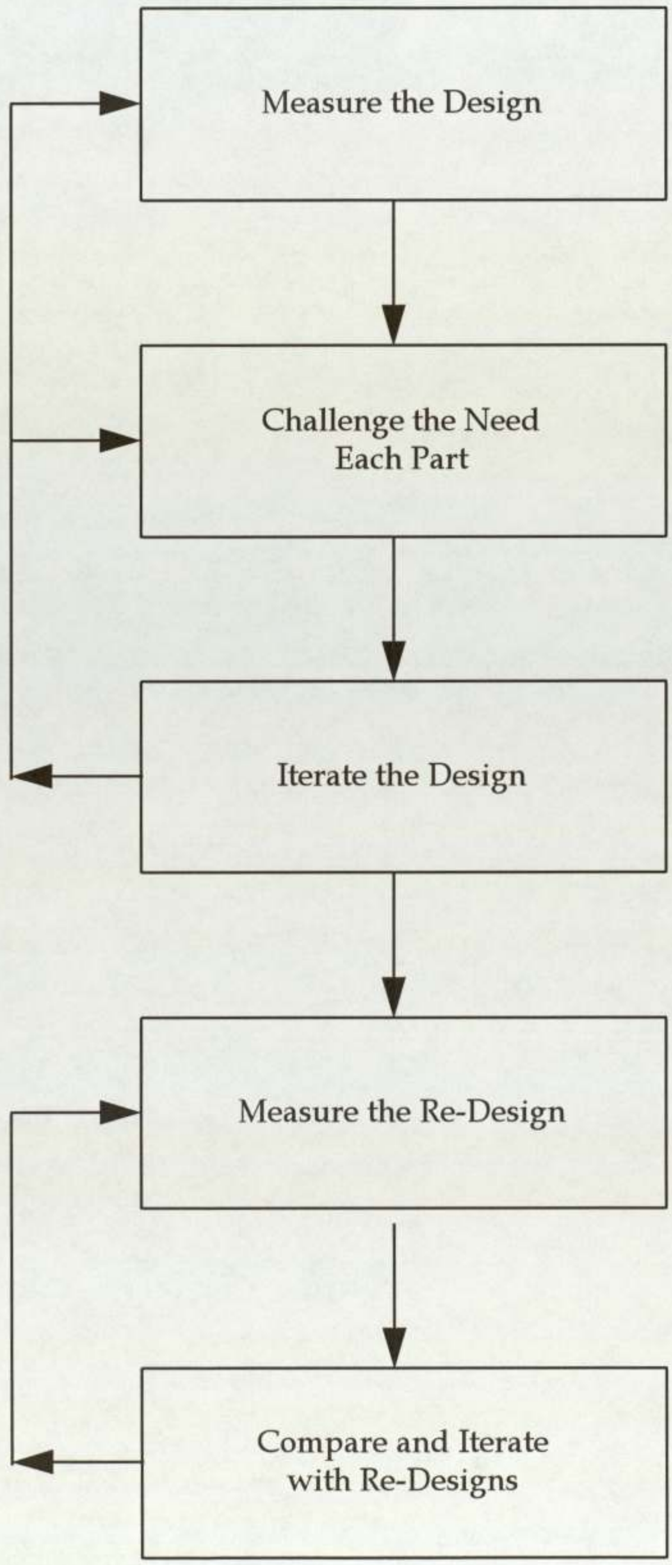


Table 4.11: Example of Assembly Operation Elements and Penalty Points

Operation	Penalty Points
Move part downward in straight line	0
Move part horizontally in straight line	20
Move part diagonally downward in straight line	30
Move part upward in straight line	30
Move part along circular path in vertical plane [includes turning a screw and cases in which part, such as a wire, is deformed by rotating movement (winding or wrapping)]	30
Move part along a circular path in horizontal plane [includes turning a screw and cases in which part, such a wire, is deformed by rotating movement (winding or wrapping)]	30
Maintain relative position (fixture) of attaching part or part on which attachment is made (example: fixing unstable part manually or with a jig); use for only one assembly operation element	20
Maintain position (fixture) for more than one subsequent operation; deform soft or flexible parts; form accurately	40
Turn over or stand up part on which attachment is made (when two or more parts are attached, points are charged to only the first part)	40
Bond parts with adhesive; lubricate parts	20
Join part by heating (example: shrink fit)	20
Join parts by staking, clinching, riveting, or mechanical press fitting	20
Join parts by welding	20
Join parts by soldering or brazing	30
Machine parts by turning, drilling, milling, etc. when attachment is made	60
Form parts by bending, cutting, or shearing when attachment is made	20

horizontal, diagonal, upward or circular depend on the difficulty or time of the operation.

The penalty points for each motion required for assembly should be combined to obtain an overall penalty score for the design. From this, the assembly time and cost can be estimated. Three important metrics defined in the DFS method are parts count, assembly time and assembly efficiency. By objectively describing the proposed product design with these metrics, a base is formed on which to improve the design.

Challenge the need for each part: After describing the assembly motions and calculating the design score, the product team will scrutinise the design to identify ways to eliminate parts and simplify the design. Three questions are used to identify those parts that are theoretically not required. If the answer to all three questions is 'No,' then the part can theoretically be eliminated or combined into another part.

1. Does the part move relative to it mating part?
2. Must the part be different in material or isolated from its mating part?
3. Must the part be separate because disassembly and reassembly for service would otherwise be impossible?

Iterate the design: The first design is never the simplest or most cost-effective. The analysis and score of the original design identify areas for possible improvements. The design team must then re-design and improve the product on the basis of this information and attempt to eliminate the unnecessary parts. Two major goals are to reduce parts count and reduce assembly time.

Measure the re-design: After the re-design, the DFS metrics should be re-calculated. The penalty score, parts count, assembly time and assembly efficiency are calculated for the re-design.

Compare and iterate with re designs: The value of the above metrics can best be understood by comparing it with the original design. Normally, the values of penalty score, parts count, assembly time and assembly efficiency are compared for the original and the re-design to evaluate the degree of design improvement.

Conventionally, overall product reliability and maintainability are improved usually at the expense of the longer development intervals. Deploying the DFS method will result in enhanced levels of reliability and maintainability, since there will be fewer and less complex parts in the design that can fail or be assembled incorrectly.

A significant amount of industrial research has been conducted on developing guidelines which provide descriptions of reliability and maintainability (R&M) fundamentals for manufacturing machinery and equipment [e.g. SAE and NCMS, 1993; GMC, 1991; Ford Motor Company, 1990]. These guidelines basically embrace the concept of up-front engineering and continuous improvement in the design process for machinery and equipment. The guidelines are not intended to be a standard or guidebook on R&M. It simply presents standard reliability-based techniques, tasks and activities as they apply to the life cycle of machinery and equipment, and gives sequence of R&M actions to be followed.

Taking on the above theme, Blache and Shrivastava [1993] provide guidelines which can be used to consider and assess the maintainability of machinery or equipment during their design process. In effect, the guidelines act as an audit tool for evaluating the maintainability of design. Table 4.12 details the main components of these guidelines.

4.5.3 Models Assessing the Effectiveness of CE

In providing a comprehensive review of the CE process, Winner of the Institute for Defence Analysis [cited in Zangwill, 1992] provide some case study findings of the benefits of CE. Table 4.13 shows how CE has produced savings in cost, schedule, time and more importantly quality and reliability. Similarly, a recent survey on the application of CE in the UK aerospace industry

Table 4.12: Design for Maintainability Guidelines

Description of Guideline
Reduce the need for maintenance to a minimum
Reduce the complexity of required maintenance tasks
Reduce the required levels of maintenance skills and the training required for them
Establish maximum frequency and extent of preventive maintenance to be performed
Provide characteristics in its components that will result in minimum downtime
Provide optimum accessibility to all equipment and components requiring frequent maintenance, inspection, removal or replacement
Provide for adequate, clear and rapid identification of parts and components that may be replaced or repaired
Eliminate, wherever possible, the need for special tools
Reduce to a minimum the number and types of repair parts and components needed to support the maintenance
Provide for maximum interchangeability
Reduce amount of supply required
Provide bearings and seals of sizes and types that will require minimum of replacement and servicing on a life cycle basis
Select adjustable items to take care of wear
Provide gears of adequate size and type to satisfy all overload requirements and be suitably derated on a life cycle basis
Provide simplified go/no-go (self diagnostic) automatic, built-in fault isolation capabilities and calibration equipment as feasible, practical or cost-effective
Provide quick disconnect devices for rapid removal and assembly of components
Ensure that a minimum number of fasteners is used and when feasible that the fasteners can be operated rapidly, preferably without the use of tools
Provide for rapid cleanability
Ensure that component modularisation design is used, as appropriate. Design modules to be repairable

Table 4.13: Savings Due to Concurrent Engineering

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% on savings on bid for reactor and missile projects	Significant savings (reduction from 45 weeks to eight hours) in one phase of high speed vehicle preliminary design	Scrap reduced by 58%; rework cost reduced by 29%; non-conformance cost reduced by 38%; weld defects per unit decreased by 70%; 68% fewer changes on reactor
Boeing Ballistic Systems Division	Reduced labour rates by $28/hr; cost savings by 30% to 40%	Part and materials lead time reduced by 30%; one part of design analysis reduced by over 90%	Floor inspection ratio decreased by over 66%; material shortages reduced from 12% to 0; 99% defect free operation
AT&T	Cost of repair for new circuit pack production cut by at least 40%	Total process time reduced to 46% of baseline for 5ESS	Defects reduced by 30% to 87%
Deere and Company	30% actual savings in development cost for construction equipment	60% savings in development time	Number of inspectors reduced by 66%
Hewlett-Packard Instrument Division	Manufacturing costs reduced by 42%	Reduced development cycle time by 35%	Product field failure rate reduced by 60%; scrap and rework reduced by 75%
IBM	Product direct assembly labour hours reduced by 45%	Significant reduction in length of design cycle; 40% reduction in electronic design cycle	Fewer engineering changes; guaranteed producibility and testability
Northrop	30% savings on bid on a major product	Part and assembly schedule reduced by 50% on two major sub-assemblies; span time reduced by 60%	Number of engineering changes reduced by 45%; defects reduced by 35%

identified some reasons for implementing CE [Betts and Tookey, 1995]. Table 4.14 details the primary reasons given by respondents. As can be seen from the Table, one of the primary reasons for applying the philosophy of CE was to improve (1) product quality and reliability, (2) productivity, (3) utilisation of resources and (4) reduce customer complaints.

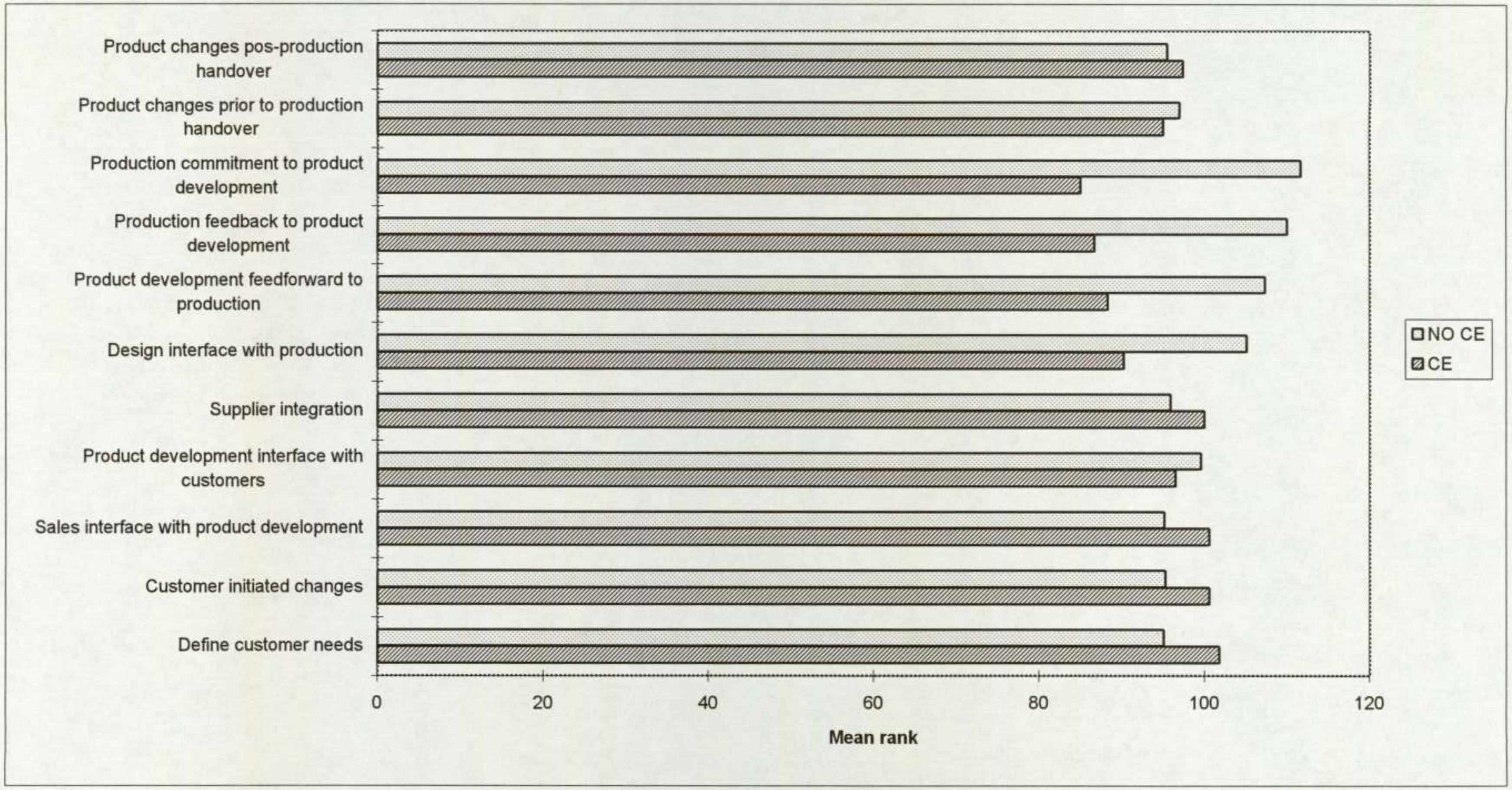
Table 4.14: Primary Reasons Driving the Implementation of CE

Driving Factor	Proportion of Respondents Agreeing with Statement (%)
Improve Quality and Reliability	77
Increase Market Share	39
Improve Productivity	100
Improve Utilisation of Resources	92
Reduce Time-to-Market	62
Reduce Costs	77
Reduce Customer Complaints	84
Reduce Lead-time	46
Increase Technical Innovation	8
Improve Morale	8
Improve Delivery	8
Maximise Process Capability	8

A survey conducted by Poolton and Barclay [1995] suggests that one major benefit of adopting CE is its ability to effect change among the engineering functions (see Figure 4.19). In particular, it seems that CE is more conducive to the free-flow of information between design and production. Firms that use CE are also more likely to gain the early commitment of production engineering to the development process. In contrast, those firms that do not use CE express greater problems in gaining production commitment to product design.

However, while it is tempting to conclude that the adoption of CE entails a reduction in the number of engineering changes (as detailed in Figure 4.19), there was no support found by Poolton and Barclay for this conclusion. Therefore, firms that use CE were just as likely to experience high rates of engineering changes as those firms that did not use CE. One likely reason is

Figure 4.19: Firms Use versus Non-Use of Concurrent Engineering



that many firms may have just introduced CE and therefore few had the opportunity to assess the maximum benefits. New systems and procedures to support CE take time to become established and so the benefits are likely to be effected in the medium and long term, as opposed to the short term. Hence it could be expected that firms with the greatest experience of CE are less likely to experience problems across the new product introduction interfaces than those firms that had recently introduced CE.

Given that CE was originally conceived by large companies, many small to medium sized enterprises (SMEs) face specific problems in the implementation of CE. A recent research into the product development process [Barber and Attewell, 1995] identified four main barriers to implementing CE in SMEs. The first of these problems is the requirement to have a dedicated team specifically allocated to a single design project. Many SMEs cannot afford to tie up personnel in this way. Another problem is the lack of understanding of what concurrent engineering involves and an ignorance of the design tools (e.g. QFD, DFS). The fourth barrier is the lack of training which given to personnel before implementation of CE. Barber and Attewell [1995] advocate the use of a part time dedicated team to overcome the resource problem and recommend the development of a methodology and guidelines for furthering the understanding and implementation of CE within SME manufacturing organisations.

4.6 The Effects of Vendor Evaluation Criteria on Reliability

A plethora of research studies contrasting quality and reliability management approaches adopted by Japanese and Western manufacturers exist. Some examples are the work of Cole [1983], Deming [1982], Ebrahimpour [1985], Feignbaum [1985], Garvin [1986], Dale [1993] and Juran [1981]. A common outcome of these studies is a description of the role that vendor supplied parts and materials have in the area of quality, reliability, cost and other performance measures. For example, it has been estimated that in some US manufacturing firms over 40 per cent of all quality and reliability problems were caused by vendors [Leonard and Sasser, 1983]. Thus, for many firms, it is of utmost importance to establish specific vendor evaluation criteria. The choice of a suitable vendor can mean the difference between the success and failure of a product during service.

