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

Volume II

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# PART II

# RELIABILITY MANAGEMENT OF MACHINE TOOL TECHNOLOGY: OPERATION, PROBLEMS AND ISSUES FOR FIRMS

## 7. A Longitudinal Evaluation of Reliability Management Practice in Cincinnati Milacron (UK) Ltd

### 7.1 Introduction

This chapter provides an in-depth longitudinal evaluation of Cincinnati Milacron's (CM) product reliability operations. Given the diversity and complexity of reliability management and engineering, the study covered CM's design, manufacturing, assembly and customer service operations. Therefore, reliability issues can be seen to interact at all levels in the hierarchy of decision centres. The study itself forms the basis for developing a generic methodology for improving the reliability of machine tool products.

The longitudinal study was made possible through the full co-operation of Cincinnati Milacron. The research sponsored by CM enabled the researcher to both observe and study the process of reliability achievement and improvement at first hand, and to collect operational data where feasible. In this way, the researcher enjoyed much greater access than is common in most other types of industrial research. Fundamental drawbacks associated with longitudinal case studies, for example considerable degree of commitment needed from co-operating managers, was also avoided through this route.

### 7.2 Research Methodology

In an effort to study some aspects of the reliability management process in detail, a longitudinal study was undertaken. Vitalari [1985] indicates significant advantages for longitudinal studies over data collected at one point in time, claiming that they:

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

The longitudinal case study was generated by methods of 'action research'. This involved both participant and non-participant observation (i.e. an ethnographic approach was adopted). Of particular relevance to the case study presented below is the ability of longitudinal analysis to help ensure that

unbiased data is collected. This contrasts with the information that might be collected by short interviews, whereby parts of the organisation may use the exercise to let a biased view emerge. Clearly, there are a number of disadvantages of longitudinal analysis, particularly concerning the general applicability of conclusions drawn. However, given the objectives of the analysis, it was felt that the 'richness' of information generated more than compensated for the potential lack of generality.

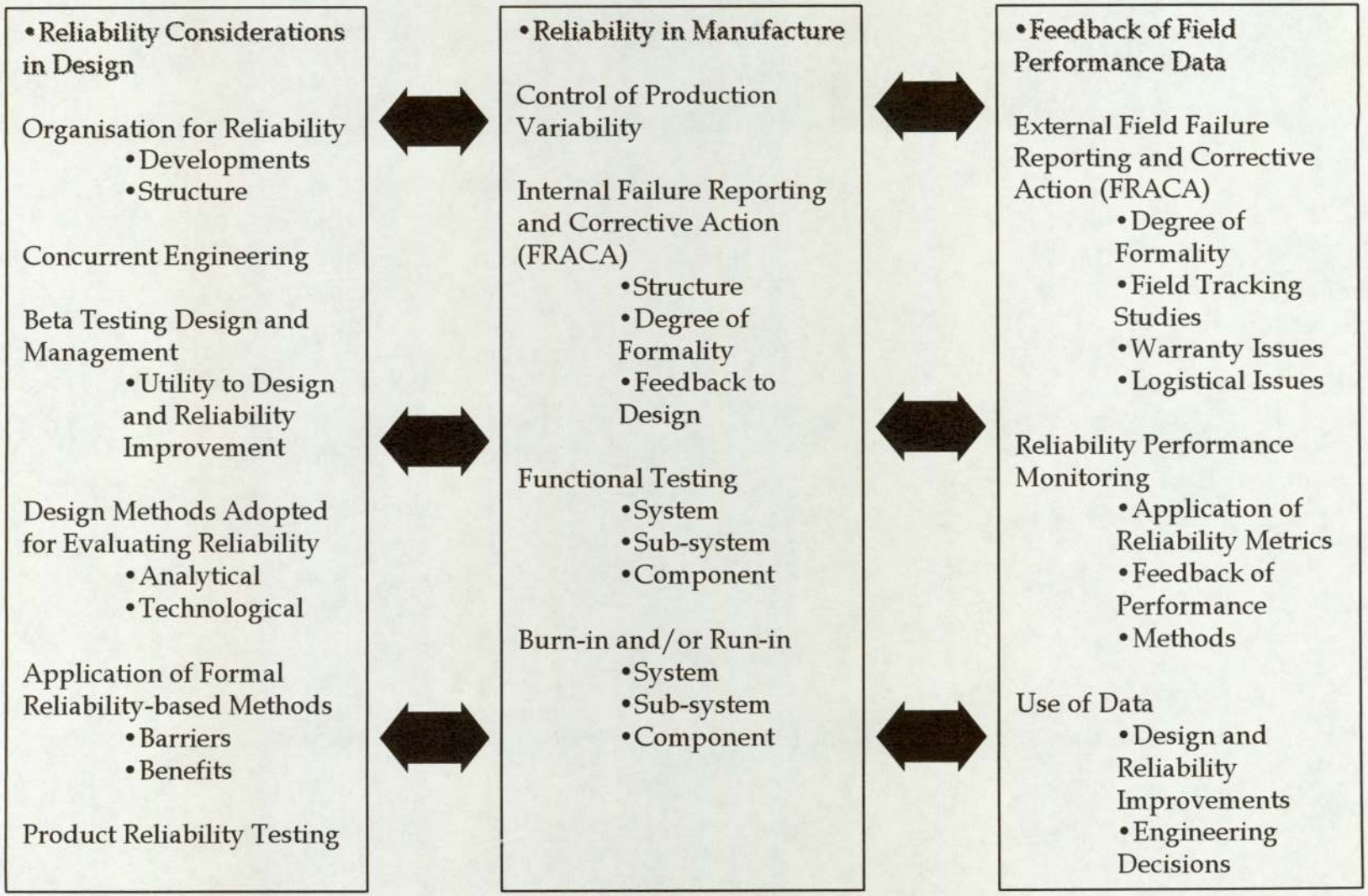
Within the action research framework, data on the reliability management process was collected by using four different, but complimentary approaches. These approaches included:

- Interviewing formally and informally Cincinnati Milacron's engineering management personnel.
- Interviewing formally and informally vendors of Cincinnati Milacron.
- Consulting documentary sources such as project reports, archives, internal material and data.
- Extended participant and non-participant observation which gave a significant depth to the research [Gill and Johnson, 1991].

The use of these four approaches aligned well with the aims of the research and enabled a detailed picture of the reliability management process to be built up. The case study was descriptive and exploratory in nature rather than analytical. In other words, it focused on the phenomena whose variance is described rather than the identification of independent, dependent and extraneous variables. The use of a descriptive rather than analytical study can be justified on the basis that the study was concerned more with generality rather than precision and the intention was to be unobtrusive rather than obtrusive.

Figure 7.1 illustrates the scope of the longitudinal study. It must be emphasised that this is not just a diagrammatic arrangement, but formed the framework for the study.