The quality and reliability requirements of procured materials and parts are usually established as a result of the team effort of several departments such as purchasing, manufacturing, engineering, quality control and where relevant service departments [Cherry, 1988]. The goal of vendor selection is to identify suppliers capable of delivering materials and parts which consistently meet the quality and reliability requirements specified by buyers. Once vendors are selected then they are periodically rated to ensure that they continue to maintain their quality standards. The most popular method employed by virtually all manufacturing organisations is to develop a list of criteria on which vendors are evaluated [Pettit, 1984].

A review of the literature indicated that Japanese and Western firms use very different criteria for vendor evaluation. The indications are that Japanese organisations, as well as American firms emulating Japanese quality and reliability control methods, will concentrate on criteria regarding the vendor's quality while in traditional Western firms, purchasing and engineering departments will focus on the vendor's cost as the primary tool of evaluation [e.g. Ebrahimpour, 1988; Ebrahimpour and Mangiameli, 1990; Garvin; 1984].

It is also assumed in the literature that Japanese firms, and their non-traditional Western emulators, consider it more important than do traditional Western manufacturers to have a high quality vendor because the quality of commercial parts is strongly linked to business performance. On the other hand, the literature indicates that traditional Western firms, if they link vendor selection criteria to business performance at all, will view price as having the dominant effect [Deming, 1982; Garvin, 1984].

4.7 Some Issues in the Collection and Analysis of Field Reliability Data

While, many models stress the importance of designing in reliability upstream in the design process, the ultimate test of a manufactured product is how well it performs in the field. Accordingly, the collection and analysis of field reliability and related performance data forms an important part of the reliability improvement process. Such data can be used in many ways by a manufacturer, including [Lawless and Kalbfleisch, 1992]:

- To assess field reliability and make comparisons with engineering predictions.
- To provide information for product modification and design improvement.
- Reliability analysis.
- Analysis of reliability characteristics (for example lifetime distribution, failure mechanisms).
- Investigation of relationship between reliability and environment or operating conditions.
- To assess the effects of engineering changes.
- Life cycle costing.
- To estimate and explain warranty costs.
- To aid in the design of warranty and spare parts replacement programmes.

Nevertheless, many manufacturers pay insufficient attention to the collection of field performance data. One reason is that comprehensive data are often seen as expensive to obtain and another may be a lack of familiarity with methods of reliability analysis.

4.7.1 Examples of Industrial Reliability Studies

Many studies on reliability based on the use of field information have shown the usefulness of such data as decision tools in the area of reliability and design improvement. Some broad examples of these reliability analysis studies is detailed below:

Fire-fighting vehicle and equipment: Studies on the reliability of fire-fighting vehicles and equipment identified principal causes of system failures at both subsystem and component level [Keller, Al-Saadi and Leckie, 1992]. In identifying these principal causes of system failure, recommendations were put forward for possible design modifications for eliminating principal causes of failure. The study also evaluated that failure frequencies of the items studies were generally highest in the first year of operation. This, the study concluded was most likely the cause of defects not identified by manufacturers prior to delivery.

Machine tool products: Reliability and maintainability studies of computer controlled (CNC) machine tool products using statistical approaches, identified many failure characteristics and lifetime distributions of machine tool products [Keller et al., 1982; Yazhou et al., 1995]. Several conclusions were drawn from these studies:

- The Weibull and lognormal distributions were found to provide suitable vehicles for the analysis of the failure characteristics of CNC machines.
- The failure pattern of machine tools during the warranty period fits the exponential distribution.
- Similarly, the lognormal distribution was found to provide the best fit to describe repair time distributions.
- The availability of CNC machines studied was in the range of 82% to 85%.

- Approximately two thirds of the total system down time is due to non-active repair times.
- The Duane plot provides a convenient means of monitoring the reliability growth for the CNC system.
- A new damped oscillatory phenomenon of the Duane growth curve was observed for the hydraulic and mechanical systems.

Well Completion Equipment (Offshore Industry): There are many reliability analysis studies conducted on these equipment, particularly from a risk and safety assessment perspective. For example, a recent reliability study on Surface Controlled Subsurface Safety Valves (SCSSV) provided a valuable decision basis for the oil companies, as well as providing a unique source of feedback on performance for the downhole equipment manufacturers [Molnes and Sundet, 1993]. In concluding, the researchers emphasise the use of their data in purchasing decisions. The tendency of the majority of purchasers to emphasise minimum purchasing costs rather than minimum lifecycle cost for wells indicates a lack of understanding of the importance of reliability, both regarding safety and well production availability. This is not only true for the offshore industry, but also applies to the general manufacturing industry.

Asset Replacement (Regional Electricity Companies): Using a case study approach, Freeman [1996] provides a detailed account of the use and analysis of failure data in the development of more efficient replacement procedures for pole mounted transformers (PMTs). He stresses that inappropriate choices of statistical distribution for representing fault data can lead not only to greater uncertainty about when to replace but, more seriously, can systematically mislead the analysis on what their best policy for replacement should be. It was evaluated that an extreme value (Gumbel) distribution provides a far more effective option for representing failure data of PMTs than a previously publicised method based on the Weibull distribution.

Aircraft Products and Equipment: Kern [1978] studied the failures in avionics equipment and attributed the reliability problems to definition, operational and environmental factors. Definition factors are semantic-based and are caused primarily by differences in failure criteria definitions. Operational factors include the impact on reliability resulting from maintenance, handling and equipment use. Finally, environmental factors relate to the practice of using a single factor regardless of aircraft type. Similarly, a more recent study on the application of the Weibull distribution to model the wearout characteristics of aeroplane tyres revealed the significance of the Weibull model in modelling the reliability of aeroplane tyres [Sheikh, Al-Garni and Badar, 1996]. It was concluded that a resulting three parameter Weibull reliability model can be used to (1) schedule a preventive policy for tyre replacement corresponding to an optimal level of tyre reliability, (2) determine logistic support for a specified planning horizon and (3) assess comparatively the quality and performance of tyres of different manufacturers.

4.7.2 Pitfalls and Practical Considerations in Reliability Analysis

A variety of graphical and analytical techniques for analysing product life data have been developed over the past few decades [e.g. Hahn and Shapiro, 1967; Nelson, 1982; Mann, Schafer and Singurwalla, 1974; Bain, 1978]. These techniques are, however, easily misused. Due to the special features of product life data, special techniques, such as the Weibull distribution, have been developed for their analysis. Some of these features are detailed below [Hahn and Meeker, 1982a]:

Censored Data: The data are often frequently censored, i.e. some, and often most, of the units have not failed at the time of analysis. All that is known about such units is that their failure times exceed their running (or censoring) times. Some reasons are (1) a product decision is needed immediately even though all units have not yet failed, (2) units have been removed from service and (3) units have been retired from service.

Moreover, field data are often multiply or progressively censored (i.e. the units have varying running times. This would be the case if units were installed or removed from service at different times or units were subject to different usage rates. Multiple censored data also arise in analysing a specific failure mode for products with independent competing failure modes.

Lifetime distributions: The normal distribution does not play a key role as a model for time to failure. A skewed distribution is suggested for many products because relatively short failure times may be quite likely, but negative times are impossible.

Confidence Levels: Lower tail distribution percentiles, such as the time by which one, five or ten per cent of the product population is expected to fail, are frequently of primary interest.

Extrapolation: There is a need or tendency to extrapolate beyond the range of the available data. For example to estimate the probability of survival to five years based upon only two years data.

A frequent complication in reliability analysis is the inadequacies in reporting data [Lawless and Kalbfleisch, 1992; Robinson and McDonald, 1987; Kalbfleisch and Lawless, 1988]. Some of the common problems that arise in practice are as follows:

- Only failures are reported. The running times of the units which are still operating must be estimated.
- Only some failures are reported. The probability of a failure being reported may depend upon the failure type (covered by warranty or not covered by warranty).
- The actual elapse time of the units during service.

The life distribution of a product that is manufactured over a period of time can change from one production period to the next [Hahn and Meeker, 1982b]. Changes in the design or manufacture of a product over its life cycle may improve reliability. This is especially likely for new products for which defects discovered one early units are removed one later ones. In other cases reliability, may deteriorate due to the adverse consequences of a cost reduction or a relaxation of inspection and testing standards. Thus, field life data for a product manufactured over a period of time may involve a mixture of time to failure distributions. Therefore, even though units made at a particular time may have a simple time to failure distribution, the ensemble of all units may not.

In practice, one often does not know whether reliability changes over time. It is, therefore, generally advisable to conduct separate analyses for each production period. This allows comparison of the results and to combine them only if this seems appropriate. Separate analyses, however, are not possible in the following circumstances:

- A unit's production period is not known.
- Production periods are not well defined.
- The data are too scanty for reasonable dissection.

A frequent complication in analysing life data from different production periods is that there are more long-time results for the early production units than for the more recent ones. This can lead to wrong conclusions if the data are analysed as a single group.

Some further situations that can lead to a mixture of time-to-failure distributions are different manufacturing plants and variations in specifications. An extreme product mixture situation arises when a failure type can occur only in a subset of the population. For example, those units (1) on which an operator skips a step in an assembly operation or (2) that are made from a particular batch of raw materials or (3) that include a particular optional accessory, such as an air conditioning unit for an automobile. This situation is closely related to the concept of immunity from a failure mode perspective.

Product mixtures also result from different environments. For some products, such a domestic appliances, the environment may be assumed to be homogeneous. Other products may be subject to widely different operating environments. The likelihood of incorrect conclusions is greatest if the exposure times differ for the population.

Similarly, multiple failure modes should be differentiated from population mixtures. Population mixtures breakdown a population into different mutually exclusive groupings of units. Such sub-populations result from differences in the manufacture or use of the product. Multiple failure modes are the different ways in which a particular unit in one of the sub-population may fail.

Hahn and Meeker [1982b] have proposed some guidelines for the analysis of product life data and reflects the views of other proponents in this particular field of reliability management [e.g. Lawless et al., 1992; Lawless; 1983; Moltoft, 1994; Ansell and Phillips; 1989]:

- Develop a precise statement of the problem at the outset. For example, state the practical problem questions to be answered from the life data analysis.
- Be modest in your expectations, especially with regard to extrapolation. It may be unreasonable to expect any statistical analysis to provide a good estimate of five-year based upon two year data.
- Remember that simple models, such as the Weibull and lognormal, might be reasonable time-to-failure distributions for simple products, or single components in larger products, but might be quite inappropriate for a complex system.
- Plot the data first on probability or hazard paper. A few well chosen plots are often more informative than reams of computer output and also provide useful guides for more formal analyses.
- Conduct separate analyses by sub-populations, such as production periods, product subgroup, operating environment, etc., and by individual failure modes, when the data permit. The separate results can always be combined - if this turns out to be appropriate.

- Analyse the data under alternative assumptions to assess the sensitivity of the results, especially if extrapolation is involved. The use of the Weibull and lognormal distributions leads to large differences in the extrapolations from the electromechanical device data.
- Be inquisitive and obtain as much information about the product and the data as possible. A good understanding of where, when and how the product was made and how it can fail is important in deciding how the data should be analysed.
- Be imaginative in analysing the data. Remember that standard textbook problems are generally found only in textbooks.

4.7.3 Data Sources for Reliability Analysis

Information on field reliability is obtained in various ways:

- Field tracking studies.
- Warranty and failure data.
- Reliability databases.

Longitudinal field tracking or follow-up studies where a group of units is closely monitored over time are of course ideal, since they provide maximal information and may be analysed with an array of well known methods [e.g. Kalbfleisch and Prentice, 1980, Lawless, 1982; Cox and Oakes, 1984; Davidson, 1988; Ansell and Phillips, 1990]. Studies of this type are sometimes conducted on a per unit basis and the samples are usually small. The purpose of such studies is to provide assurance that products are of satisfactory quality and perform as required. The principle steps involved in planning a successful field tracking study are [Amster, Brush and Saperstein, 1982; Kremer, Saraidaridis and Sripad, 1988; Broggi and Salari, 1988]:

Defining study objectives: Objectives can be classified as detecting problems, quantifying known problems, verifying quality audit information or reliability predictions, establishing problem causes, measuring the impact of design or manufacturing change(s) and evaluating the product.

Planning data collection to meet those objectives: Most of this planning is aimed at answering questions like (I) What data will be collected? (II) How will the data be collected? (III) In what study population will the data be collected? and (IV) How much data (sample size) will be collected?

Planning for successful data analysis: In broad terms, there are three things that generally get done with field-tracking data. The first is estimating failure or replacement rates using appropriate reliability analysis techniques. The second is searching the data for anomalies. For example, equipment types that have high failure rates, or failure causes that frequently occur. Finally, the data received from field tracking studies can be used for making comparisons of product performance among different types of equipment and product variants.

Where there is a general need to assess the reliability of equipment before market introduction, beta testing provides an ideal means of achieving this. The basic idea of beta testing is simply [Dolan and Matthews, 1993]:

> "to see if the product does what it is designed to do."

While most firms do extensive alpha testing prior to the beta phase, they recognise that the demands put on the system by end users cannot always be anticipated. In addition to the basic function check, data can be obtained pertaining the desired design refinements to the product. However, most design-change ideas surfaced by a beta test are passed on to product development for incorporation in the next generation of the product. Beta testing is most valuable when [Sweetland, 1988]:

- Users are heterogeneous.
- Potential applications of the product are not fully understood.
- Alpha testing is unable to guarantee a "bug-free" product.

- Product complexity limits the potential sample size in product use tests.

From the perspective of reliability, beta testing should place greater emphasis on product design and performance feedback [Stern, 1991]. Typically, beta testing of industrial related products employs relatively limited sample sizes and the practices seem to be less sophisticated. For example, although almost two-thirds of the industrial product projects studied by Cooper and Kleinschmidt [1986] utilised some type of beta testing, only 14% of those incorporated a consistent written protocol.

Warranty or failure data are a much larger source of information for many products. A warranty is a contractual obligation offered by a manufacturer in connection with the sale of a product [Berk and Zaino, 1991]. The warranty states that the manufacturer agrees to remedy or compensate the buyer for certain defects or failures in the product for a specified time or amount of usage after the sale. Traditionally, a commercial warranty provides for free repair or replacement if the product fails due to defects during the warranty period. Several studies provide detailed case studies on the analysis and prediction warranty claims and cost based on failure data [see, for example, Myrick, 1990; Kalbfleisch, Lawless and Robinson; 1991].

Manufacturers who support a warranty clause usually collect details about repairs or claims during the warranty period. For example, with many engineered products the date of installation, the date and type of repair and the serial number are routinely obtained. There are, however, problems with warranty or failure data. For example, the exact number and the ages of units in service at any point in time are often unknown. In addition, the failure database maintained by many companies are account driven and not set up to facilitate reliability analysis [Kalbfleisch et al., 1988; Robinson et al., 1987]. As a result, it is necessary to supplement warranty or failure data with information from other sources.

Standard reliability databases which contains quantitative information on the reliability of engineering components are another source of information. For example, the Reliability Analysis Centre [in Davidson, 1988] in the US provides a database of reliability information for non-electronic parts. Similarly in the UK, the Atomic Energy Authority [in Davidson, 1988] operates a national centre for safety and reliability (NCSR) which provides commercial reliability data on electronic and mechanical parts. Cross-sectional samples or surveys to assess reliability are also carried out by manufacturers, often in response to a perceived problem. For example, Kalbfleisch and Lawless [1991] discuss a car study on brake pad wear where car owners were randomly sampled from those having purchased cars from selected dealers over a particular time period. Potential problems with such studies include the possibility that selection for the study is response-related and that data may be heavily censored or truncated.

Published sources of failure and repair statistics are quite limited, particularly for mechanical equipment. A sub-group of the IMechE Mechanical Reliability Committee has therefore carried out a number of studies to identify and evaluate the main sources of mechanical reliability data currently available. The principal sources identified and evaluated by the Working Party are shown in Table 4.15. The majority are in the public domain. This information has been published as a series of data sheets which provide a guide to reliability assessment. The data sheets were prepared by members of the Data Acquisition Working Party who are all practising reliability engineers.

Although the Working Party has concentrated on reviewing sources of mechanical rather than electronic data, many of the sources include both. Table 4.16 indicates typical components covered within several different equipment categories in the data source documents.

Table 4.15: Principal Reliability Data Sources

Data Sources	Title	Publisher and Date
CCPS	Guidelines for process equipment reliability	American Institute of Chemical Engineers, 1990
Davenport and Warwick	A further survey of pressure vessels in the UK (1983-1988)	AEA Technology - Safety and Reliability Directorate, 1991
DEFSTAN 0041, Part 3	MoD practices and procedures for reliability and maintainability Part 3, Reliability prediction	Ministry of Defence, 1983
R. F. de la Mare	Pipeline reliability; report 80-0572	Det Norske Veritas/Bradford University, 1980
Dexter and Perkins	Component failure rate data with potential applicability to a nuclear fuel reprocessing plant, report DP-1633	EI Du Pont de Nemours and Company, USA, 1982
EIREDA	European industry reliability data handbook	EUROSTAT, Paris, 1991
ENI Data Book	ENI reliability data bank - component reliability handbook	Ente Nazionale Indrocarburi (ENI), Milan, 1982
Green and Bourne	Reliability Technology	Wiley Interscience, London, 1972
IAEA TECDOC 478	Component reliability data for use in probabilistic safety assessment	International Atomic Energy Authority, Vienna, 1988
IEEE Std 500-1984	IEEE guide to the collection and presentation of electrical, electronic sensing component and mechanical equipment reliability data for nuclear power general stations	Institution of Electrical and Electronic Engineers, New York, 1983
MIL-HDBK 217E	Military handbook - reliability prediction of electronic equipment, Issue E	US Department of Defence, 1986
OREDA 92	Offshore Reliability Data, 2nd edition	DnV Technica, Norway, 1992
D. J. Smith	Reliability and maintainability in perspective	McGraw-Hill, 1964
NPRD-3	Non-electronic component reliability data handbook - NPRD-3	Reliability Analysis Centre, RADC, New York, 1985

Table 4.16: Typical Components within Equipment Categories

Equipment Category	Typical Components
Rotating	Pumps, compressors, turbines, motors
Static	Pipelines, flowlines, valves, vessels
Instrumentation	Sensors (temperature, pressure, level) and controllers
Safety	Fire pumps, safety valves, interlocks
Process	Pumps, compressors, valves, vessels, piping
Electrical	Cables, motors, PCB's, lamps, relays, circuit breakers

Note: Categories are not intended to be mutually exclusive

In preparing the data sheets the Working Party has not offered any judgement as to the quality, applicability or validity of the data contained within them. The sole purpose has been to provide guidance on a number of useful sources and their content for engineers with a need for numerical mechanical reliability data. However, it must be stressed that it is extremely unlikely that better data sources exist in the published literature at the present time.

4.7.4 Root Causes in the Difference Between Field Reliability and Predicted Reliability

The inability to relate predicted and field reliability has proven to be extremely costly. It has been shown that the "inaccurate predictions of reliability characteristics may result in non-optimum allocation of resources, and, in turn, low levels of operational readiness [Miller and Moore, 1991]. As a result, many researchers have studied the factors which contribute to the significant difference between field and predicted reliability. A solution to the reliability difference is possible if the factors can be identified, properly measured and subsequently controlled.

Lynch and O'Berry [1986] collected over two years data on 500 aircraft systems deployed at 10 operational sites. They concluded that the most significant factor affecting field reliability was the maintenance/logistics support-related environment including the actions and interactions of the key elements of service personnel, management, equipment and spares. In addition, they discovered that only 20 per cent of the field reliability problems were related to hardware problems.

MacDiarmad [1985] examined several studies and concluded that the terms, operational and contract reliability were generally defined differently and served totally different purposes. He contended that the manufacturer and user should recognise that the contractual and operational reliability are fundamentally different terms in concept, in measurement method and in usage. He stressed that the main point was not necessarily recognising the difference but attempting to establish a relationship between the two reliability parameters.

Balaban and Kowalski [1984] identified limitation associated with field data collection systems and attributed the reliability differences to three areas:

- Representatives of the laboratory environment.
- Accuracy of specifications.
- Inherent variability of the operating systems.

First, even though systems predictions are based on the best data available, the analyst works in an environment that limits the accuracy of any reliability estimate. Predictions must incorporate the effects of "moving targets" such as design changes, the use of non-representative hardware or software interfaces, inadequate test equipment, manuals or a lack of appropriate qualified operators or support personnel. Balaban and Kowalski [1984] indicated that there are always trade-offs between test length, test timing and test realism which limit the accuracy or quality of the initial reliability estimates.

Secondly, improper assumptions concerning the physical operating conditions, including usage assumption and support concepts, are understandably significant issues. Finally, despite attempts to develop perfect estimates, similar hardware operated under supposedly similar conditions can exhibit widely varying reliability characteristics.

In conclusion, the difference between predicted and field reliability estimates can be attributed to many factors, only some which are controllable. A list of the major contributing factors are presented below.

1. Definition, operational and environmental problems
2. Prediction Techniques/Assumptions
3. Test Plan Results
4. Fault Isolation Techniques
5. Analysis and Test Weaknesses
6. Improper Assumptions
7. Reliability Measurement Methods
8. Statistical Variability

4.8 Summary

This chapter has presented a taxonomy of the various approaches to the management of product reliability. In particular, the chapter has reviewed technical and management literature relating to reliability assurance activities during product design, collection and analysis of reliability data and the use and effectiveness of reliability-based techniques. The next stage in the research was to formulate and develop the technical guidelines and the overall research methodology.

5. Technical Guidelines: Research Questions and Hypotheses

5.1 Introduction

This chapter aims to produce a comprehensive breakdown of the research programme and sets the technical guidelines which will act as the base for the management of the research project. Specifically, the chapter describes the aims and objectives of the study, the hypotheses to be tested, the research questions in relation to the hypotheses and the selection of the variables to be examined.

5.2 Experimental Design

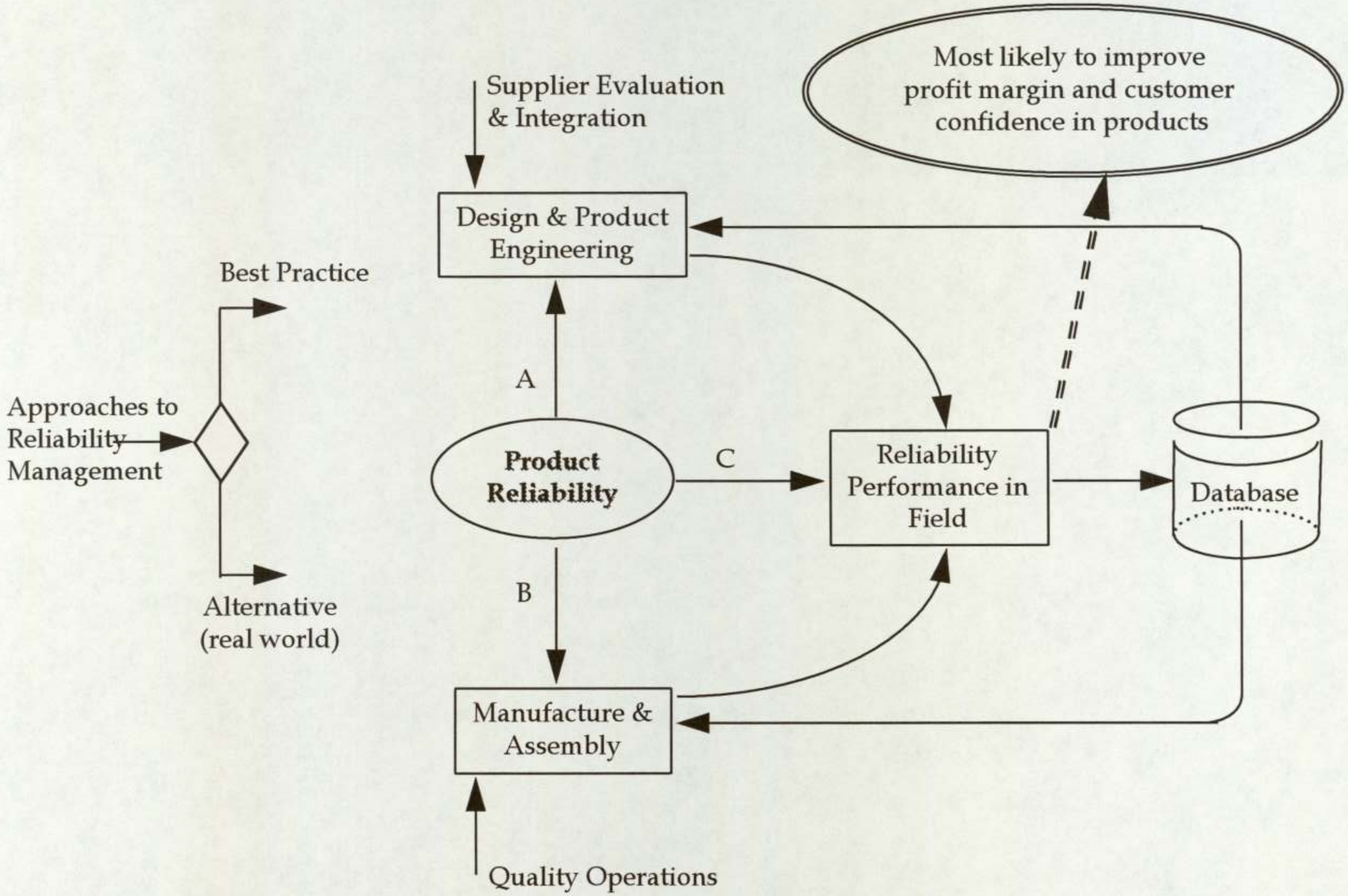
From the detailed examination of the technical literature on reliability management (reported predominantly in chapters 2 and 4) two key observations were made:

1. Product reliability performance is closely linked to the engineering decisions and approach taken during the design and manufacturing process. Factors that needs to be considered are reliability evaluation of supplier parts, engineering methods (e.g. modular design) used to assess and reduce reliability uncertainty, quality operations, application and effectiveness of concurrent engineering.

2. The only means of improving reliability is through the effective use of field performance data. Factors that needs to be considered are use and feedback of field performance data to effect design improvements, quantitative assessments of reliability and measures used to monitor reliability performance.

The empirical investigation of reliability management of machine tool technology will involve close examination of these factors. Although we will collect and analyse data relating to the above factors, the real focus of the project will be to use the data in such a way as to develop a generic methodology for reliability improvement of machine tool products.

Figure 5.1: Conceptual Model of Basic Factors Affecting Reliability Performance



5.2.1 Conceptual Model

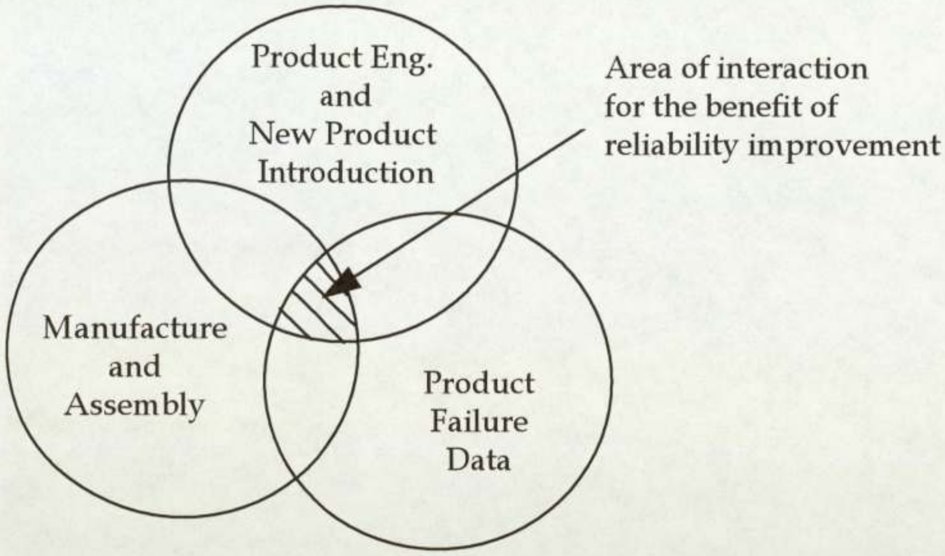
In developing the research upon which the generic methodology is based, an analytical framework, in the form of a conceptual model, was developed to enable the researcher to structure the observations. The analytical framework has both been derived and further developed using a combination of existing models and theories on reliability engineering and management.

Depicted in Figure 5.1, the framework stresses the need to consider product reliability issues from the perspective of design and product engineering, assembly operations, and field performance during service. In this thesis, product engineering refers to incremental improvements in functional performance, durability, maintainability and other design attributes. Therefore, the capacity to both manage and improve product reliability in machine tool manufacturing firms will be analysed in terms of three functions:

- Product engineering and new product introduction.
- Production data feedback to design.
- Product failure data during operational use.

However, it is important to point out that reliability performance cannot be explained completely by the competencies of the above three business functions. For example, the process of using new technologies for achieving commercially successful results may lead to significant improvements in product reliability. This process of using new technologies is both dynamic and unpredictable, because it includes systematic as well as random elements. This investigation is concerned with the systematic elements which has an influence in the process of improving machine tool reliability. It is also important to note that reliability performance depends not only on the effectiveness of each of the business operations, but also on the interaction between them (Figure 5.2). The effectiveness of this interaction is critical in establishing whether a particular reliability improvement effort is a success.

Figure 5.2: Interaction Between Product Engineering, Assembly and Service for the Benefit of Reliability Improvement.



In developing the analytical framework it has also been argued that analysis of reliability management practice should not become divorced from the 'real world' of the firm. As such, while much early work has been conducted exclusively at a conceptual level, in developing the present work the framework which has been drawn up not only accounts for various 'models' for solving reliability management problems at the operational level, in a specific 'best practice' way but also takes account of the 'real world' situation.

However, these models will provide particular perspectives on the coherence and linkages between structural aspects and management practices such as ways of enhancing product reliability during product introduction or the structural and procedural aspects of engineering activities. In some cases, it may be possible to ascertain the impact of these models in terms of enhancing product reliability. Further, these models may also be used as points of reference for description and analysis of the practice of reliability management. Examples of the models selected, some of which can also be defined as a structured technique for improving product reliability, are listed below:

- Concurrent or simultaneous engineering (CE).

- Design for assembly and/or manufacture (DFM/A).
- Quality function deployment (QFD).
- Design of experiments (DoE) and/or Taguchi methods.
- Value engineering and analysis.
- Design and process failure mode and effects analysis (FMEA).

The conceptual model, therefore, provides the framework for empirically testing the links between product reliability and various dimensions of engineering activity. The hypothesis which underpins the model is that product reliability is a quality factor over time which is most likely to increase customer confidence in products and lead to improved profit margins. An extension of this view is that benefits of reliability at an operational level carry on through to business performance. In the model, the need to analyse reliability management from both an operational and engineering viewpoint has also been addressed.

5.2.2 Influential Factors and Approaches to Reliability Management Practice

As illustrated in Figure 5.1, two approaches to reliability management practice have been defined. One approach termed 'best practice' is seen as an universal prescription, or emulation of 'text book' approach, for the management of product reliability. Best practice models detailed above may be adopted in this approach or may form elements of the overall reliability management system of an organisation. As discussed in chapter 4, this type of approach is more prevalent in Japanese and most Western multi-national firms who have adopted the 'Japanese Total Quality Control System' [see Dale et al., 1991].

The other approach termed 'alternative' reflects the real world situation and the specifics of the industry. These specifics are mainly the relative size and resources of a firm which acts as a constraint for adopting 'best practice' models. This point is of particular relevance for small to medium sized companies (SME's). However, research has shown that medium sized engineering based firms can also adopt 'best practice' models through the formation of 'part time' development teams [Barber et al., 1995]. This, as Barber advocates, overcomes the human resource problems.

However, another significant specific is the importance of sectoral variety. The challenges for reliability management obviously differ between sectors [see Benchmark Research, 1994]. For example, the characteristics of product reliability and changes in reliability standards (e.g. European Standards and Legislation) in the electronics and semiconductor industry differ from those in chemicals or textiles industry.

Different levels of reliability effort and different kinds of expertise are required in each industry. For example, burn-in and stress screening, alongside a structured route of product reliability optimisation are most likely to be prevalent in the electronics industry. However, in the mechanical engineering sector reliability may be built in through nominal engineering and manufacturing activities. Therefore, techniques such as burn-in and stress screening may not be relevant.

The industrial structure, technological content and intensity of competition also differ between sectors, again requiring firms to develop and adopt specific levels and types of reliability management practices. That does not mean that in every sector or technological field there is one obvious 'best practice' that all firms must follow. In every sector, a variety of firms with different approaches towards the management of product reliability are able to optimise and improve product reliability at a satisfactory level. Nevertheless, the technological and structural characteristics of a sector define and limit the range of viable courses of action that a firm is able to undertake.

Although the above specifics exert a great deal of influence on the actions and options available to firms, they cannot determine the details of management behaviour. Empirical evidence and theory obtained from a broad literature base has also indicated that management commitment and attitudes as well as knowledge and understanding of 'best practice' models and techniques are influential factors in the practice of reliability management (see chapter 4).

Other management factors also enter the equation such as organisation, experience of applying these techniques to different situations and functions and training. These causal factors have a significant effect, regardless of industry type.

It is important to highlight that these factors and specifics of the industry (discussed above) may not have an effect in isolation, but their accumulation causes a cascade effect which can then exert a profound influence in the effectiveness of reliability management practices. Figure 5.3 illustrates this point. It will obviously be necessary to take account of these industrial specifics and factors when analysing reliability management practices in the machine tool industry.