Figure 7.1: Framework of Longitudinal Study



### 7.3 Company Background

Cincinnati Milacron UK Ltd, an acknowledged market leader of machine tool products, is part of the multi-national Cincinnati Milacron Corporation which has its parent organisation in the state of Ohio, USA. CM UK operates in an industrial market characterised by high rates of product innovation, discreet customers and intense foreign and domestic competition.

The company is one of a relatively small number of large UK machine tool firms operating in a highly cyclic and volatile market. Cincinnati Milacron can be characterised as being a large sized company, with annual sales in the region of £90 million and a workforce of approximately 500 employees.

The main area of business activity is in the design, manufacture and marketing of computer numerical controlled (CNC) vertical machining centres (VMCs) and turning centres (TCs). The VMC product range comprises of 4 product families or line of products. Each line of products have 5 - 7 product variants. Similarly, the product range for the turning centres comprises of 2 line of products, each having 3 product variants. The company also imports a significant number of machine tool products from the USA parent company.

Through a more rigorous market and production strategy, the company has moved to a position where its machine tool production can be characterised as being high volume, high variety. Current output range from 1700-2000 units per annum.

The UK company also specialises in the design, manufacture and commissioning of flexible manufacturing systems and cells (FMS) to individual customer requirements. The VMC and turning centre range of products are also sold as part of an FMS package.

### 7.4 Overview of the Reliability Management System

This section describes the fundamental approaches adopted by CM to the management of product reliability. It examines the overall design and

operation of the reliability management process within the integrated business environment.

### 7.4.1 Competitive Factors

Competition in the machine tool industry is characterised by a rapid rate of product innovation which intensifies the sector's market dynamics. This means that there is a substantial drive for new product design and development to achieve technically sophisticated products. Product technology and technical characteristics remains an important area in which companies can achieve competitive edge. However, increasing customer discrimination and demands for more product customisation means that the approach of producing technically sophisticated high volume products for the market is no longer a viable option for the industry in general.

These customer and product aspects, together with the saturation of markets and the fact that machine tool users are increasingly able to distinguish between the life cycle costs (LCC) and overall performance between the products of different companies, have led to an increase in competition for sales between the major companies within the machine tool industry. As a result of gaining competitive edge, CM have laid increasing emphasis on factors other than price. A list of these factors, compiled on the basis of informal interviews with management is given below:

- Price.
- Performance, in terms of accuracy, operational reliability, flexibility, speed of operation, power, rigidity.
- Product design, in terms of incorporation of the latest technology.
- Product quality and reliability.
- Variety within product ranges.
- Configuration to individual customer needs.
- Delivery performance.

- After sales service.

During the course of the longitudinal study it became apparent that CM have laid increasing emphasis on issues concerning product reliability in general. This is particularly so in the area of field reliability. This is reflected by the fact that product reliability is considered to be an important variable by CM within the many competitive factors such as price, delivery performance and after sales service.

### 7.4.2 An Overview of the Reliability Appraisal and Improvement Process

The evidence of the longitudinal study suggests that no formal system or programme exists for appraising and improving reliability on a systematic and regular basis. Similarly, the reliability improvement process is not formally separated from other fundamental engineering activities. Given the nature of the manufacturing activity, there are no written guidelines, established methods, mechanisms or organisational structures that needs to be adopted to assess and analyse product reliability issues. For example, as the majority of the constituent parts and components are commercial, this significantly reduces the scope for a structured and formal route to be adopted for reliability appraisal and improvement. Supplier development therefore becomes an important element of the overall reliability appraisal and improvement process.

*Reliability Appraisal During Design and Manufacture:* Within the design and development process reliability is considered and appraised through the designer's own experience and judgement, rather than following a pre-determined set of written rules and guidelines on appraising reliability. Increasing reliance is given on development activities and alpha testing which forms an important element of the reliability appraisal process. Similarly, the recent introduction of beta testing ensures identification of manufacturing and design deficiencies to be identified and corrected prior to market introduction.

Design sensitivity analysis, failure analysis, maintainability analysis, environmental sensitivity analysis and stress/life analysis forms the pinnacle of

the reliability appraisal process during the design stage. Reliability is therefore subjectively evaluated through the use of these techniques.

Relative to the design process, a more formal approach to reliability appraisal is adopted during the assembly stages of the machine tool manufacturing process. At every stage of the assembly process, the product goes through a functional testing process which limits defects being passed on to the next stage of the build process. Cyclic testing of important sub-systems (for example the spindle assembly) enables all basic functions to be tested. Unique to the reliability appraisal process is a 24 hour continuous cycle reliability test which every product goes through prior to shipment.

*Reliability Improvement:* No phased or measurable approach to monitoring and improving reliability has yet to be adopted. Fundamentally, increases in the costs of warranty or increased field unreliability were more likely to provoke the need for reliability improvement. In other words, either the cost of warranty had passed a define threshold, or a sudden change in the number of failures of a particular component raises the need for further investigation. The principal cost changes influencing the decision to improve the reliability generally were increases in cost of spare parts. Labour or service intervention costs is not monitored on a periodic basis and therefore does not influence any change in reliability or maintainability. From a management perspective, field reliability problems are reviewed on a weekly basis through 'field service engineering request' (termed FSER's) meeting.

### 7.5 Organisation Issues of Reliability

Relative to the management of product reliability, this section considers organisation within the UK machine tool division of the Cincinnati Milacron Corporation.

Key influences of the organisational structure to the operation of the reliability management process is analysed. Consideration of the management organisation is important for any study dealing with reliability management

because it is in the organisation domain that the majority of vertical and horizontal interaction of reliability activities can be observed and subsequently analysed.

Due to the power structure within companies, decisions made at the high levels of organisation also shape, to a large degree, the processes at an operational level and the scope of operational managers in dealing with product reliability issues. Thus it will be shown how the overall CM organisation structure, of which reliability management is a cross-functional interdependent entity, influences improvements in product reliability. CM has also sought through previous efforts to increase communication through greater human interaction. Central to this development have been the implementation of Total Quality Management (TQM) principles and practices.

### 7.5.1 Type of Organisational Structure

The organisation structure of CM exhibits a high degree of functional specialisation. Overall, a decentralised organisation structure exists at senior and middle management level, for dealing with product reliability issues. No senior management position exists which solely deals with the reliability or the overall quality management process. Although the Customer Service Director has the responsibility of managing 'Product Quality' this is only the case for field failures and warranty operations. This position has little direct influence on design assurance, manufacture and supplier quality control aspects of product reliability.

At an operational level, a decentralised management structure deals with product reliability issues rather than an independent management unit or group. Distinct breaks exist between, for example, Product Design (including Product Development), Manufacturing Engineering (including Assembly Operations) and Customer Service Operations. Despite the introduction of 'Wolfpack' design and development teams during the 1980s, intended to co-ordinate and integrate Marketing, Design, Manufacturing and Customer Service for the introduction of new products, organisation for the major design

of products still exhibits a functional and hierarchical appearance. The Wolfpack development teams, an initiative devised by the parent company for use throughout the CM organisation was used as a means of promoting the application of concurrent engineering practices and multi-disciplinary problem solving.