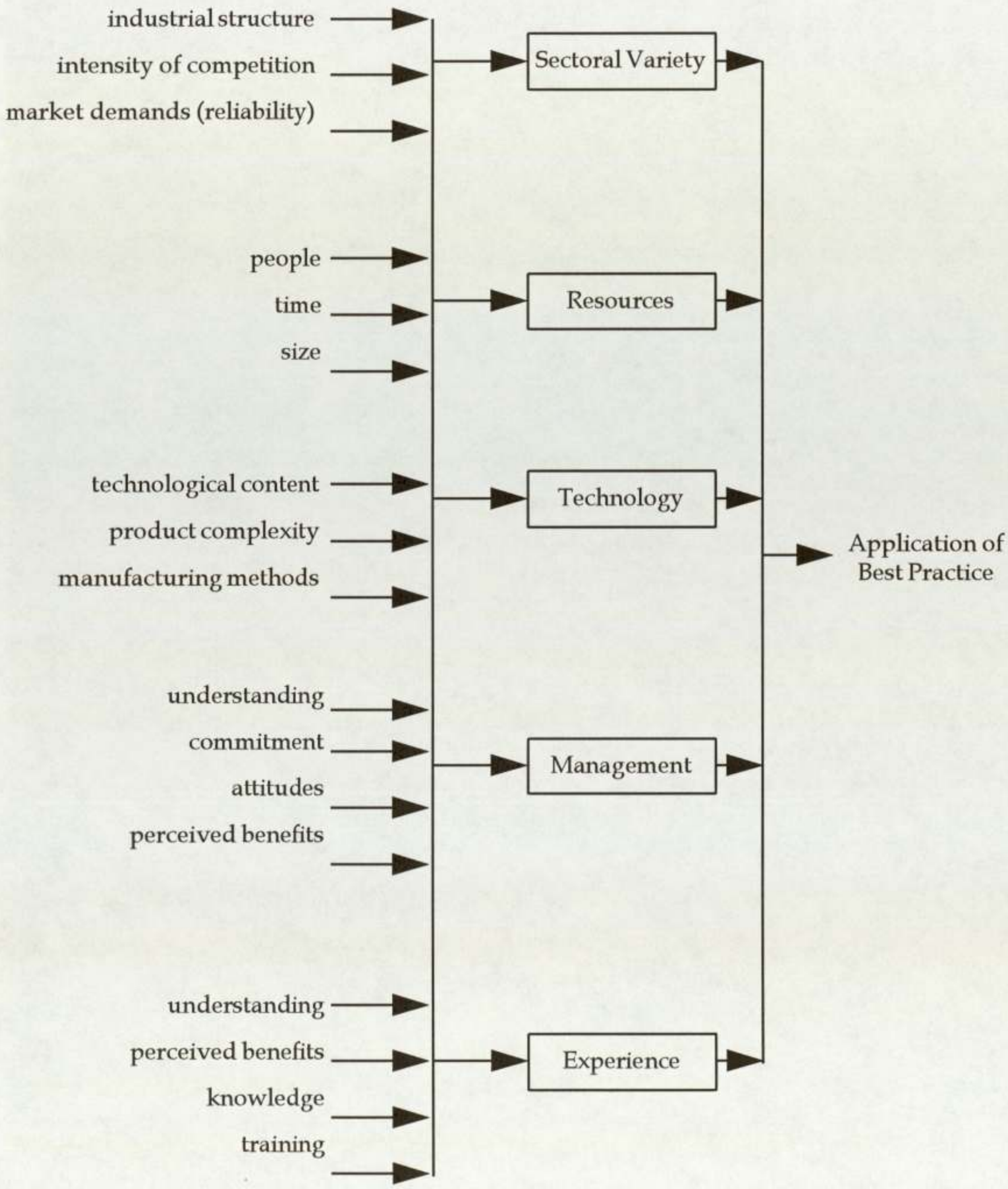
5.2.3 Differences and Similarities Between 'Best Practice' and 'Alternative Approach' to Reliability Management

Seven engineering operations have been defined to distinguish between the 'Best Practice' model and 'Alternative Approach.' In other words, differences will exist between the two models in their actions taken to complete the seven engineering operations. These operations have been defined with the aid of information collected from the literature survey and preliminary work with the case study company, Cincinnati Milacron. The author defines these processes as being:

> 'dimensions differentiating the best practice model from the alternative approach.'

The seven dimensions are (I) Reliability Appraisal during Product Design, (II) Design-Manufacture-Service Interface, (III) Supplier Involvement in New Product Design, (IV) Production Feedback to Engineering Design, (V) Post-Production (Service) Feedback to Engineering Design, (VI) Use of Formal Methods and (VII) Reliability Performance Measurements. The key foundations of these dimensions are briefly elaborated below:

Figure 5.3: The Cascade Effect of Influences on Reliability Management Practice



(I) Reliability Appraisal : The degree to which reliability is considered and assessed during the product design stage is critical to the reduction of downstream failures. A practical reliability programme which incorporates reliability requirements into the design process and ensures that reliability uncertainty is analysed and assessed is to be adopted.

(II) Design - Manufacture - Service Interface : Inclusion of the manufacture and field functions in major design reviews provides the mechanism for identifying potential manufacturing, assembly and field issues which may affect reliability performance downstream. Thus, it provides the catalyst for reducing the scope of failures occurring downstream in the product introduction cycle.

(III) Supplier Involvement in Product Design : Supplier involvement early in the design of a product ensures that supplier parts reliability is assessed upfront. Similarly, the importance of supplier evaluation and selection forms an important part of reliability achievement.

(IV) Production Feedback to Engineering Design : As well as feedback of manufacturing and assembly related problems, the use of production test data forms an important part of the reliability improvement process.

(V) Post-Production (Service) Feedback to Engineering Design : This reliability-related operation forms an important part of the overall reliability improvement process. Early feedback of failure data to effect design improvements will reflect the 'real world' operating conditions of a machine tool product.

(VI) Use of Formal Methods : Application of formal reliability methods will facilitate the investigation of root causes of reliability-related problems to be conducted on a systematic and analytical basis. Such methods can be used at any stage of the life cycle of a product.

(VII) Reliability Performance Measurements: Use of a comprehensive measurement system which includes reliability and financial measures is essential to

monitoring the reliability performance of machine tool products. Creating a closed loop between measurement, review and action is also essential.

Table 5.1 illustrates the similarities and differences between the 'best practice' model and the 'alternative approach' in their approaches to conducting the seven engineering operations. This table will provide the basis for evaluating whether or not a manufacturer is adopting the 'alternative' or 'best practice' model for the management of product reliability. In evaluating which of the two models a manufacturer is adopting, a significant number of the dimensions must be positive either way.

5.2.4 Machine Tools and Reliability Management

In defining the differences and similarities between the alternative approach and the best practice model (see Table 5.1), one of the main hypothesis (Ho) that is put forward for testing in this dissertation is as follows:

> despite the growing awareness and recognition of the importance of reliability to customer confidence in machine tool products, manufacturers nevertheless will adopt the 'alternative' approach (as defined in Table 5.1) towards the engineering and operations management of product reliability.

This hypothesis is put forward against the background of the literature survey reported in chapter 4. In relation to the seven dimensions discussed above, some of the most productive work relating to the area of reliability management in manufacturing industry has concluded that:

I) Little or no consideration is given to reliability requirements during the new product introduction process. Reliability is assessed through engineers own experience and judgement, and product testing [see Garner et al., 1994].

II) Little or no interaction between design, manufacture and the service functions for the benefit of identifying potential reliability problems upstream in the design process.

Table 5.1: Differences and Similarities between 'Best Practice and 'Alternative Approach'

Dimension	Best Practice	Alternative
Engineering Design and Reliability Considerations	Practical system, integrating reliability considerations into engineering projects (e.g. through multi-functional team work)	Driven primarily through nominal design-manufacture activities Design for reliability based on engineers own experience or reliability growth testing
Design - Manufacture Interface	Upstream, early consideration of all elements of the product life cycle through CE principles	Lack of manufacturability and field issues consideration early in the process Lacking in consistency and continuity
Supplier Involvement in New Product Design	Upstream in the 'NPI' process Supplier evaluation driven by reliability-cost, rather than cost alone	Upstream in the 'NPI' process, but only in terms of part/component functionality Lacking in continuity and commitment
Production Feedback to Engineering Design	Systematic feedback Both technical and statistical related	Primarily observation based Lacking in continuity and integrity
Post-Production (service) Feedback to Engineering Design	Systematic feedback Both technical and statistical related	Primarily observation based No systematic feedback Lacking in continuity and integrity
Formal Methods	Application of formal methods where necessary	Little or no application of formal methods Resistant to implementation
Reliability Performance Measurements	Quantified and derived on a statistical basis Closed loop between measurement, review and action	General, indeterminate and observation based Open loop between measurement, review and action

III) Among several factors used to evaluate vendors, manufacturing firms emphasise the importance of product quality and reliability, on-time delivery and price. However, firms are believed to give the highest weight to price as a vendor evaluation criterion. Similarly, supplier involvement upstream in the product design is minimal [see Ebrahimpur et al., 1990].

IV) Manufacturers make little use of both post-production (field data) and production data to effect design improvements [see Lawless et al., 1992].

V) Little or no use is made of formal reliability related methods to aid in the process of reliability improvement. [see Abed et al., 1989].

VI) A closed loop between performance measures of reliability, review of problems and actions taken is rarely achieved [see Lawless et al., 1992].

The above findings are more applicable in the general manufacturing industry, rather than being specific to a particular industry. However, the objective of the above proposition is to examine whether these findings relate to the machine tool industry. For further support of the formulated hypothesis (Ho), it is important to highlight the following notes on the industry:

1. Competitive threats are seen as the least significant by the mechanical engineering sector re-inforcing the 'impression' of a traditional sector resistant to change in terms of approaches towards reliability or quality management. However, the use of high quality machine tool products determines to a large extent the progress made in the productivity and competitiveness of the manufacturing industry and the technical quality of the products manufactured. Further, reliability can be a key selling point of machine tool products and the market demand is of high reliability.

2. Although machine tools can be characterised as a high technology, high complexity product, the majority of the product improvement and innovations activities relate primarily to suppliers of machine tool equipment and sub-systems. In this context, most of the specialised reliability engineering activities are carried out by the supplier and a structured route to reliability optimisation will also be adopted, as generally illustrated in Figure 5.4. This is particularly common for electrical and electronics technology of machine tools and suppliers of military equipment where some of the reliability activities and tools enlisted in Table 5.2 are adopted. In this case, this leaves little scope for machine tool manufacturers adopting a route of action, similar to that of Figure 5.4, for reliability improvement of machine tools.

3. It has already been stressed in Part 1 of this thesis that in many machine tool firms, there may be no established methods, mechanisms or organisational structures for reliability management. This can be the case even in large engineering based firms, but will more often be found in small and medium-sized firms, such as machine tool manufacturers. Where reliability management activities have been explicitly defined and formally separated from other engineering activities, it remains often implicit or self-evident in medium sized companies. However, this does not mean that questions about matters and issues of reliability management are irrelevant to machine tool manufacturers.

A first assessment of the approach adopted by manufacturers towards reliability management can be made by examining the 'coherence' between the general quality and reliability improvement system of the firm and the structure of its reliability management activities. This will quite often remain a rather subjective judgement, based on the impressions derived from talking to a few spokespersons. Nevertheless, if a manufacturer is able to explain the logic of the firm's reliability improvement activities in view of its overall reliability system, this gives a clear indication of the approach adopted.

Figure 5.4: A Structured Route to Reliability Optimisation During Design

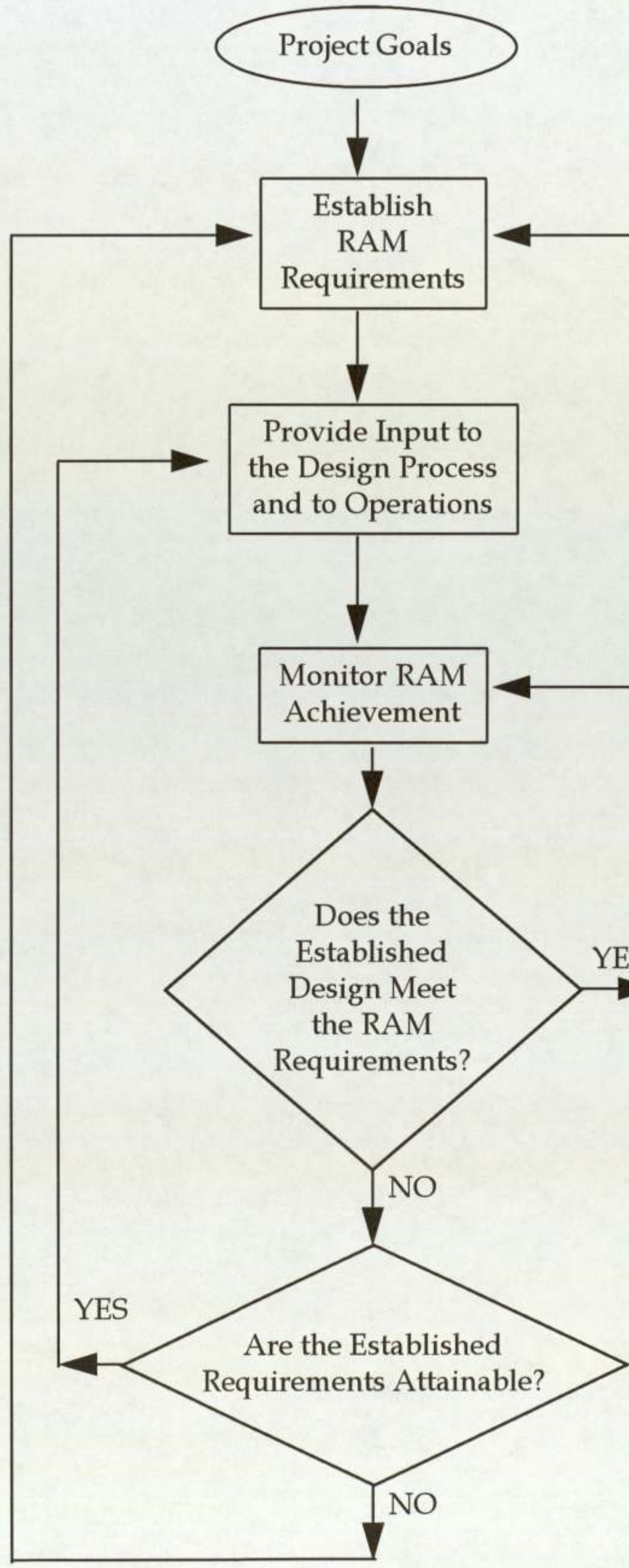


Table 5.2: Reliability, Availability and Maintainability (RAM) Activities and Tools

- Management
  - RAM Programme Plan
  - RAM Review Process

- Modelling and Analysis
  - Block Diagram Analysis
  - Failure Mode, Effects and Criticality Analysis
  - Fault-Tree Analysis
  - Markov Analysis
  - Event-Tree Analysis
  - Cause-Consequence Analysis
  - Maintenance-Engineering Analysis
  - Life-Cycle Cost Analysis
  - Sneak Circuit Analysis
  - Part-Count Analysis
  - Growth Analysis

- Testing
  - RAM Test Plan
  - Test, Analyse, and Fix Process (Growth Testing)
  - Environment Stress Screening
  - Reliability Qualification Testing
  - Production Reliability Acceptance Testing

- Data Collection and Analysis
  - Generic Data Development
  - Failure Reporting, Analysis and Corrective Action System

- System Design and Logistics
  - Redundancy and Diversity
  - Modularity and Diagnostics
  - Reliability Vs Maintainability Trade-off Studies
  - Part Control Programme
  - Part Derating
  - RAM Procurement Specifications
  - Preventive Maintenance Programme
  - Corrective Maintenance Programme
  - Spare-Part Programme

A final step in the exploration of reliability management approaches adopted by machine tool manufacturers is an analysis and evaluation of the methods, routines and organisational structures used to set goals and priorities for the reliability improvement effort and other reliability-related activities. The information relates to:

a) The stated reliability management system of machine tool firms and how this compares with the actual operational and engineering activities of reliability improvement. These activities relate to:

    - The mechanisms of feedback of field performance data to product engineering and whether they drive key design, manufacture and assembly activities or merely react to them.
    - Use of warranty data in management decision making on reliability improvement.
    - Supplier involvement and integration during new product introduction.
    - Supplier evaluation criteria.
    - The extent of concurrent engineering adaptation.
    - The extent to which reliability and other related technical issues are considered at each stages of product design and during major design reviews.
    - Experience of firms which have tried best practice models and reliability improvement techniques.
    - The monitoring of major engineering changes.
    - Cycle testing and inspection during assembly and whether formal techniques are used for monitoring purposes, for example statistical process control (SPC).

b) The actual reliability components of the firms reliability management process. How proactive are these components and what business functions do they encompass? How and when are these components introduced in the design and manufacture process, at the outset, during the process, or as an afterthought?