Fundamentally, the organisation design of CM for managing product reliability can be characterised as being engineering based, as opposed to being quality assurance (QA) based. Figure 7.2a shows the basic concepts of an engineering based organisation for reliability which closely mirrors the CM reliability management organisation detailed in Figure 7.2b. Similarly, Figure 7.3 illustrates a typical QA based organisation for reliability. The engineering based model has been adapted from the US parent company. As the literature seems to advocate, this type of organisation is more prevalent in the USA [O'Connor, 1991]. It is therefore of no surprise that CM UK being part of a US based company adapts to this model.

The adaptation of the engineering based model within CM primarily places responsibility for reliability to the Design Engineering Manager. In this context, the design engineering function controls the 'quality' of design and carries out design modification and improvement through informal feedback of field performance data from Customer Service. Design modification and improvement also includes assessing both the field reliability performance of commercial parts. The decentralised QA function at CM has no direct influence on reliability improvement activities. The overall responsibilities of QA include quality control and sample inspection of production and assembly activities. Similarly an independent function exists for managing the quality system procedures (abbreviated to QSPs) and audits. It does not effect any influence in reliability engineering activities which is primarily driven by the design engineering function through liaison with relevant departments.

As several different activities contribute to the reliability effort of a product, it becomes extremely difficult to be categorical about the optimum organisation

Figure 7.2a: Example of a Engineering Based Reliability Organisation

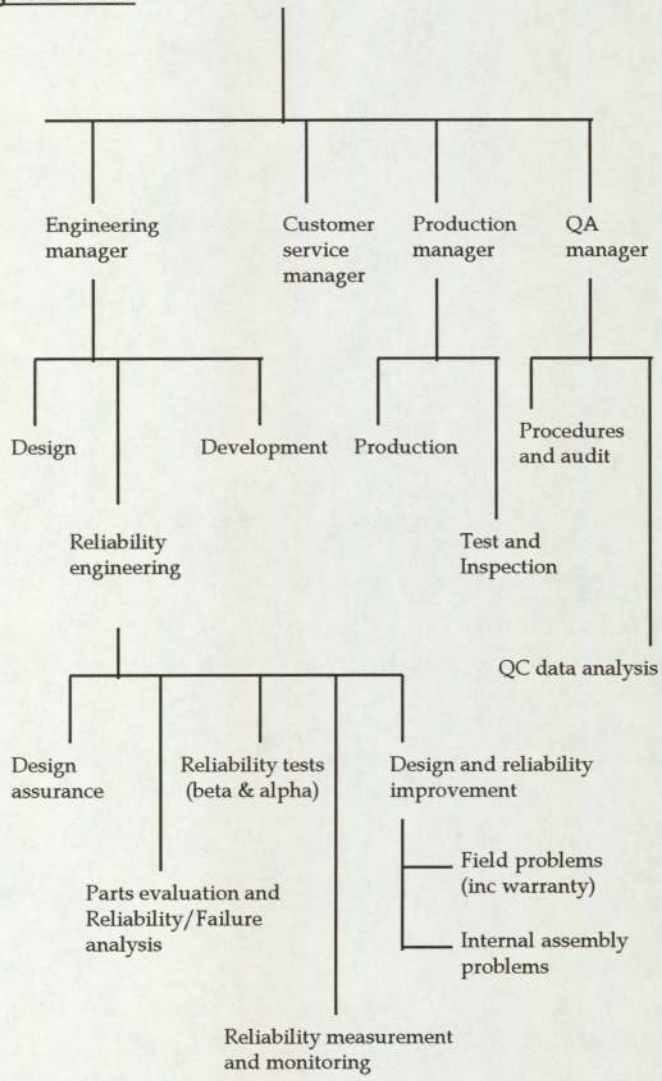



Figure 7.2b: CM Reliability Management Organisation

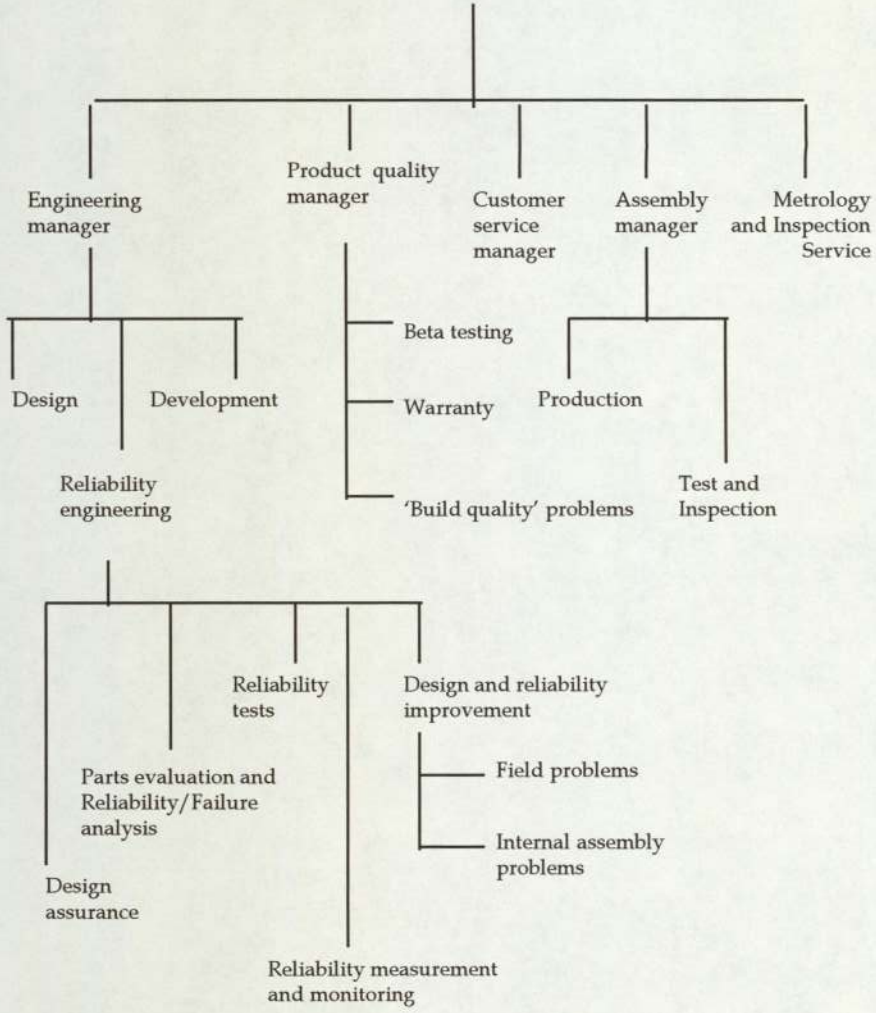
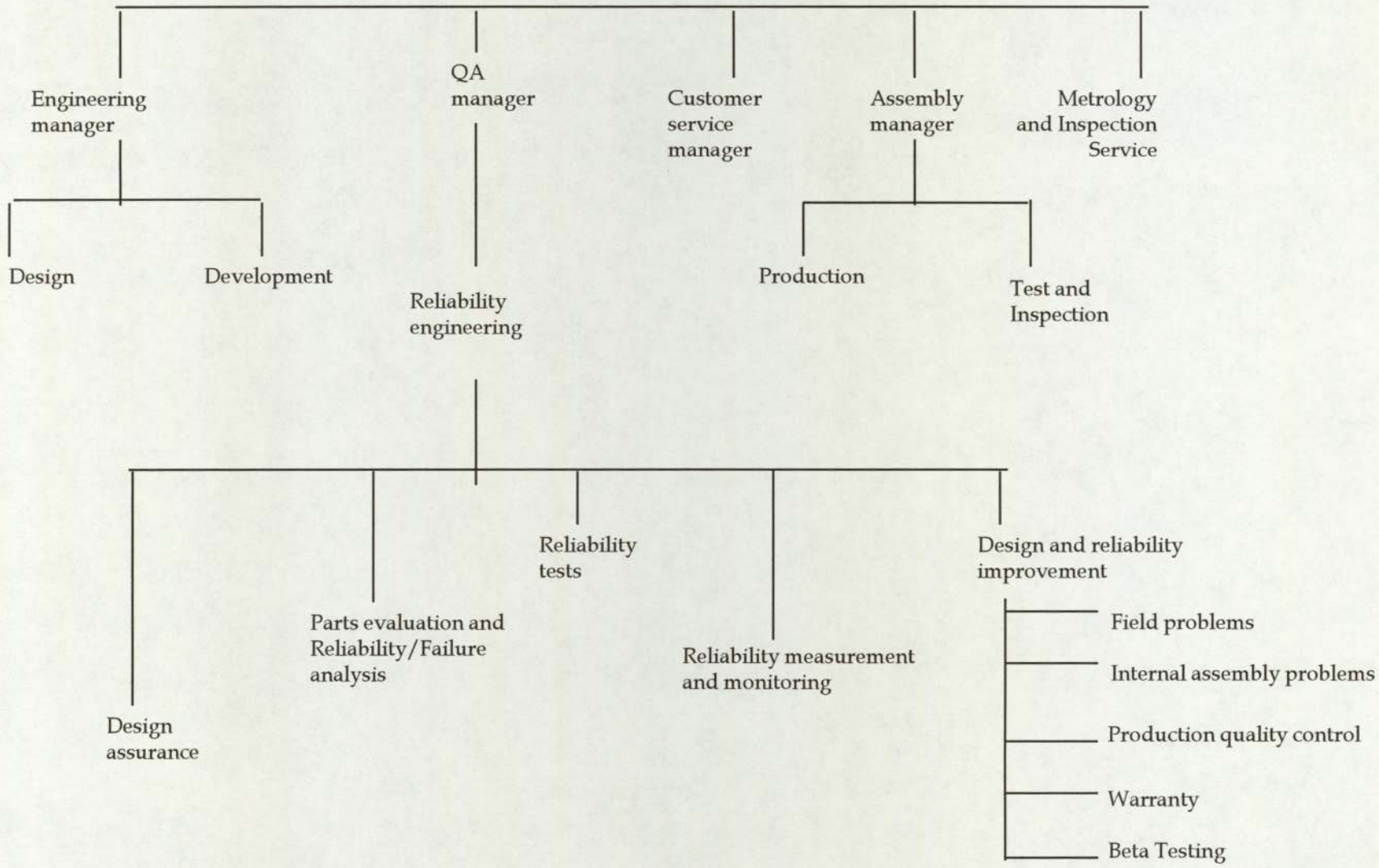


Figure 7.3: Example of a QA Based Reliability Organisation



to ensure effective management of product reliability. Reliability is affected by design, development, production quality control, supplier reliability and service activities. In the QA based model, the reliability engineering team interfaces mainly with the engineering departments, while quality control is mainly concerned with production. However, there is close co-ordination of reliability engineering, quality control and field data collection and analysis functions. For example, a common failure data collection and analysis system can be operated, covering product development testing, production and field use. The QA based organisation also allows easier integration and co-ordination of some tasks that are common to design and production.

However, the engineering based organisation of CM has fundamental advantages, over the QA based approach. For example, machine tool products require a significant amount of innovative design (especially for mechanical based systems). Therefore, the engineering based model allows more of the reliability effort to be directed towards design assurance, such as design reviews and development testing. Furthermore, it has been observed that the majority of field reliability problems are product design or supplier parts related. In this respect, the engineering based model allows direct interaction between design and customer service to solve high failure rate items and problems in the field. In the QA based approach, the Quality Manager would have interfaced with the Design Engineering Manager and the Customer Service Manager to co-ordinate such activities. The engineering based model also allows some form of decentralisation of reliability engineering activities.

It is important to emphasise that the main question to be addressed in deciding which type of organisation should be adopted is whether the split of responsibility for reliability activities inherent in the engineering based organisation can be justified in relation to the amount of reliability effort considered necessary during the design and development phase.

### 7.5.2 Organisational Development for Reliability

The CM senior and middle management structure have been radically reoriented since the late 1980s and early 1990s in response to a more focused strategic direction, market strategy and technological innovation. In comparison to this, organisation changes for reliability at the operational level have been more incremental and cosmetic in nature and still exhibits a functional and hierarchical appearance. Nevertheless, the development and subsequent appointment of a 'Product Quality' Manager in 1995 has had some minor impacts on the re-organisation of reliability-related operations.

This organisational development aligned with senior management objectives of improved product quality and customer satisfaction. Fundamentally, the responsibility of the new management position was directed at managing and co-ordinating the quality achievement and improvement activities. This organisational shift gave some subjective indication of CM adopting some aspects of the QA based organisation model to reliability improvement. However, there was no evidence to substantiate that the QA model was adopted to its full entirety. For example, the new position was not responsible for easier integration of tasks that are common to design, production and service.

However, despite this new organisational development, no direct influence on design and supplier development aspects of reliability was observed during the course of the longitudinal study. These critical reliability-related tasks were left to the sole responsibility of the Design Engineering and Chief Buyer. The new appointment was more directed towards managing, planning and co-ordinating the following product quality and reliability tasks:

- Initial 'build quality' of new products.
- Beta testing and management of new products.
- Managing and improving individual and on-going quality issues and problems during assembly and field operation.

- Warranty management and cost reduction

The development of this quality management position has had three major effects in an intangible sense, on the operation of some aspects of 'reliability' activities. Firstly, the re-direction of responsibility for the operation of beta testing paved the way for a structured and continuous feedback system between beta sites and the design function. Through the new product quality manager, every reported problems or customer ideas from beta sites are documented and fed back to design engineering for incorporation into the design or for corrective action purposes.