The research effort was guided by the above two research questions. The testing of the hypothesis (Ho) was carried out by examining in detail the reliability management systems of a number of machine tool manufacturers. The objective was to ascertain whether a statistically significant number of manufacturers adopt the 'alternative' approach to the management of product reliability, as defined in Table 5.1. In other words, for the hypothesis to be proved, a significant number of the dimensions listed in Table 5.1 must be a positive indicator of manufacturers following the 'alternative' approach.

A survey (using detailed questionnaires) was used as the generic methodology for testing the above hypothesis. The analysis itself attempts to gain some appreciation of, and speculate upon, the reliability management of machine tool products, and where possible, suggest transformations to the reliability management approaches to enhance machine tool reliability.

The model linkages (see Figure 5.1) are broadened and discussed below.

5.3 Link A: Reliability-based Design

The inherent reliability of a product is strongly influenced by decisions made during the design engineering process and the intensity of reliability effort. In general, the design methodology dictates the degree of reliability effort, and this effectively establishes the boundaries with respect to reliability assessment and analysis of product designs prior to production hand-over.

Inadequacies in design affect all products produced and are progressively more costly to rectify as development proceeds. Industrial studies has shown that as much as 95% of the total life cycle costs (LCC) of manufacturing machinery is determined during the conception and design/development phases [Arsenault et al., 1980].

It is therefore essential that effective reliability disciplines and principles are used which minimise the possibility of failure and which allow design deficiencies to be detected and corrected upstream in the design-manufacture process. The design process must also take into account other factors that may have a bearing on product reliability such as assembly methods, modular design concepts, supplier's component reliability, operational use and maintenance.

In view of the above discussion, Figure 5.5 details a model of the factors affecting reliability achievement during the design and development process. The model will be used as a guide to investigating the reliability management process adopted during design. The factors are categorised into three areas:

(a) Supplier Evaluation & Control : Factors that will be investigated are (I) supplier evaluation criterion, (II) supplier involvement in the design process, (III) supplier's technical knowledge base.

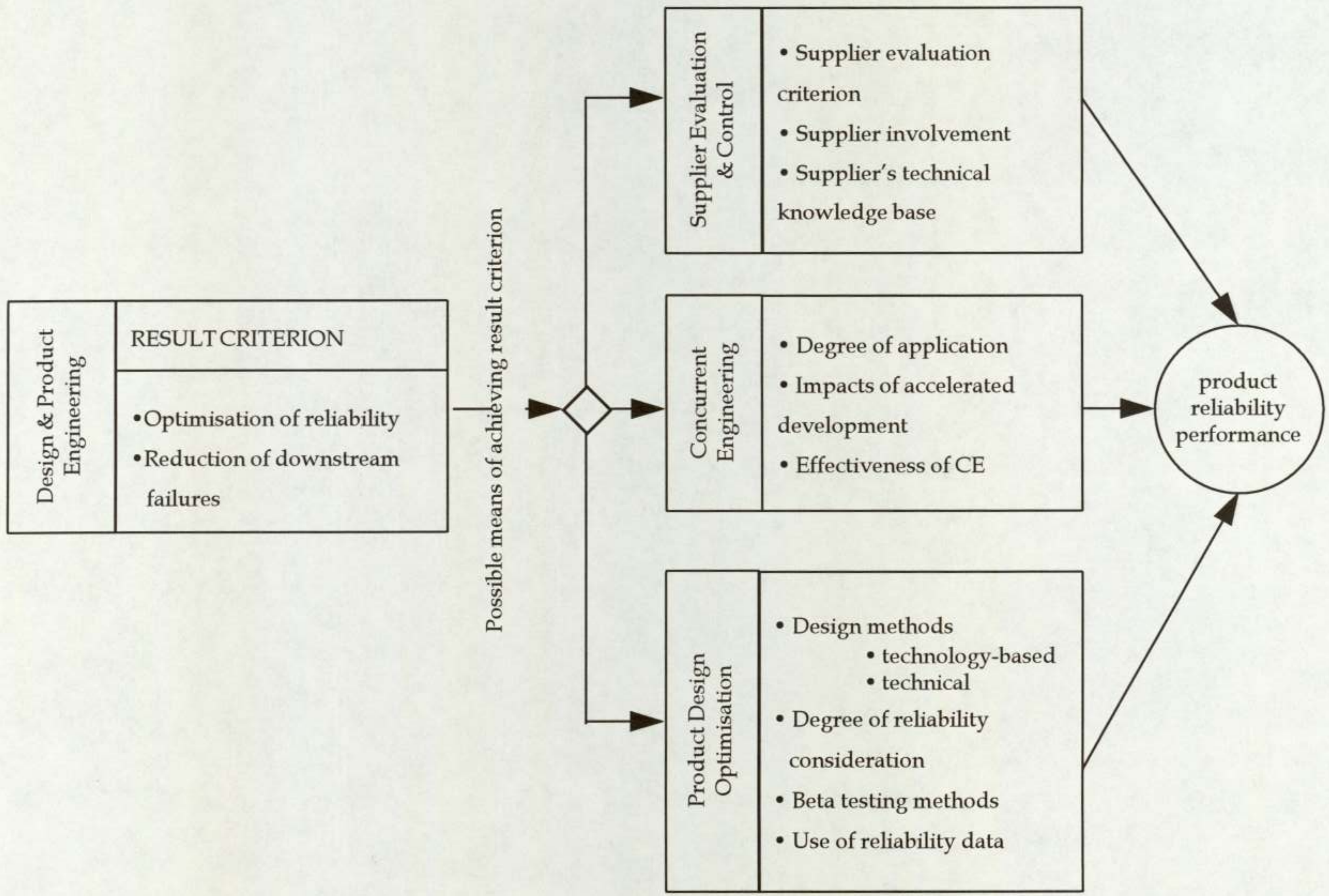
(b) Concurrent Engineering (CE) : Factors that will be investigated are (I) degree of application, (II) impacts of accelerated development, (III) effectiveness of CE as a tool for reliability improvement.

(c) Product Design Optimisation : Factors that will be investigated are (I) application of design methods, (II) degree of reliability consideration, (III) application and effectiveness of beta testing, (IV) use reliability performance data during design.

5.3.1 Integration of Reliability-related Activities during Product Design

The investigation of reliability and related activities during new product introduction involves a series of steps. Basically, the initial objective is to evaluate the extent to which reliability is considered during the conceptual, design and development, product testing and prior production handover. Following this, the next step is to establish the methods used to achieve and improve the inherent reliability of the machine tool product during this

Figure 5.5: A Model of Design Factors Affecting Reliability Achievement



process. In other words, the first measure will give an indication of the intensity of the reliability effort and the second will evaluate the type of methods deployed for achieving reliability.

However, simply focusing on the extent to which reliability is considered and the methods used during new product introduction will not give a detailed account of the level of reliability consideration. In order to obtain a full account, further investigation is necessary. Table 5.3 lists 15 common engineering based methods for enhancing product reliability during the product introduction process. As indicated in Table 5.3, the author has divided these methods into the following two categories:

- Eight are defined as being techniques.
- Seven as being strategies or strategy based methods.

These methods cover practically the complete pragmatic means of increasing reliability, while both reducing design leadtime and cost. These are not structured design nor engineering based methods as depicted in the literature, but the basic principles of such methods are used informally or formally by firms to control decisions regarding the optimisation of product reliability and the final design. Further details on the application of these methods will provided in chapter 8.

Firms will be asked to indicate, relatively, the degree of application or consideration given to the methods listed in Table 5.3 to reduce engineering uncertainty and enhance product reliability at a satisfactory level.

Link A focuses on these methods as categorised in Table 5.3 and expresses the following hypothesis (H1):

> Machine tool manufacturers are most likely to use strategy based methods for addressing product reliability issues, and are less likely to apply techniques as depicted in Table 5.3.

This hypothesis is suggested by the specifics of the machine tool industry and the nature of design problems (e.g. routine designs and redesigns) faced by

Table 5.3: Techniques and Strategy Based Methods of Reliability Improvement

Strategies	Techniques
Incorporation of units or sub-assembly design of existing products	Failure modes and effects on system operation
Design units or sub-assemblies of new products for incorporation into other product variants	Identification of potential failure critical components
Reduce the number of critical characteristics of the product (i.e. over design)	Supplier's component reliability
Reduce the number of parts and process steps	Previous field performance data and issues e.g. (maintainability, reliability, accessibility issues)
Design the product for ease of maintenance and repair	Process variation and design for manufacture
Modular design concepts	Functional variation during use
Use of proven technology	Design reviews
	Load-strength analysis

machine tool designers. Previous similar empirical evidence and the preliminary case study work also supports the justification for putting forward the above hypothesis.

The hypothesis was tested by examining whether or not a statistically significant number of manufacturers use the strategy based methods for optimising machine tool reliability during new product introduction. This provided a positive indication of the approach taken by manufacturers for optimising reliability during product design stage. Correlation analysis and multiple regression analysis were used to test the hypothesis.

Further, the analysis of such reliability and related activities will provide the basis for evaluating whether or not:

- Reliability assessment is carried out through nominal design engineering activities;
- Or through integration of basic principles of technical based methods within such activities.

In furthering the above analysis, design reviews forming an important element in the overall reliability improvement process are examined. In this context, the investigation was focused on establishing whether reliability and maintainability related problems, supplier's reliability performance, assembly problems, field failures of products are addressed during any preliminary, critical or general design or product reviews. The objective was also to establish the degree to which these areas are covered.

5.3.2 The Impacts of Concurrent Engineering

A brief but concise discussion was given in Chapter 6 on the impacts of concurrent engineering (CE) in terms of improved product development performance and therefore improved product quality and reliability. Indeed, literary evidence has suggested leadtime reductions of between 35 and 60 per cent, improved design quality (and therefore reliability) of upwards 50 per cent and scrap/rework reductions of up to 75 per cent. However, no factual evidence of these benefits are provided.

Some researchers go further and cite the maturity effects of CE implementation and state that a distinct learning curve exists for CE. For example, a firm operating CE for 8 years plus is likely to yield greater benefits in terms of improved interface and communication between product design, process design and manufacturing, than a firm operating CE for up to 3 years [Poolton et al., 1996]. However, this can be said of other best practice models depicted in the reliability-related literature. Although these findings have been constrained in favour of the largest industries (e.g. the automotive and the aerospace), many other firms have turned to CE as a 'common-sense' way of developing new products.

However, detailed analytical studies of the impacts of CE to product reliability improvement are relatively rare and lack actual data to support the claims. Accordingly, many studies have failed to identify the downstream impacts of accelerated development and whether CE leads to any substantial quality and reliability improvements, as the literature seems to indicate. Link A therefore specifically focuses on this issue and expresses the following sub-hypothesis (H2):

> CE provides the platform for the free-flow of information and interface between product design and manufacturing, but this does not necessarily lead to any substantial improvements in product reliability.

Initially, the literature provided the basis for this assumption which was then supported by the researcher's experiences of working in the case study firm, Cincinnati Milacron UK Ltd. In view of this, three research questions were formed for guidance in the testing of the hypothesis, namely:

1. How is concurrent engineering actually working?

2. What are the positive and negative side effects?

3. What are the downstream impacts of such accelerated development?

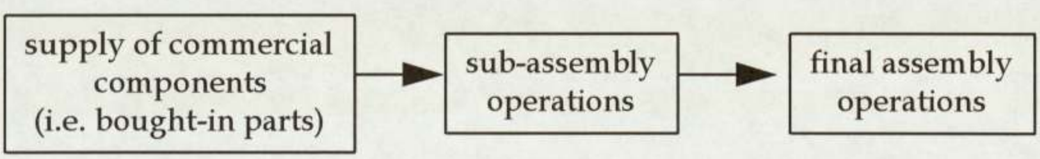
Beyond the sole question of examining a firm's purpose for adopting CE principles, partially or fully, the research was geared towards establishing the design and manufacture and reliability related problems experienced during new product engineering. Firms were asked to indicate the extent to which CE has improved the problems within their organisations.

To test the hypothesis, one-way analysis of variance (ANOVA) was performed to establish whether any significant differences exist among the firms with respect to the 'problems' experienced during new product engineering. This was evaluated against the criteria of CE operation and non-operation. The basis of these statistical experiments will be discussed as and when required.

5.3.3 Vendor Evaluation Criteria and Integration

Given the structure of machine tool manufacturing operations which is mainly concerned with manual assembly of products (Figure 5.6), vendor evaluation and integration form key areas in the continuous improvement process of machine tool reliability.

Figure 5.6: Structure of Machine Tool Manufacturing Operations



The nature of the manufacturing operations, as illustrated in Figure 5.6, therefore implies that the reliability of the manufacturer's product will, to a degree, be as good as its vendor supplied parts. Additionally, it has been estimated that in some US manufacturing firms over 40 per cent of all quality and reliability problems were caused by vendors [Leonard et al., 1983]. This figure is a general indicator of the scale of vendor-related problems in the manufacturing industry and the figure for the machine tool industry is expected to be higher. Thus, for many machine tool firms, it is of absolute importance to establish specific vendor selection criteria. Furthermore, it is essential that first line vendors are integrated in every new product introduction for the enhancement of reliability.

The review of literature indicated that among several factors used to evaluate vendors, manufacturing firms emphasise the importance of product quality and reliability, on-time delivery and price. However, as the literature seems to indicate, firms are believed to give the highest weight to price as a vendor evaluation criterion. The first hypothesis (H3) tests this argument using the machine tool industry as a point of reference:

> Among several factors used in the vendor evaluation criteria, machine tool firms are expected to emphasise price and on-time delivery and are less likely to emphasise product quality and reliability as a major criterion for evaluating vendors.

For the purposes of this hypothesis, specific variables (e.g. technical design capability, vendor's quality management) was selected as criterion for evaluating vendor's reliability. The basis for selecting the type and number of variables will be discussed in Chapter 8 of this thesis, as and when required. Firms was asked to indicate the relative importance they give to these variables against price and on-time delivery. The analysis, was then performed based on three factors:

- two single item variables (price and on-time delivery)
- one multi-item variable (vendor's reliability)

The hypothesis was tested by three one-way analysis of variance (ANOVA). Price, on-time delivery and vendor's reliability was the main three variables. The basis for setting up the ANOVA experiment will be discussed in Chapter 8 of this thesis, as and when required.

Further to the above, the literature suggests the existence of a positive relationship between vendor evaluation criteria and perceived business performance measures, such as improved product design, higher productivity. In his study of room air-conditioner manufacturers, Garvin [1983] found that the primary objective of vendor evaluation in the firms with the highest performance was to obtain the highest quality and reliability of parts. On the other hand, in the firms with the poorest performance, the primary objective was to obtain parts and materials with the lowest possible prices.

The second hypothesis examines the differences in the link between the vendor evaluation criteria and perceived business performance. The objective of this analysis is to evaluate the type of relationship that exists between vendor evaluation criteria and perceived business performance within machine tool firms (H4):

> Managers of machine tool manufacturing firms perceive a strong link between vendor evaluation criteria and general business performance. Specifically, a stronger link is expected to be towards price and on-time delivery and general business performance.

Three sets of hierarchical multiple regressions were used for the purposes of testing this second hypothesis. One set of hierarchical multiple regressions was used for each vendor evaluation criteria (price, on-time delivery, and vendor's reliability). The basis of setting up these experiments will be discussed as and when required.

In addition to the above, the extent of supplier integration and involvement during new product engineering and whether the involvement significantly differs between the conceptual and the design/development stages was investigated. In order evaluate the extent of supplier integration and involvement, the following hypothesis is postulated (H5):

> the level of commitment shown by manufacturers and suppliers alike depends heavily upon the value the supplier's component adds to the machine tool product, which in turn affects the level of supplier integration and involvement in the design process.

For the purposes of testing this hypothesis, the following question is put forward:

To what extent are supplier knowledge bases incorporated within new product engineering?

Qualitative and quantitative measures were derived using methods of action research. This was the primary method to test the above assumption. The basis and the philosophy of action type research in relation to this thesis will be discussed in the next chapter.

5.3.4 Beta Testing as a Tool for Product Reliability Improvement

The benefit of beta testing in product design and development is a theme of many recent writings. There are many methods for and varying extents of beta testing. Beta testing can validate the product concept, eliminate performance problems prior to market introduction and serve as an effective sales promotion tool. Figure 5.7 shows three major classes of purposes of beta testing [Dolan and Matthews, 1993]. These are product function, product support/marketing mix and sales promotion. Firms do not pursue each of these benefits in every beta test case. However, product basic functioning is the core of figure 5.7 because the majority of firms testing industrial products have this as their primary purpose. This piece of research particularly focuses on industrial product testing where greater emphasis on product design and performance feedback is given and typically employs relatively limited sample sizes [Stern, 1991].

Figure 5.7: Beta Test Purposes

Beyond the sole question of exploring the design and management behind beta testing, the research is primarily concerned with analysing from a qualitative perspective the utility of beta testing as a pragmatic tool for identifying and eliminating minor design deficiencies during the latter stages of product design. In view of this, the following hypothesis is postulated for the purposes of examining the utility of beta testing (H6):

> the reliability of machine tool products can be significantly enhanced through the deployment of beta testing.