Secondly, the new position allowed assembly 'quality' problems (i.e. quality of build) to be continuously measured across a range of indices, monitored and corrected through relevant departmental functions. Finally, some aspects of field reliability such as problems experienced during installation at customer sites or quality of stocked machines after shipment to the US parent company received direct corrective action.

Closely aligned with senior management objective of reducing the cost of warranty, a project management team was created with the objective of reducing the cost of warranty. The creation of this team was bought about through a revision of the operating cost measures and performance of warranty. The team consisted of operational managers and supervisors from relevant disciplines, but was primarily driven by customer service. Further, the project was primarily driven by cost aspects rather than reliability improvement aspects. However, high failure rate items were investigated to ascertain root causes and formulate engineering action to either eliminate or reduce the cause of failure. To strengthen this activity and recognising the importance of warranty operations, responsibility of the day to operation of 'warranty cost reduction' project was handed to the new Quality Manager. This further organisational re-structuring enabled proper co-ordination of warranty returns, allowed periodic review of warranty costs and more direct

interaction between design and customer service which was lacking to some degree.

It is important to highlight that this change in organisational structure has not abdicated the reliability responsibilities from product engineering, service, purchasing and assembly functions. Neither has there been a full shift towards a QA based reliability organisation. This is primarily because the engineering based reliability organisation structure is seen to be a more applicable and effective means of ensuring integration of reliability management activities. The key factor for this organisational change, as shown in Figure 7.4, has been the need and importance to home in on key production and field quality issues. This is conducted through interaction with external and internal business functions.

### 7.5.3 Key Observations

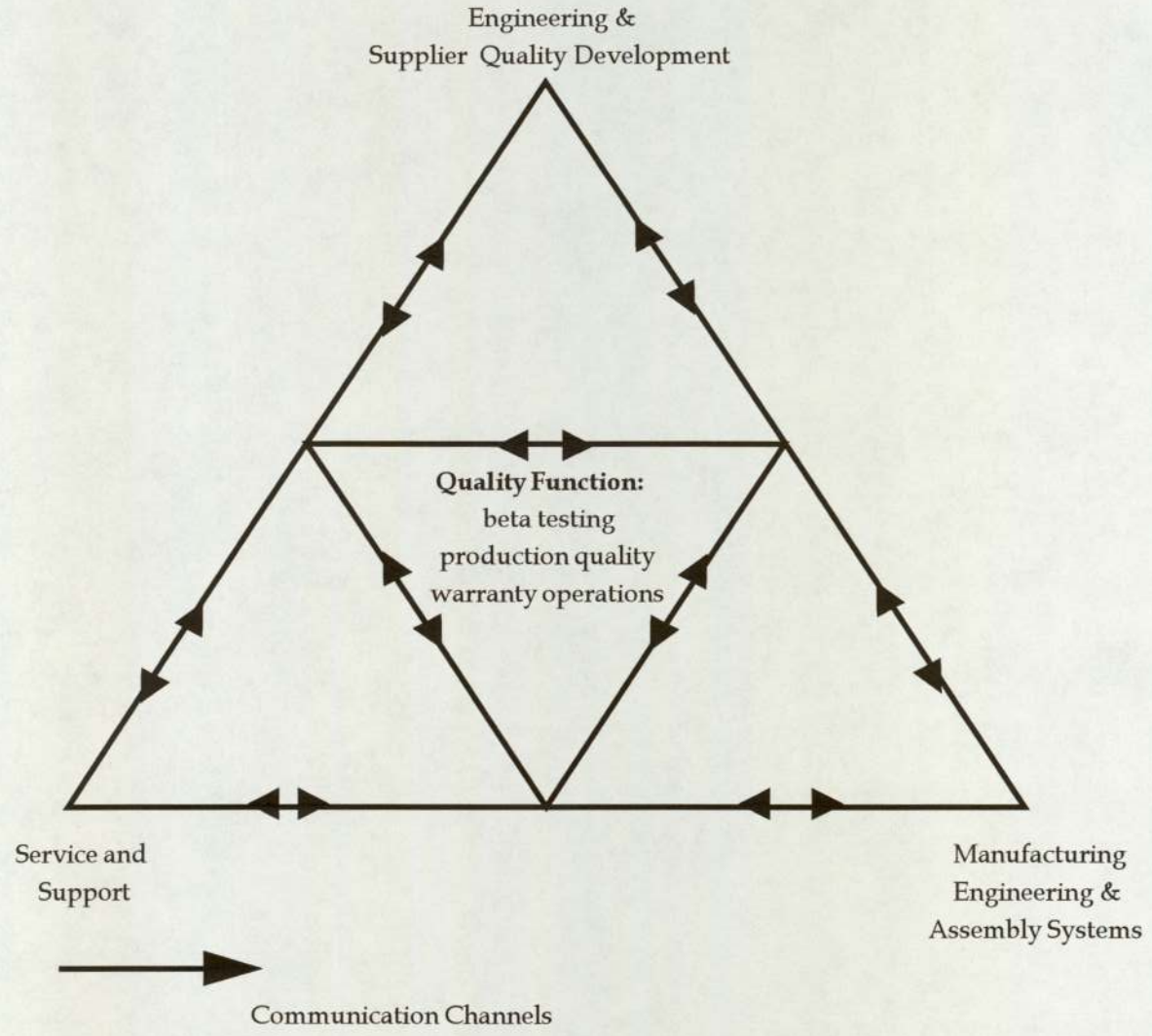
- A decentralised organisation structure is adopted at senior and middle management level for the operation of the reliability management process. Similarly, a decentralised QA function exists, with no responsibility for reliability improvement or achievement.

- An engineering based organisational model for the management of product reliability is adapted by CM which allows all reliability improvement and achievement activities to be conducted from the viewpoint of product design.

- Although the QA based approach has significant advantages, (e.g. allows easier integration of common engineering tasks and operation of a common failure data collection and analysis system), the engineering based model of CM has proved to be successful in the following areas:

    - All reliability improvement and achievement activities are primarily focused and driven by design engineering.

Figure 7.4: Communication Links of the 'Product Quality' Function



- A considerable amount of innovative mechanical design is involved in the design of machine tool products and therefore the engineering based model allows more of the reliability effort to be directed towards design assurance.

- A new 'product quality' function was introduced to the CM organisation structure to improve (1) warranty operations, (2) build quality of new and existing products and (3) management of beta testing sites. The following intangible benefits could be identified through this new function:

    - Reduced assembly defects being passed onto the customer was achieved through this organisational shift.
    - In addition to this, beta testing was given more depth and importance in terms of better feedback and interaction with the customer to iron out minor design and manufacturing deficiencies before market introduction.
    - The re-structuring of warranty operations has (1) given more importance to investigating high failure rate items, (2) enabled a structured field failure reporting and corrective action system to be established and (3) allowed better planning and scheduling of warranty returns.

- The type of organisation adopted is much less important than the need to ensure integrated management of the reliability engineering activities. So long as design, development and manufacturing engineers properly address reliability issues during the design and manufacture stage and field reliability issues are addressed on a periodic basis by design engineering, functional department loyalties are of secondary importance. Similarly, centralisation or decentralisation of reliability-related activities is of secondary importance.

## 7.6 Reliability in Design

Reliability performance during use is greatly influenced by the design and manufacture of the machine tool product. This section describes design and manufacturing activities that are specifically related to the achievement and continuous improvement of machine tool reliability. In particular, attention will be given to methods and tools used to appraise reliability during the design phase.

It must be emphasised that there is no specific reliability programme that CM adheres to, either during the design and manufacture of new products or for the purposes of improving reliability throughout the life cycle phase of a machine tool product. The objective of this longitudinal study is to adopt a systematic approach and investigate the activities and tasks that either:

- Have some bearing on maximising the reliability of CM's machine tool products concurrently with the design and development process or;
- Which improves the reliability throughout the design, development and operation cycle.

### 7.6.1 Concurrent Engineering: Degree of Manufacturing, Service and Vendor Involvement in Product Design

There has been a growing awareness of the importance of manufacturing and service personnel involvement in the design process, especially for the introduction of new products due to their potentially wide ranging downstream impacts. Thus, during the late 1980's efforts towards implementing and adapting to concurrent engineering (CE) principles and practices were given consideration. This resulted in CE being advocated as the best practice model for the introduction of new products in the CM quality systems manual. The introduction of CE also aligned well with senior management objectives of:

- Reducing the design to manufacture lead time and time to market.
- Reducing the frequency of downstream failures, especially during the design and manufacturing phase and initial market introduction.
- Improving product quality and reliability.
- Lowering product development and manufacturing costs.

The main effect of introducing CE has resulted in early involvement of manufacturing personnel during the 'conceptual design' phase of the product introduction process. The usual practice during the concept phase was that design and manufacturing engineers would initiate the conceptual design using their knowledge and understanding of assembly and manufacturing facilities and requirements. This activity was carried out simultaneously. This period of consultation helped identify areas that needed to be addressed during the initiation of detailed design of the machine tool product by product design engineers. One feature of cross-functional integration during this phase of the product introduction process was that it tended to increase the design and development timescales. However, this was offset by a reduction in the number of engineering changes to suite manufacturing and assembly requirements. A senior design engineer explained that participation of manufacturing engineers early in the design process was not simply a pro forma activity:

> "Manufacturing have a lot of influence. We made a lot of initial design changes based on their input."

However, it became apparent during the course of this study that cross-functional integration of design and manufacturing personnel does not extend throughout the product introduction process. On completion of the concept design, the temporary collection of functional specialists which make up the project team tended to dissolve away with little or no integration or participation until the new product design reached the assembly and build stage.

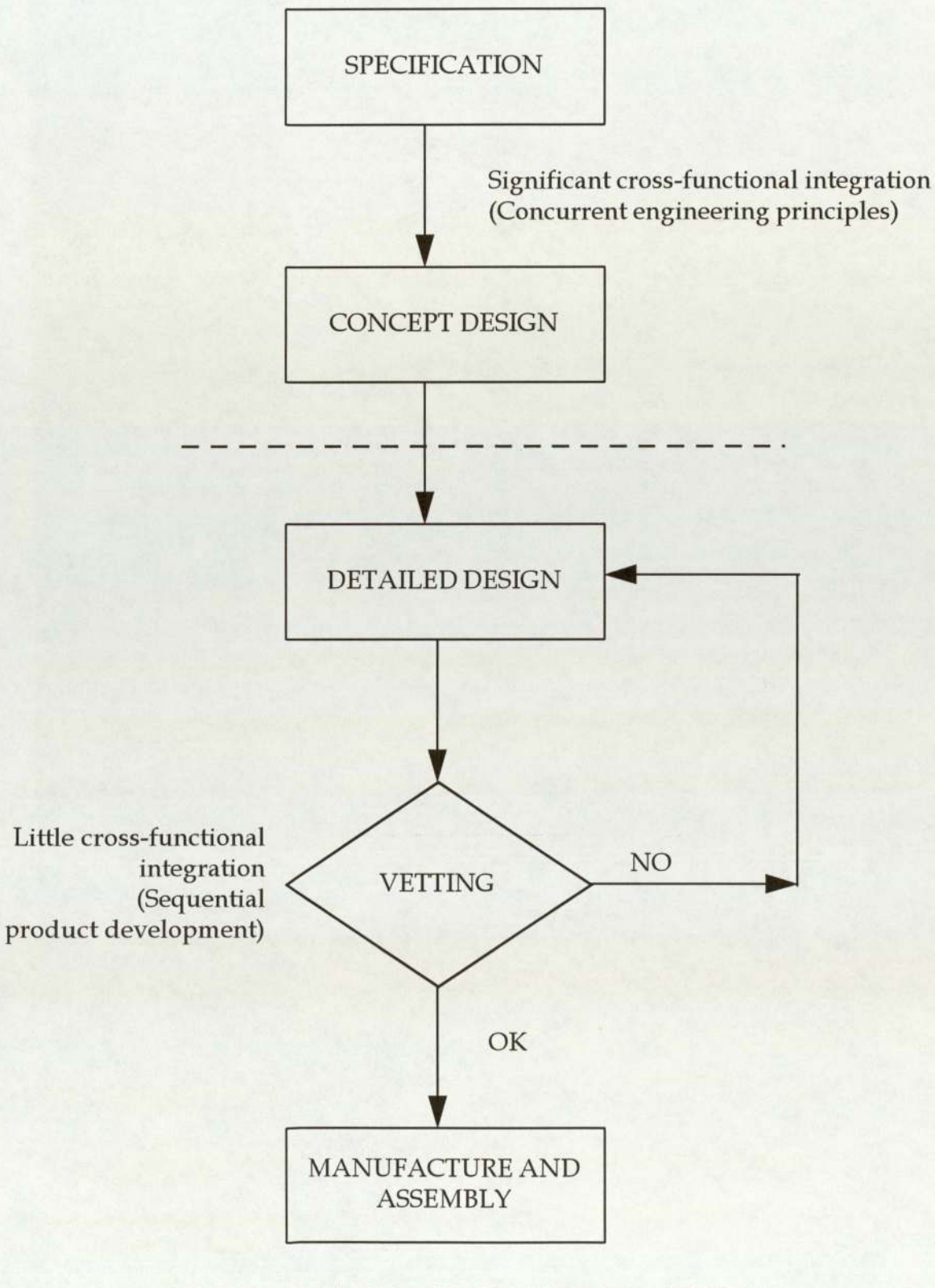
Manufacturing and assembly personnel are not consulted during the detailed design phase of new products and, as a result, new product designs tend to be "thrown" at the manufacturing engineering group with no substantial prototyping activity and little consideration of manufacturability and assembly issues. In that context, the design to manufacturing link is partially adopted. Although design engineers consulted with manufacturing engineers, this tended to be on an individual basis rather than on a project team basis. Full design for manufacture and assembly analysis is not carried out.