Having already conducted a comprehensive search of the literature to assess current thinking on beta test design and management and obtain chronicles of actual beta test programmes from a wide variety of industries, the research followed a two stage process.

Stage 1 involved a case study of beta testing as employed at Cincinnati Milacron. This identified key issues in design and management and measured the ability of beta testing as a tool for enhancing product reliability prior to market introduction. Along with the literature review, the case study provided the structure for field investigations in the form of a survey and allowed for generalisations to be made. Together, the two research stages provide the basis for developing an explicit set of key management guidelines for effective beta programme management from the perspective of reliability improvement.

5.4 Reliability in Manufacture

The main cause of production-induced unreliability, apart from rework of scrap, is the variability inherent in manufacturing processes. Variability exists in all manual and automatic processes and also exists in bought-in components. Latent or abnormal defects escaping the final testing are also the cause of product unreliability during early life (infant mortality). Latent defects is said to be directly proportional to the defects per unit in the entire manufacturing process. Controlling manufacturing variability is therefore a significant part of the reliability improvement process.

The control of production quality is primarily concerned with measuring, controlling and minimising these variations in the most cost-effective way. Figure 5.8 illustrates the essential result criterion of this function and the mechanisms by which these results can be achieved. Such methods and activities as inspection, statistical process control (SPC), unit and cycle testing during essential assembly stages will form part of the control of production quality. More importantly, the function of failure reporting, analysis and corrective action, together with effective monitoring and feedback is the key to the control of production quality.

The principal question of link B is:

Whether or not firms are actually adopting this approach to the control of production quality?

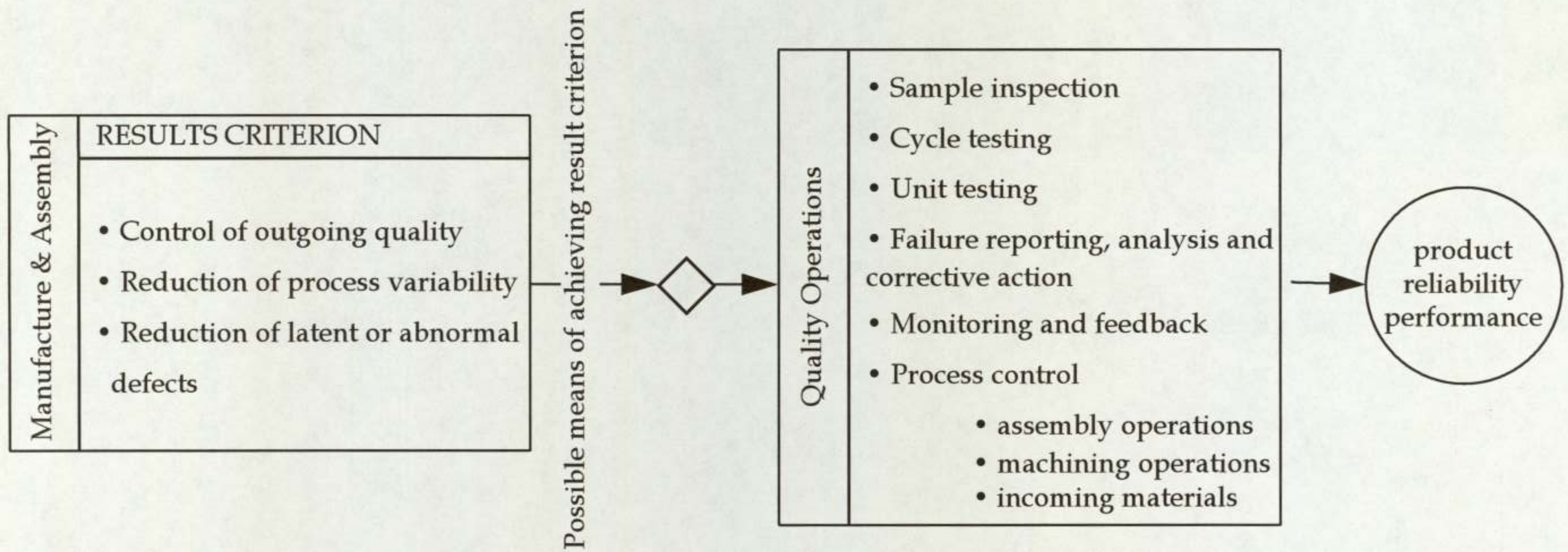
A combination of case study approach and survey techniques using questionnaire design was utilised for the purposes of investigating this research question. The basis for selecting such methods will be discussed as and when required.

5.5 Link C: The Feedback of Field Performance Data

Link A postulated that the inherent reliability of a product and field reliability performance is strongly influenced by decisions made during the design engineering process and the intensity of reliability effort. In addition this, Link B highlighted the importance of controlling outgoing quality of the assembled machine tool product for reducing early life failures. Although manufactured products are typically subjected to a reliability assessment during their design and development and sometimes during their manufacture and assembly stages, comprehensive analysis of product performance during operational use is less common for various reasons.

The literature advocates that the ultimate test of a manufactured product is how well it performs in the field, that is, in the hand of the end user.

Figure 5.8: A Model of Manufacturing Factors Affecting Reliability Achievement



Accordingly, the collection and analysis of data on the field performance or reliability of products forms an essential part of the reliability management process. Such data can be used in many ways by a manufacturer, including [Lawless and Kalbfleisch, 1992]:

1. To assess field reliability and make comparisons with engineering predictions.
2. To provide information for product modification and improvement.
3. To asses the effects of design changes.
4. To estimate and explain warranty costs.
5. To aid in the design of warranty, maintenance and parts replacement programmes.

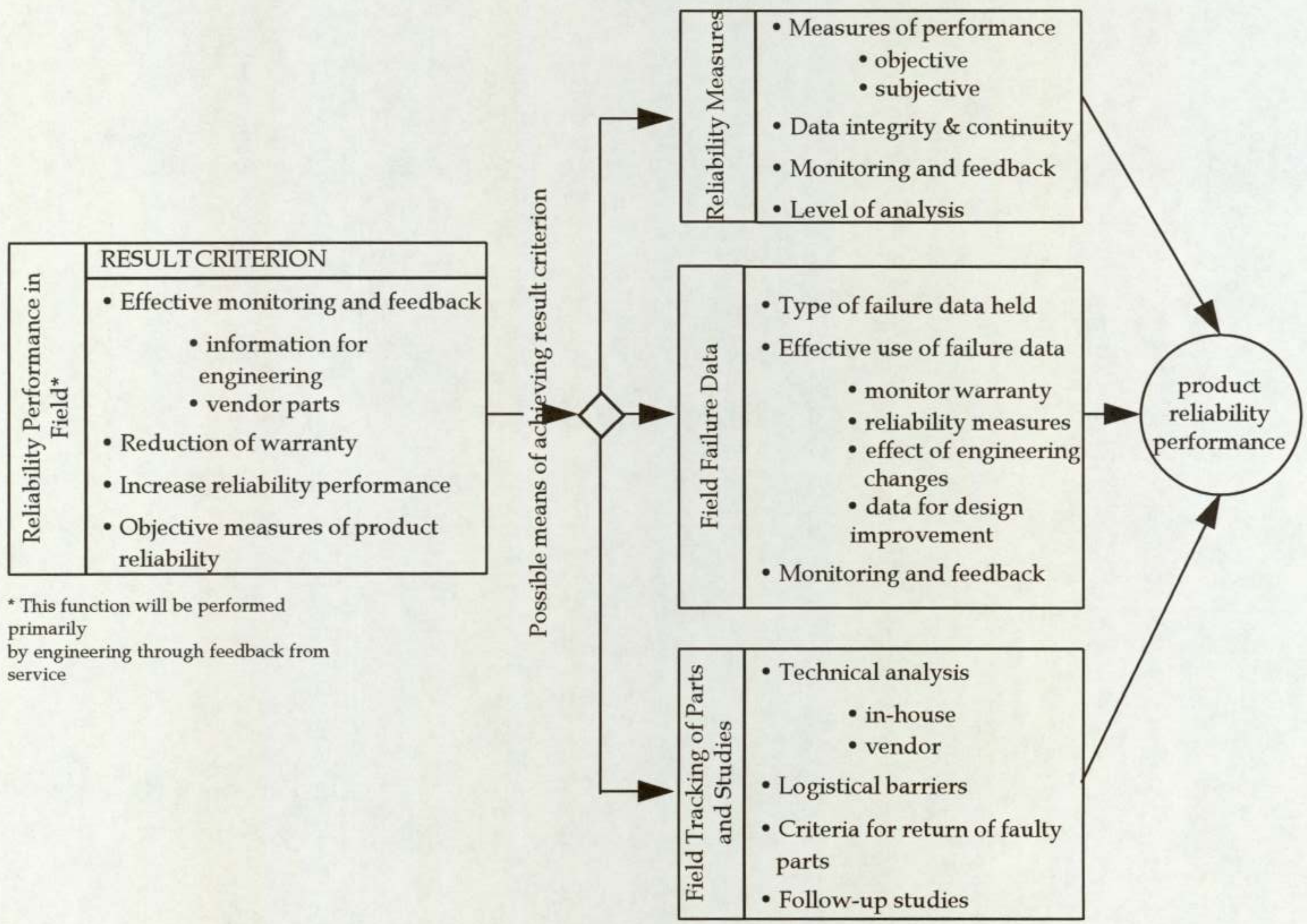
Nevertheless, many manufacturers pay insufficient attention to the collection and analysis of field performance data. One reason is that comprehensive data are often seen as expensive to obtain. Another may be a lack of familiarity with methods for response-selective observational schemes and for combining information from different sources. However, as the literature seems to indicate, management commitment and understanding of the importance of collecting and analysing field performance data also contributes to this problem.

Figure 5.9 illustrates the main objectives of monitoring field reliability performance. This is detailed in terms of the main principle result criterion for this particular function and the ways in which this can be achieved.

From the context of this research thesis, the detailed review of the literature indicated a lack of interest and insufficient attention on the part of machine tool manufacturers in assessing quantitatively the performance of products in the field except when major problems arise. Link C tests this presumption by addressing the following principal hypothesis (H7):

> collection and quantitative assessment of field performance data are either not being carried out satisfactorily or they are not being fed back to design engineering in a timely and systematic basis.

Figure 5.9: A Model of Field Factors Affecting Reliability Performance



* This function will be performed primarily by engineering through feedback from service

Specifically, manufacturers will not make any significant use of such data for addressing items 1 to 5 above. It is expected that a lack of quantitative knowledge about the utility of measuring failure rate of machine tools, inadequacies in reporting field failure data, together with management commitment are potential barriers to the effective operation of this important reliability task.

The hypothesis was tested through the use of simple statistics. The research effort in relation to the above hypothesis was guided by two key questions:

1. To what extent is field performance data utilised and quantitatively analysed for the purposes of systematically improving the reliability of machine tool products?

2. If the hypothesis proves to be true, what changes in organisational structure and practice are needed to implement and adopt an adequate field reliability performance monitoring and feedback system?

In particular, the investigation was particularly concerned with:

- Mechanisms that drive such practice.
- The type of failure data held.
- The type of reliability characteristics used as a measure of reliability performance.
- The extent of technical analysis of field failures and the potential logistical barriers encountered in the operation and tracking of faulty parts.

5.5.1 Failure Distribution of Machine Tools

In industrial practice, many measures of product reliability (e.g. MTBF, failure rate) are derived at without actually validating the underlying distribution of product life. The potential barrier is the lack of knowledge on methods of reliability analysis. Many practitioners, therefore derive reliability characteristics through adopting the exponential distribution, without realisation. The incorrect use and assumption of an exponential distribution (with or without realisation) together with bad engineering discretion in interpreting the data may lead to deficiencies in the statistical relationship been obtained. This subsequently will lead to misleading results and may even consequent bad engineering. Therefore, it is frequently useful to test, on the basis of life test or field failure data, whether or not one is justified that the underlying distribution of product life is exponential.

There has been little research conducted on the probability distribution and failure analysis of machine tool products. Of the those studies that has been conducted, the results indicate that the underlying failure distribution of machine tools can be characterised as being exponentially distributed. The second hypothesis of link C tests this assumption (H8):

> the underlying failure rate of machine tools is constant.

The process of validating this hypothesis involved investigating appropriate graphical and analytical procedures which are useful for determining whether or not the underlying failure distribution of machine tools is exponential. The focus of this investigation was to discuss some methodological issues in the collection and analysis of field reliability data of machine tools. Further to this, the analysis is concerned with:

- Calculating the mean time between failure (MTBF) of CNC machine tool products.
- Cross comparing the MTBF of conventional machine tool products with that of CNC machine tools. Past reliability studies conducted on machine tools have quoted an average MTBF figure of 500 hours for conventional machine tools.
- Identifying the extent to which supplier parts reliability contributes to the failure of machine tool products.
- Identifying the main reliability problems inherent in machine tools.

- Whether a software tool can be developed for calculating MTBF of machine tool products using field failure data.

5.6 Tools and Techniques for Product Reliability Improvement

In Chapter 4, the use and application of tools and techniques (e.g. QFD, FMEA, Taguchi methods) as formal mechanisms for the improvement of product reliability was cited. A wide range of literature exists within the wider body of quality and reliability management describing variety of problems associated with the use and application of specific reliability tools and techniques. They can be broadly classified as a lack of:

- Management support.
- Understanding of the process and or/technique.
- Planning with regard to training and implementation.

The application, diffusion and implementation of these methods has been examined across different industries and point out to the relatively under utilisation of such methods. In particular, empirical evidence has pointed out to the relatively low levels of spread of these methods within the mechanical engineering sector when compared to say the automotive industry. Influenced by these research findings and supported by the preliminary case work, the following hypothesis has been put forward (H9):

> the application and diffusion of formal tools and techniques are relatively low within the machine tool and machine tool equipment industry.

In testing this hypothesis, the most commonly used reliability tools and techniques were identified for use in the research. A complete listing and a brief definition of each of the tools and techniques will be given later in the thesis, alongside the methodology.

The hypothesis was tested through a combination of correlation analysis, multiple one-way analysis of variance (ANOVA) and multiple regression analysis.

In addition to the above hypothesis, the following three sub-hypothesis are tested in order to support the main hypothesis (H9i, H9ii and H9iii):

> formal methods are not structured in such a way which can be more acceptable and useful within machine tool companies.
>
> there are some methods which are more acceptable than others.

The above two sub-hypothesis are suggested by the fact that some reliability-related methods are rigid and mechanistic in their structure, while others are more flexible in application.

> The design engineering process can be significantly enhanced within machine tool companies through the application of well structured methods.

This sub-hypothesis is suggested through the support of previous empirical evidence.

The main hypothesis and the sub-hypothesis were pursued through addressing the following key questions:

1. How widespread is the use and application of reliability tools and techniques within the machine tool industry?

2. What techniques are being adopted?

3. Are some methods more acceptable than others?

4. What are the barriers and difficulties encountered in implementation and application?

5. Are these barriers unique to an individual technique or found across all tools and techniques?

6. Can formal methods be structured in such a way which can be more acceptable and useful within machine tool companies?

7. What are the key successful factors in their effectiveness?

8. Can a methodology be developed to align reliability tools and techniques with the engineering function of a business?

5.6.1 The Effectiveness of Reliability Related Tasks

Although there is widespread technical and management literature on reliability techniques and reliability-related tasks, there is little attempt in the academic literature to measure either through a qualitative or a quantitative approach the effectiveness of such methods as a facilitator for reliability improvement. Given their diversity and complexity, difficulties can arise when they are used without forethought and purpose, with any improvements likely to be random and spontaneous rather than consistent and comprehensive.

Within the overall objective of examining the diffusion and application of formal reliability methods within the industry, one of the main intent of the survey is to measure the effectiveness of tasks a company undertakes during any stages of the design and manufacture process specifically to enhance machine tool reliability (H10)

Based on the results of the survey and assuming that generalisations can be made, machine tool manufacturers can then focus on tasks that have the most effect on improving reliability and reduce or eliminate the reliance on tasks that have the least effect on improving reliability. In other words, a conceptual model can be derived which would identify critical reliability tasks that have proven to be effective in improving machine tool reliability.

The idea was influenced by a previous empirical study carried out by Lindsley [1994], primarily on electronics based companies in the USA.

For the purposes of this research, the term 'reliability-related task' describes particular tasks undertaken either directly or indirectly to facilitate machine tool reliability improvement. It does not necessarily relate to formal methods as briefed on above. However, a manufacturer can apply such methods to particular tasks which facilitate reliability improvement of some description.