As an alternative to the up-front involvement of manufacturing personnel in the detailed design phase, the current process of appraising the manufacturability and assembly issues is carried out through a procedure termed 'vetting'. The vetting procedure is sequential and iterative, and does not have any element of concurrent design. Figure 7.5 illustrates the iterative nature of the vetting system.

The usual practice of the vetting procedure is that design engineers would initiate and complete the detailed engineering drawing using their knowledge and understanding of assembly and manufacturing facilities and requirements. The drawing is then passed onto a relevant manufacturing engineer, through the engineering change process. Manufacturing personnel would then critically evaluate the potential in terms of general assembly and manufacturability problems that may arise downstream in the process. The evaluation of manufacturing faults and errors is recorded on a document called the 'drawing review form' and passed back to the design engineer. This 'over the wall' effect is iterative and can involve up to two to three stages of vetting before production release. Clearly such vetting procedure can be eliminated through the creation of a multi-disciplinary project team which can address these issues up-front in the design, on a collective basis, rather than more downstream in the process.

Appendix K shows an example of the drawing review form. As shown, in Appendix K, the vetting is carried out against a number of manufacturing

Figure 7.5: The Iterative and Sequential Nature of the Vetting Process



variables. Examples of specific variables which have a bearing on enhancing the final reliability are provided below:

- Material Suitability.
- Manufacturing Tolerances.
- Overall Component Form.
- Existing Technology.
- Vendor Suitability.

Although the design to manufacturing link is partially adopted, the aim is to extend the CE philosophy of 'full' integration throughout the product introduction process. The purpose of this is to comply with the CE principle of total participative design and development process. This improves the chances of accepting the final design of the machine tool product when it reaches the manufacturing phase. The objective is then to minimise the effects of downstream failures through significant consideration and appraisal of manufacturing issues such as machining, design of jigs and fixtures, material considerations, manufacturing cost, assembly methods and testing, engineering tolerances, methods of manufacture (e.g. fabrication as opposed to casting and vice versa).

CM has recognised the need to improve this communication and actions are being taken to rectify the situation. For example, the manufacturing engineering manager has recommended the use of design review milestones to the design engineering manager. This initiative is currently under consideration and has been described as:

> "... the process of conducting design reviews from a functional perspective, at specific design milestones, will enable cross-functional integration to extend beyond the conceptual design phase, enabling critical manufacturing attributes to be appraised early and before the new product design reaches assembly."

This initiative will enable CM to fully adapt CE from an engineering management perspective. However, until an integrated and multi-disciplinary

focused approach to the design of new products is adopted and expanded throughout the product introduction process, it is difficult to see how the design to manufacturing link can be operated efficiently.

However, although cross-functional integration does not fully exist at a functional level, new projects review meetings are held at an operational level. At this level, functional managers from purchasing, design engineering, project management, quality, manufacturing engineering and assembly make up the New Projects Review Board. The sessions are normally chaired by the Project Manager. The terms of reference of the Board were as follows:

- To monitor the performance against major milestones and report progress to senior management.
- To review vendor performance throughout the product introduction process.
- To monitor and review capital expenditure.
- To review and action design or manufacturing problems causing possible slippage's.

The primary task of the Project Review Board is to ensure that key milestones are being achieved on time and that expenditure do not exceed the allocated capital to the design project. To this end, the project team establish outstanding engineering activities which has a major influence on the project, identifying at an early stage reasons for possible slippage's or problems. Appropriate actions are then proposed to resolve the situation with minimal impact on the underlying design and manufacturing activities and timescale constraints. Status of vendors and vendor performance during the course of the product introduction process is also monitored in order to assess their impact on the product introduction process.

Although members of the Project Review Board forum made only limited contribution to design for manufacture analysis, they are regularly informed of major flaws on any aspect of the design and manufacture of the product.

Proposals would be made by the Project Review Board regarding eliminating design and manufacturing deficiencies early in the product introduction process. Minutes are normally produced for each Project Board meeting, which set out the issues raised and the member who has to be responsible for resolving it. Outstanding activities and actions were highlighted as 'repeats' if the issue was not resolved by the next meeting.

Service involvement in new product design is a key factor in achieving optimum maintainability and reliability of the final design. However, there is little interaction or integration of service personnel during the introduction of new products. Lack of resources and time constraints are the two main barriers which inhibit the involvement and integration of product service specialists in the early part of the design process. Clearly these barriers are a problem, as noted by a senior service personnel:

> "it is difficult for service personnel to be involved in new product introduction on a regular basis... time and availability of resource is our major barrier."

The use of service expertise can help to identify current maintainability, durability, accessibility, extreme operating conditions, environmental and identification of current field issues which needs to be considered during the course of the design process. Designers tend to use their own judgement and past experience when addressing these service issues, rather than upon the consultation and expertise of service personnel.

In the introduction of new products, first line vendors are not involved in any stage of the design and development process, but are regularly consulted outside this process by engineers. This is particularly so, as the design of the product begins to take shape. For example, Development Engineers regularly interact with relevant vendors during testing of new commercial parts. Given that the majority of constitute parts of a machine tool product are commercial, Design Engineers are constantly involved with suppliers to ascertain an optimum design solution to a particular design specification.

Regarding the criterion used to select first tier suppliers, aspects such as price, performance, fitness for purpose, quality, reliability, on-time delivery are evaluated. In some cases, the 'quality management' aspects are also investigated to provide indications on the way in which the supplier conducts their quality and reliability improvement process. Although, in the majority of cases price becomes a dominant variable in the selection of suppliers from a cost perspective, functional performance of the vendor supplied part is evaluated prior to selecting the supplier. Considerable evidence is gathered on the reliability of vendor supplied part through critically addressing functional performance. It is also important to emphasise that within the vendor evaluation criterion, proven suppliers in terms of high reliability and value are consistently used to reduce the reliability uncertainty factor.

While engineering management change has been the driving force in the adoption of CE practices at CM, a number of technological changes have supported and enabled the process. The recent implementation of a 3D computer aided engineering (CAE) package has provided the following potential for improvement of mechanical system design for reliability and maintainability of CM's machine tool products:

- Allows the designer to accomplish basic reliability analysis such as geometric modelling and maintainability analysis, and iterate design trade-offs.
- Increase the capability to manage data and data flow, improve timeliness of feedback and ensure automatic update of the integrated database.
- Permit designers to pro-actively influence the creative design process, both directly and by installation of design rules and design algorithms.
- Allow significant improvements in communication and data transmission between the design engineer and the other relevant personnel such as manufacturing.