Table 5.4: Summary of Research Design

Hypothesis or Research Question	Number	Research Method	Method of Testing	Chapter
Despite the growing awareness and recognition of the importance of reliability to customer confidence in machine tool products, manufacturers nevertheless will adopt the 'alternative' approach (as defined in table 5.1) towards the engineering and operations management of product reliability	Ho	Questionnaire Design Survey Action Research	Detailed examination of reliability management systems to measure statistically all dimensions enlisted in table 5.1	12
Machine tool manufacturers are most likely to depend upon the technical based methods for addressing product reliability issues, and are less likely to apply analytical based methods as depicted in Table 5.3.	H1	Questionnaire Design Survey	Correlation Analysis Multiple Regression Analysis	8
CE provides the platform for the free-flow of information and interface between product design and manufacturing, but this does not necessarily lead to any substantial improvements in product reliability.	H2	Questionnaire Design Survey	ANOVA	8
Among several factors used in the vendor evaluation criteria, machine tool firms are expected to emphasise price and on-time delivery and are less likely to emphasise product quality and reliability as a major criterion for evaluating vendors.	H3	Questionnaire Design Survey	ANOVA	8
Managers of machine tool manufacturing firms perceive a strong link between vendor evaluation criteria and general business performance. Specifically, a stronger link is expected to be towards price and on-time delivery and general business performance.	H4	Questionnaire Design Survey	Multiple Regression Analysis	8

Table 5.4: Summary of Research Design

Hypothesis or Research Question	Number	Research Method	Method of Testing	Chapter
The level of commitment shown by manufacturers and suppliers alike depends heavily upon the value the supplier's component adds to the machine tool product, which in turn affects the level of supplier integration and involvement in the design process.	H5	Action Research Questionnaire Design Survey	Qualitative Measures	7 & 8
The reliability of machine tool products can be significantly enhanced through the deployment of beta testing.	H6	Action Research Questionnaire Design Survey	Qualitative Measures	7 & 8
What are the main methods used to control production, particularly outgoing quality?	—	Questionnaire Design Action Research	Qualitative and Quantitative Measures	7 & 8
Collection and quantitative assessment of field performance data are either not being carried out satisfactorily or they are not being fed back to design engineering in a timely and systematic basis.	H7	Questionnaire Design Survey	Descriptive Statistics	10
The underlying failure rate of machine tools is constant.	H8	Action Research	Reliability Analysis Techniques	10

Table 5.4: Summary of Research Design

Hypothesis or Research Question	Number	Research Method	Method of Testing	Chapter
The application and diffusion of formal tools and techniques are relatively low within the machine tool and machine tool equipment industry.	H9	Questionnaire Design Survey	ANOVA Correlation Analysis Multiple Regression Analysis	9
Formal methods are not structured in such a way which can be more acceptable and useful within machine tool companies.	H9i	Action Research	—	9
There are some methods which are more acceptable than others.	H9ii	Questionnaire Design Survey	—	9
The design engineering process can be significantly enhanced within machine tool companies through the application of well structured methods.	H9iii	Action Research	—	9
Effectiveness of reliability-related tasks	H10	Questionnaire Design Survey Action Research	Descriptive Statistics	9

The use of Likert scale and descriptive statistics was used to facilitate the analysis of this assumption.

5.7 Summary

In relation to the main research objective defined in chapter 1 of this dissertation, this chapter has detailed the overall design of the research. A summary of the research design is given in Table 5.4. This table provides the following details:

- A summary of the hypotheses and research questions.
- The research method adopted for each of the hypothesis.
- The main method of statistical testing for each hypothesis.
- The chapter number where the findings are reported.

The next chapter discusses the two main generic methodologies used in this piece of research and the basis of their selection. Specific methods and experimental analysis used for the purposes of testing the hypothesis and research questions are dealt with in the thesis as and when required.

6. Research Methodology

6.1 Introduction

As detailed in chapter 1, despite the attractions of case studies of reliability management processes in machine tool companies, the basic characteristics of this approach were unsuitable for this particular research inquiry. In particular, the researcher being sponsored by Cincinnati Milacron hindered the possibility of conducting further case studies of other machine tool companies. A decision was taken to adopt a longitudinal form of a case study using methods of action research [see Gill et al., 1991] and administering of a comprehensive postal questionnaire to collect data on the practice of reliability management across the machine tool industry [see Fink et al., 1986].

The application of action type research enabled detailed investigations to be carried out into the specifics of reliability management practice, where as the administering of questionnaires enabled generalisations to be made. Both methodologies were used to test the hypotheses and research questions formulated in the previous chapter.

This chapter aims to produce a detailed account of both these approaches. Following the discussion on action research, the chapter describes the design of the six questionnaires used in the survey. In conclusion, the chapter details the response rate of the survey and the statistical package used to analyse the survey data.

6.2 Action Research

The Dutch psychologist Van Leent [cited in Hofstede, 1968, p. 104] uses three dimensions to describe types of research. Theory building he terms research 'in-height'; research 'in depth' is the attempt to find the philosophical bases of the problem; and research 'in width' starts from the empirical world, which it investigates in detail applying relevant theory from all disciplines. Research 'in width' has certain similarities to the present approach in that theories from several disciplines are being applied. However, it has more in common with applied research, in which known theories are applied to an operating problem without attempts at theoretical development. The current research project is viewed as a type of action research than as a form of applied research.

Rapoport [1970] described action research as aiming:

> '.... to contribute both to the practical concerns of the people in an immediate problematic situation and to the goals of social science by joint collaboration within a mutually acceptable ethical framework.'

Foster [1972], although satisfied with what Rapoport has said, added:

> '.... and the intention of the parties, although with different roles, to be involved in a change process of the system itself.'

Action research is therefore concerned with solving an immediate practical problem, adding to the existing body of knowledge in that particular field, and instigating change. Whereas applied research would only produce a solution to the immediate problem, action research is also concerned with solutions which are broadly applicable to other similar situations.

Change is of great importance in action research. Lewin [1947], who is generally regarded to be its founder, put great stress on the client problem solving change characteristics of the research in its natural settings. Similarly Chein, Cook and Harding [1948] also stress the change agent role of the action researcher by comparing with the laboratory scientist whose task ends with the discovery without having to put into practice.

Another distinguishing feature of action research is its 'collaborative/dialogue mode' [Cherns, 1976] whereby both the nature of the problem and the approach to the solution are jointly determined. Warr [1977] extended a typology used by Cherns which clearly indicates how the joint nature of the research differentiates it from other research types (see Table 6.1).

When the research is instigated the collaborating organisation may have no more than a 'feeling' that all is not well within the research area. It is then for

Table 6.1: Typology of Research Types

	Nature of the Problem	Method to be Used for Solution	Role of External Practitioner
1a	Predetermined by practitioner	Preselected by practitioner	Basic Researcher
1b	Predetermined by practitioner	Jointly determined	Applied Researcher
2a	Predetermined by the organisation	Preselected by the organisation	Technician
2b	Predetermined by the organisation	Jointly determined	Consultant
3	Open for joint examination	Jointly determined	Action Researcher

the action researcher and the collaborating organisation to jointly diagnose and define the problem area as well as jointly agreeing on how to tackle the problem.

Foster [1972] has distinguished four types of action research:

1. Diagnostic, which may or may not lead to action.
2. Participative, which characteristically commits the client or researcher to action.
3. Empirical, which is essentially applying change and recording what happened.
4. Experimental, which utilises control groups, comparative treatments and outcomes.

The present research utilises all of the above types of action research to some extent, but is seen as falling between one, two and four. The initial period of the research and much of the output is of a diagnostic nature, yet certain part of the research are essentially change oriented, to which Cincinnati Milacron and the researcher are committed.

6.2.1 Characteristics of Action Research

Warr [1977] identified seven characteristics of action research which help to indicate how such research relates to the current project.

1. Action research is change oriented and places 'emphasis on intervention to alter and improve an operational system.'

A distinct similarity can be seen here because the objective of this research is to analyse the reliability management system such that a generic methodology for the improvement of machine tool reliability can be developed.

2. The action researcher is closely involved in the change process.

If the findings of the current research prove to be acceptable to Cincinnati Milacron, part of the remit is to implement required changes.

3. The action researcher has data available to him which would not normally be accessible.

Clearly the data available to the author is of a highly confidential nature and is only available to personnel within the company.

4. The research is theory oriented. The action researcher is not 'only a person trying to help change a situation; he wants to learn and generalise from the process.'

The objective of the present study is to solve the problem posed by the 'case study' in such a way that it also contributes to the existing body of knowledge in this area.

5. Roles and relationships change over time.

Increasingly over the research period the author has involved himself in other engineering related tasks. Similarly, members of the company, particularly the Industrial Supervisor, have increasingly been involved with the actual research itself.

6. Action research creates tension.

The author was occasionally aware that he was 'serving two masters'; those of the collaborating organisation and those in the academic world of Aston University. Sometimes decisions had to be made which were not in line with the desires of one or the other or indeed both. Also the recommendations, in that they suggest change, may also be viewed as having some tension creating properties.

7. Action research reduces the gap between research and application.

As Warr [1977] puts it:

> 'the research is itself directly and immediately applied. The goal is one of learning and doing at the same time.'

This is precisely the objective of this research. The reason for the existence of this research is that Cincinnati Milacron desired a practical solution to a real problem and thus the whole project is geared up to fulfilling this desire.

Action research is therefore concerned with two components:

1. Entering an organisation and observing a system within that organisation (participant observation).

2. Subsequently producing information which can be used to bring about change (intervention theory). The information produced should have an applicability both to the collaborating organisation and a wider audience.

6.2.2 Participant Observation

Participation observation of a system in question is an essential pre-requisite of the production of valid information and change. Several stages of action research can be expected to involve some form of participant observation, which has been defined by Schwartz and Schwartz [1955] as involving someone who:

> '....is in a face to face relationship with the observed and, by participating with them in their natural setting, he gathers data. Thus the observer is part of the context being observed and he both modifies and is influenced by this context.'

Schwartz and Schwartz [1955] have divided participant observation into three types:

1. Where the observer is an integral member of the group (active observation).

2. Where the observer poses as a member but is not really one (pseudo-active observation).

3. Where the observer is simply passive.

Part of the current research has involved direct active involvement in the system, but at occasions the observation has been of a more passive nature.

6.2.3 Intervention Theory

Action research is a form of intervention where the researcher can be regarded as a 'change agent.' The role of the change agent has been defined by Argyris [1970] as:

> '.... to enter into an on-going system of relationships, to come between or among persons, groups, or objects for the purpose of helping them.'

Argyris goes on to say that a further characteristic of intervention is that the system must exist independently of the intervenor. Thus, in the current research effort, the author is (the change agent) intervening into an existing part of the reliability management process for the purpose of obtaining beneficial change.

According to Argyris, above and beyond the problem itself, there are three essentials for objective intervention:

1. The generation of valid and useful information. Such information is that which describes the relationships between the factors which create them.
2. The ability to exercise a free and informed choice.
3. Internal commitment on the part of the sponsoring organisation to act on the choices made.

Simply producing change is not a sufficient criterion for judging the success of the intervention, as change for change's sake is often counterproductive. The primary objective of the change agent is to generate valid information. This information should be in a useable or manipulative form and should be available such that the sponsoring organisation can understand the relevant factors. It is obviously important that the cost of obtaining, using and understanding this information should not be beyond the capacity of the system.

A further criterion for evaluating the success of a change agent is that the problem should be solved and implemented in such a way that it does not recur. Similarly, the intervention must occur without deteriorating and hopefully enhancing the effectiveness of the problem solving, decision making and implementing processes within the organisation.

These criteria described by Argryris are similar to those conceived by the author for determining the success of the research project. That is, primarily that the research will produce valid information which Cincinnati Milacron will wish to use and implement. Cincinnati Milacron therefore must be convinced that the proposals achieve their primary objective of defining a mechanism of measuring machine tool reliability. Subsidiary objectives set by the company are that a procedure be developed for continually monitoring the relative and on-going reliability performance of their complete range of machine tool products and secondly that this procedure be implemented within the organisation.

6.2.4 Case Study Approach

The study of the reliability management process which the research is concerned with is limited primarily to one organisation, that is Cincinnati Milacron. The research being so limited has much in common with a longitudinal case study approach, which implies that there are applicability problems of the research to similar problem areas. There are indeed certain problems with this type of action research in terms of applicability. Because organisations are complex and varied in their nature, reliability management systems have been established on similar lines such that they 'fit' the requirements of the organisation. This limitation, however, is avoided by the deployment of a series of questionnaires.

However, the aim of this research is not only to solve the problem posed by the sponsoring organisation, but also to draw generalities which will be applicable to the body of reliability engineering and management literature.

There is a high demand for the research in this area to be of a practical nature as much of reliability engineering and management theory is still viewed by operational managers as an academic exercise. The case study part of the research should therefore be of a practical and applicable nature if it is not to be rejected as being theoretical by the managers who are to implement it.

One of the benefits of the case study type of research is the unique opportunity it offers for empirical data gathering in an area that would not normally be accessible to the researcher. Likewise it offers a chance for research in a practical situation thus helping to ensure that any theory building is of a practical nature and applicable nature and more importantly applicable in other similar situations.

Glaser and Strauss [1970] believed that action research produces results which are applicable to organisations displaying similar characteristics. In reliability theory, this is the most a researcher can hope to achieve, primarily because of the necessarily pragmatic nature of that theory. Indeed for conclusions in this area to be broadly applicable they should ideally be presented in the form of a range of possibilities. Such a range would allow organisations to select solutions to fit their particular organisational characteristics.

Similarly, Warr [1977] is aware that the goals of action research, to satisfy both the demands of scientific advancement and provide a satisfactory solution to the problem, are not easy ones to jointly achieve:

> 'the collaborative nature of the project means that neat experimental designs and completely systematic data collection methods are not always possible.'
>
> Nevertheless,
>
> '.... there is a great deal that can be done in the way of structured observation and quantitative data gathering.'

The present research has accepted that traditional scientific methods are not always applicable. However, it consistently attempts to approach the problem in an structured and where possible quantitative manner.

6.3 Role of the Questionnaires

This section deals extensively with the techniques and questionnaires of the survey that will be carried out for the project. The survey will provide original data that will go into the study of reliability management practices. It should be underlined here, that the survey will not be the only source of information for the production of the thesis. On the contrary, the survey should provide information that is supplementary to information that is already available from other sources. Ideally, the survey will start where desk research finishes and then move beyond the limits of knowledge.

Questionnaires, especially aimed at managers, will be limited in duration and is focused on the core hypotheses and questions detailed in Chapter 5.

The objectives of the survey at this stage were to:

1. Examine the reliability management practices of machine tool manufacturing companies. The aim of this analysis is to aid in the identification of the key areas and activities conducted at various stages of the product life cycle which contributed to the reliability improvement effort.

2. Compare current practice with reliability management theory. The knowledge of reliability practices provides researchers with information on which reliability methods are used in practice and if theoretical models can be confirmed by practice.

3. Present the findings in such a way as to enable other machine tool companies to make both use of the data and make comparisons with their own results.

Further to the above objectives, the questionnaires was developed to elicit sufficient information to justify or refute both the main and some of the secondary hypotheses (see Chapter 5) which underlie the analytical framework.

It also provided the information that might explain the reasons for the current situation of reliability management practice in the machine tool industry. The questionnaire sample had also to be shown to be representative of the UK machine tool companies.

6.3.1 Respondents of the Survey

As the investigation is concerned with reliability management, which is considered to be an engineering management function of an organisation, it will be important to find practitioners at the operation level of an organisation, i.e. engineering managers, manufacturing engineering managers, customer support managers. It is unlikely that the survey will find managers that call themselves 'Reliability Manager.' In some cases, managers of the product engineering function or a 'product quality manager' could have that function. However, the function of reliability management is clearly much broader than that of engineering management or any other management function for that matter. For example, the engineering manager may be responsible for the programming of product engineering activities and new product introduction, but not for the reliability analysis and assessment of product designs, or facilitating the measurement of reliability performance. The reliability management function is far more complicated and involves interactions and coherence between persons at different levels and functions in the organisation. The survey is therefore not restricted to one particular manager and will target the following practitioners:

- Engineering Managers.
- Manufacturing Engineering Managers.
- Customer Support and Service Managers.
- Senior Engineers.
- Technical or Engineering Directors.

6.3.2 Design of the Questionnaires

The approach adopted for the development and piloting of the questionnaires is illustrated in Figure 6.1. It follows the procedure outlined by Saraph, Benson and Schroeder [1989].

Pilot questionnaires were produced and tested within the case study company. In addition to this, the questionnaires were reviewed by the Technical Committee of the Machine Tool Technologies Association (MTTA) and by the Advanced Manufacturing Technology Research Institute (AMTRI) based in Macclesfield. This was made possible through the author's personal contacts built up over the course of the research project and Cincinnati Milacron being a member company.

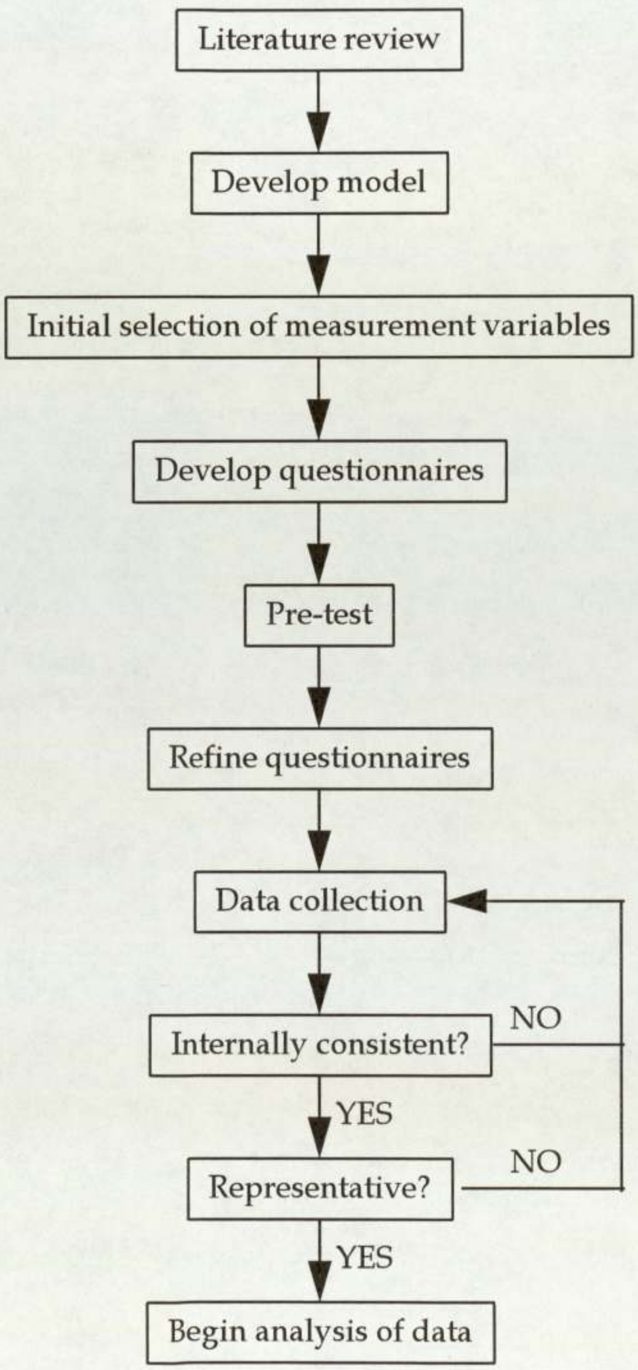
The Technical Committee of the MTTA is made up of representatives (mainly Directors) from member companies and technical staff of the MTTA. This committee provided the test base for piloting the study. Various communications held with these two industry bodies and others can be seen in Appendix B. After relatively few amendments and with further consultations with academics the final questionnaires were produced.

Six questionnaires (including a company profile form) were developed. The full set of questionnaires can be seen from Appendix C to H. These included questionnaires on:

a) *Company Profile;* This questionnaire addressed to the Managing Director is concerned with obtaining general information such as company size, the main manufacturing activity (e.g. metal cutting, metal forming, special purpose machine tools), and number of principle product variants.

b) *Reliability Assurance Systems and Communications (Questionnaire A);* This questionnaire particularly addressed to either the Technical or Engineering Director is concerned with the overall reliability management system of the company. It is divided into two main parts. Section A asks detailed

Figure 6.1: Design and Development of Questionnaires



questions on the company's reliability assurance system and whether it provides an effective and economic means of controlling and improving the reliability of their products. Further, the questionnaire is concerned with obtaining general information on the following:

- Areas the reliability system encompasses (e.g. product engineering design, service and support, manufacturing and assembly, purchasing) and the degree of coverage.
- Reliability-related activities that form part of the overall system (e.g. statistical and technical analysis of field failure data, reliability analysis and measurement, periodic warranty review, design reviews).
- If such system does not exist, whether machine tool reliability improvement is accounted for through routine engineering and operational activities, quality assurance (primarily production quality) or addressing field and in-house failures.
- The predominant style of communicating reliability related issues (e.g. formal as opposed to non-formal and 'in writing' as opposed to 'never in writing') and the frequency (e.g. very regular or complete ad-hoc) of communication.

Section B is concerned with whether senior management use data on reliability-related costs (e.g. warranty costs) to influence decisions regarding improvement of product reliability.

c) *Product Introduction Process and Reliability Achievement (Questionnaire B);* This questionnaire, addressed to the Engineering Manager, is divided into three main sections. Section A is concerned with the buyer-seller interaction process and the extent of customer involvement during the product introduction process. It particularly asks questions on beta testing and management, the method of selecting customer sites for such testing and the average sample number involved.

Section B asks detailed questions on the reliability-related activities that are carried out during product introduction which has a bearing on machine tool reliability. These include the typical methods used to achieve and enhance machine tool reliability during the development process, the extent of concurrent engineering implementation and the benefits of adopting this philosophy and the evaluation of supplier selection and the extent of involvement. Finally questions on the engineering change process were sought.

Section C asks detailed questions on usage, application and implementation of formal reliability-related techniques and tools (e.g. FMEA, QFD, DoE), the barriers encountered during implementation and the benefits achieved. Section C also briefly touches on the application of design reviews and the extent to which product reliability issues are incorporated in this process.

d) *Reliability in Manufacture (Questionnaire C);* This questionnaire addressed to the Manufacturing Engineering Manager is briefly concerned with the methods used to control production quality, the type of testing carried out and the internal data collection and feedback process.

e) *Reliability Improvement through Feedback of Field Failure Data (Questionnaire D);* This questionnaire addressed to the Customer Support and Service Manager is concerned with obtaining detailed information on mechanisms used to record field failure data (e.g. coded as opposed to descriptive), the type of information held (e.g. date of failure, repair time, nature of repair, cause failure, parts usage, logistics delay), the difficulties encountered in the collection and technical analysis of faulty parts from the field, the methods used to measure reliability and the extent of field failure feedback to relevant design.

f) *Tools and Techniques for Product Reliability Improvement (Questionnaire E);* This questionnaire addressed to a wide variety of Engineers (mechanical, manufacturing, software, electrical and development) is concerned with obtaining detailed information on familiarity, knowledge and understanding, and the effectiveness (as perceived by the practitioners) of the reliability-related tasks that an Engineer may or may not undertake in their daily operational activities. Full listing of the tools and techniques will be given later in this thesis.

6.3.3 Selection of Companies

Companies were targeted which were involved in the following manufacturing activity:

1. Metal cutting machine tools.
2. Metal forming machine tools.
3. Machine tool equipment and systems.
4. Special purpose machine tools.
5. Manufacturing and industrial automation equipment.

All companies taking part in the survey were primarily engaged in the design and manufacture of metal cutting and metal forming machine tools and machine tool equipment and systems (e.g. control systems). A small number of companies also manufactured special purpose machine tools and industrial process automation equipment (e.g. transfer lines), but only to a limited extent. No conclusive evidence could be drawn to differentiate between the practices of those engaged in product groups 1 to 3 and those which primarily manufactured products which fell in the 4 and 5 categories. Further some companies were involved in the design and manufacture of an extended range of machine tool products.

Data collection was primarily restricted to the largest companies of the UK machine tool industry for two reasons. Firstly it was felt that reliability management was likely to be at its most formal and 'professional' in the largest companies in the industry. Size was felt to be a strong indicator of the extent of use of professional management techniques and sophistication, an assertion supported by the work of previous researchers. Secondly, since these firms contributed most to the output of the industry, a comparison between reliability management activities in each company would provide useful guidance to reliability improvement of machine tools.

The population for the survey was carefully chosen. Given the relative size of the machine tool industry to other sectors, the sample number for the survey was small. Only 70 companies who can be defined as being engaged in the design and manufacture of machine tool products were selected to participate in the survey.

In addressing the questionnaires, the author was given access to the membership database of the MTTA and AMTRI. Where an address could not be obtained from these databases (i.e. the surveyed company was not a member), other trade publications were also consulted during the initial stages of questionnaire design. These included the 'imported machine tools and equipment directory' published by the MTTA and the 'CECIMO' directory of machine tool and equipment manufacturers.

6.3.4 Increasing the Response Rate

In order to increase the response rate of the survey several methods were adopted. The first step was to add quotations (in the form of slogans) of the benefits of product reliability in every questionnaire. These slogans were both devised by the author and where relevant quoted from journal and conference articles and other literary material. For example in the questionnaire entitled 'Product Introduction Process and Reliability Achievement' the following axiom was added at the start of the questionnaire:

> 'systematic consideration given to product reliability upstream in the design and development process will provide an engineer information regarding which of a possible multiple of design variations will result in a more reliable system, product or component. To this end, this will significantly improve downstream reliability without increasing costs.'

It was felt that through reading such axiom, the respondent would be more interested in the completion of the questionnaire. For all other axioms please refer to Appendix C to H.

Secondly, it was decided by the author to mail all the questionnaires to the Managing Director or General Manager of the machine tool organisation. It was felt that asking the managing director of the company to circulate the questionnaires to whom they have been addressed and arrange completion would give a high profile to the survey, rather than individually sending out the questionnaires to individual managers of the company.

Given the small sample number, all companies were individually contacted prior to mailing the questionnaires. This initial step bought about a response rate of 14% (10 useable questionnaires). Although this was a high response rate, relative to the sample number it was low. In order to increase this initial response rate, the next step was to get in touch with several firms who did not respond. Half of the companies were selected and contacted by telephone. The selected companies represented a random sample with the same distribution of the size of the companies like the population. In taking this step, some of the companies promised at the telephone to fill out the questionnaire.

By the end of July 1996, another 7 completed questionnaires were received taking the response rate to a moderate 24%. This was seen to be a satisfactory figure upon which to base any generalised conclusions.

6.3.5 Problems with Mailing the Questionnaire

As previous comments indicate, the machine tool industry was both relatively concentrated with a large proportion of the output of the industry coming from relatively few companies. This favoured an approach based on individual visits to each of the leading companies in the industry. On the other hand, the researcher was sponsored by Cincinnati Milacron, a leading competitor in the industry, and this created problems in approaching other leading companies from a 'sensitivity' and 'confidentiality' perspective. Further, it was already declared through the Technical Committee of the MTTA that the researcher was sponsored by Cincinnati Milacron. Taking these constraints into consideration the decision was made to utilise the method of data collection through the use of questionnaires.

The use of a questionnaire has the advantage of improving the 'comparability' of research results within the project and where similar questions are asked, also the comparability with other projects and survey studies. Mailing the questionnaire is the easiest and cheapest way to gather data. The advantage is that the involvement of the researcher is not as high for example by the method where the practitioners of the company are interviewed. Further, the received responses are generally an excellent reflection of the structure of the industry in the survey.

A problem of this survey is its extent. Overall the six questionnaires asks approximately 80 questions. Each questionnaire will occupy the responsible person for at least 20 to 30 minutes. When an executive of a company receives this questionnaire by mail without any personal contact with the researcher he will tend to put it aside. Therefore the response rate is in general lower than by any other method. Moreover, the personal contacts with the executives guarantees the participation of the companies and eliminates misunderstandings while filling out the questionnaire. In minor cases, some of the questions were obviously not answered in the right way and had to be checked again via telephone by the researcher.

6.4 Response Rate of the Survey

The overall response of the survey is detailed in Table 6.2. From this table it can be seen that this was relatively high. The useable replies in the sample was far greater than could have been produced using a case study approach. Overall a total response rate of 34% was achieved and an useable response rate of 24%. Further details of the proportion of machine tool business the companies represent is detailed in Table 6.4.

Table 6.2: Overall Response Rate to Postal Survey

	First mail out	Follow-up
Mail out	70	45
Usable Replies	10	7
Response Rate (Usable) %	14.29	15.56
Other Replies:		
Research sponsored by CM	1	—
Company size small	1	—
No time available	1	—
Other Reasons	—	4
Non-Usable Response Rate %	4.29	8.89
Total	13	11
Overall Response Rate %	18.57	15.71
Total Response Rate %	**34.29**	

Questionnaire Number	A	B	C	D	E
Usable Replies	17	16	17	17	33

Three questionnaires were received not completed with different reasons given by respondents for not completing the questionnaires. One leading manufacturer complementing the research work, stated that his company was unwilling to fill the questionnaires as they were aware through the Technical Committee of the MTTA that the researcher was employed by Cincinnati Milacron. Another company responded by stating that their company was relatively small to carry out such reliability-related activities enlisted in the questionnaires. Appendix J details these communications. The third company simply returned the questionnaires with a simple statement saying that no time was available to fill the questionnaires. The other four questionnaires were received not completed.

In addition to the response rate of the overall survey, a breakdown of the response rate by individual questionnaires is detailed is also detailed in Table 6.2. From the table, it can be seen that a high response rate was achieved for the questionnaire entitled 'tools and techniques for product reliability improvement.' This is because the questionnaire was primarily addressed to engineers and consequently several replies were received from one company. The increase in the response rate is also due to the fact that the majority of the engineers employed by Cincinnati Milacron also completed a questionnaire of this type.

In terms of employment, analysis of the size of the companies in the sample against the known size distribution of companies in the industry from which they were taken, indicated that the sample tended to over-represent larger organisations within the machine tool industry. Because machine tool companies tend on average to be on the smaller side, the size categories were defined differently. The four categories are:

1. Very large (over 1000 employees).
2. Large (500 to 1000 employees).
3. Medium (100 to 499 employees).

4. Small (under 100 employees).

Table 6.3 provides a breakdown of the responses by company size.

It was important to have machine tools and machine tool equipment as the principal activity of the respondent companies. Table 6.4 shows that the majority of the companies were engaged in machine tools. There was also a desire to spread the survey sample among companies manufacturing different machine types. Table 6.5 shows that there is a good representation of this. Because most companies manufacture more than one machine type, the total sum of the companies exceeds that of the total number of respondent companies.

In interpreting the results of the survey, it should be borne in mind that although the questionnaires were targeted to specific managers, some of the questionnaires were completed by one individual and this may well bring with it certain biases regarding reliability practices. Further in the interpretation of the number of useable questionnaires received, it is clear that no claim can be made for a fully representative sample. However, it is believed that the breadth of data for each company, in terms of the number of issues dealt with in the questionnaires, and the relative size of the industry, does allow generalisations to be made about the reliability management practices of machine tool companies.

6.5 Analysis of the Survey Results

For the purposes of testing the hypotheses formulated in Chapter 5, relevant data will be used as and when required. Where stated, statistical tests will be conducted on the data for the purposes of evaluating the hypotheses.

It is important to highlight that the findings in this thesis are based on factual evidence only and are not influenced, in any way, by opinions. The analysis and statistical measurements have been compiled from data supplied by the participating companies. Likewise, the practices and activities described are

Table 6.3: Response Rate by Company Size

Size	**% Response Rate**
Very Large (Over 1000)	5.88
Large (500 - 1000)	29.41
Medium (100 - 499)	41.18
Small (Under 100)	23.53

Table 6.4: Principal Manufacturing Activity of Companies

Manufacturing Activity	**% Response Rate**
Metal Cutting Machine Tools	70.59
Metal Forming Machine Tools	23.53
Special Purpose Machine Tools	47.06
Manufacturing and Industrial Process Automation Equipment	23.53
Machine Tool Equipment (Electrical/Electronic, Mechanical and Control Systems)	5.88

Note: The sum total of the percentages in this table exceeds 100% because the majority of companies manufacturer more than one machine type.

Table 6.5: Type of Machine Tools Manufactured

Machine Type	% Response Rate
Turning Machines and CNC Lathes	47.06
Boring and Milling Machines	35.29
Drilling Machines	11.76
Sawing, Cutting-off and Filing Machines	17.65
Grinding Machines	29.41
Machining Centres (Horizontal and Vertical)	35.29
Physico-Chemical and other Non-Conventional Machines	5.88
Gear Cutting and Finishing Machines	11.76
Mechanical Presses (Including Production and Transfer Machines)	23.53
Hydraulic Presses	17.65
Forging Machines	5.88
Plate, Sheet and Strip Working Machines	17.65
Bar and Section Working Machines	5.88
Tube Working Machines	11.76
Control Equipment and Systems	5.88
FMS, Automated Assembly and CIM	11.76
Special Production Machines	29.41

those which are being pursued, or seen as requirements, by the companies, and are based on statements made by the respondents.

So far as reliability management practices are concerned, it was not possible to draw any clear distinction between those of the more larger sized and successful companies and those of all companies taking part. Indeed, there was nothing very significant or unique about the practices adopted. Clearly, what is important, is the effectiveness with which they are applied. More importantly, along side the findings of the action research, the survey data will be utilised to satisfy the overall objective of this piece of research which is to develop a generic methodology for reliability improvement of machine tool products.

6.5.1 Statistical Analysis Packages

Before detailed design of the questionnaires, several survey analysis packages were reviewed and eventually, the decision was taken by the author to analyse the results of the survey using a purposely designed spreadsheet database. Microsoft Excel, a spreadsheet package with graphical capabilities was chosen to design the database for analysis. This commercial package was seen as being most suitable to the task and the author was fluent in the use of the package. It contains all popular statistical facilities (e.g. multiple regression analysis, ANOVA, ANCOVA) for data analysis purposes.

6.6 Summary

This chapter has discussed the basis for adopting to the questionnaire design and action type research techniques as the two main generic methodologies of the research. In the next chapters, constituting part II of the dissertation, the evaluation of the hypotheses are presented.