### 7.6.2 Reliability Considerations during Product Design

The manufacture of machine tools heavily involves manual assembly of parts and units which are largely commercial. With this type of manufacturing activity the intensity of reliability assessment and evaluation during the design and development process is not as great as it is within the component and equipment sector of the machine tool industry. In the machine tool equipment sector of the industry a structured approach to reliability is adopted. It is most likely that the reliability programme will comprise of activities such as reliability growth testing, burn-in, stress screening for electronic based components, formal use of design methods such as Taguchi Methods and FMEA. Since many of the critical reliability tasks will have been accomplished by the equipment and part manufacturers, the primary concern of the machine tool manufacturer is the effective management of the reliability management process.

Despite its attractions to the design engineering function, no formal structure or programme exists for the evaluation of product reliability during the design and development process. However, the tendency is to subjectively evaluate product reliability within the design process. Furthermore, project review meetings also forms the foundation for considering reliability issues which are of significant concern. The evaluation of reliability is normally completed through the following reliability related engineering activities:

- Geometric Modelling using the latest CAE facilities.
- Maintainability and Accessibility Analysis.
- Dynamic Performance and Stress/Life Analysis.
- Structural Analysis.
- Failure and Failure Mode Analysis.
- Design Sensitivity Analysis.
- Environmental Sensitivity Analysis.

- Specific Development and Product Testing (for example reliability growth testing).

It is important to emphasise that the above reliability oriented design activities does not constitute any programme for evaluating product reliability during the product introduction process. However, these activities are carried out on a 'where needed' or 'where relevant' basis. Some of the above activities will be carried out on a multi-disciplinary team basis. However, in the majority of the cases the above activities are conducted on an individual basis, using the engineers own judgement and experience.

As previously discussed, the recent implementation of 3D CAE workstations has paved the way for enhancing some aspects of the reliability of the product. The ability to create and modify a design several times using 3D solid modelling capabilities enables an optimum design to be achieved against stringent timescales. More importantly, the capability of the CAE tool to create geometric models which define the geometry of components and subsystems is very useful for supporting engineering design, reliability and maintainability analysis, accessibility analysis and specification of manufacturing processes and planning.

Much consideration is given on maintainability and accessibility analysis during the design and development process. Where possible products are designed for minimal maintenance. Ease of maintenance and accessibility of panels is assessed during the latter stages of the detail design stage. Maintainability analysis includes:

- Evaluation of the ability of service personnel to access panels and replaceable units.
- Evaluation of the ability of service personnel to remove and replace modular units.
- Optimum routing of electrics.

- Estimation of the time required to perform maintenance tasks, based on the accessibility of panels and replaceable units, the number and difficulty of panels and replaceable units, the number and difficulty of removal of fasteners and other maintenance factors.

The use of 3D solid modelling capabilities also enables some of maintainability and accessibility issues to be identified early in the design process. This reduces costly modifications that may need to be carried out downstream in the process. The CAE system allows analysis and evaluation of the potential for the design under development to be maintained and a mechanism for the results of analysis to be fed back into the design process more efficiently. Prior to the use of the new CAE, maintainability and accessibility analysis could not effectively be conducted until completion of the detailed design of assemblies. With new design being created in a CAE workstation, design engineers can use the 3D computer graphics as "soft mock-ups" to conduct visual maintainability analysis.

Dynamic performance and stress/life analysis is determined through the determination of loads and stresses on subsystems and components. For example spindle torque, maximum stress on a ballscrew or pressure acting on a seal. Determination of loads and stresses in mechanical systems of machine tool products is significant in identifying reliability problems early in design and correcting difficulties prior to test and production. Such analysis will identify critical modes of operation that require evaluation during test. The end result are much better tests:

- For creating critical environments that may lead to failure and;
- For minimising the amount of costly testing that needs to be carried out in operations that are of little threat or relevance to the optimum operation of the machine tool.

Similarly, structural analysis provides the capabilities for using structural geometric and material data and loads that are predicted by analysis or

measured by experiment to predict stresses, strains, displacements, natural frequencies and related structural performance factors. This analysis permits prediction of failure modes for structural components and subsystems and provides data needed to predict durability and fatigue life. Finite element analysis (FEA) are broadly used for analysis of structural components and subsystems of mechanical systems. Graphic based post-processors permit the engineer to create finite element structural models, using CAD geometric data, and to carry out analysis of structural performance. All FEA type of analysis on machine tool structures design by CM UK are carried out by the Corporate Research and Development Group based in the USA.

Failure and failure mode analysis is primarily conducted by design engineers based on their own judgement and experience. It is conducted on a subjective and qualitative basis. Failure data on existing products and comparability analysis based on field data for related products are used in the failure analysis process. The employment of qualitative failure data also enables some design improvements to be made during the product introduction process.

There are no formal procedure or system for conducting failure and failure mode analysis on designs. The activity is carried out on an individual basis and through the mental discipline and thoughts that an engineer normally goes through when developing the design. Results are not normally documented on a regular basis and reporting of the fragmented findings to interested parties is a difficult exercise in practice.

Design sensitivity analysis is carried out on a 'when needed' or 'where relevant basis.' It is a very useful analytical tool in designing for reliability. The activity is frequently conducted by design engineers to evaluate the influence of variations in design and manufacturing characteristics on system performance and reliability properties. It compliments failure analysis by showing which design characteristics should be modified to most effectively improve performance, solve technical problems and improve reliability.

Compared to design sensitivity analysis or geometric modelling, the use of environmental sensitivity analysis is less frequent. This is because nearly all machine tool products are used in similar operational environments and it becomes irrelevant to deploy such an activity during the design process. However, there are circumstances which dictate the use of such a tool. For example, changes in component reliability due to variations in temperature, humidity, dust and vibration identified during field use will justify the use of such a tool in the design process.

Environment sensitivity analysis quantifies the sensitivity of equipment reliability to variations in anticipated operational environments. Based on this sensitivity, designers provide the proper environmental control. For example optimum placement of electronic components, cooling allocation, sealing conditions, material selection, damping and ambient monitoring are considered subject to design constraints and for the purposes of optimising reliability.

Development and product testing forms a substantial part of the reliability appraisal process during the latter stages of the design and development cycle. In particular, machine performance and cutting tests provides some insights on the functional and operational performance of the machine in terms of operating speeds, operational reliability, loads and stresses. Reliance is given on these specific tests to identify any major reliability related problems.

More importantly, machine, unit or component cycle testing has significant impacts on (1) evaluating product reliability, (2) identification of design deficiencies, (3) assessing and evaluating the suitability of a part and (4) evaluating overall performance which most definitely will affect operational reliability.

In 1995, the philosophy of cycle testing was uniquely deployed during the latter stages of product development. The management objective was that every new machine tool design would undergo a reliability growth test prior to the initiation of beta testing. Several criteria for conducting the reliability growth test was available to the management team:

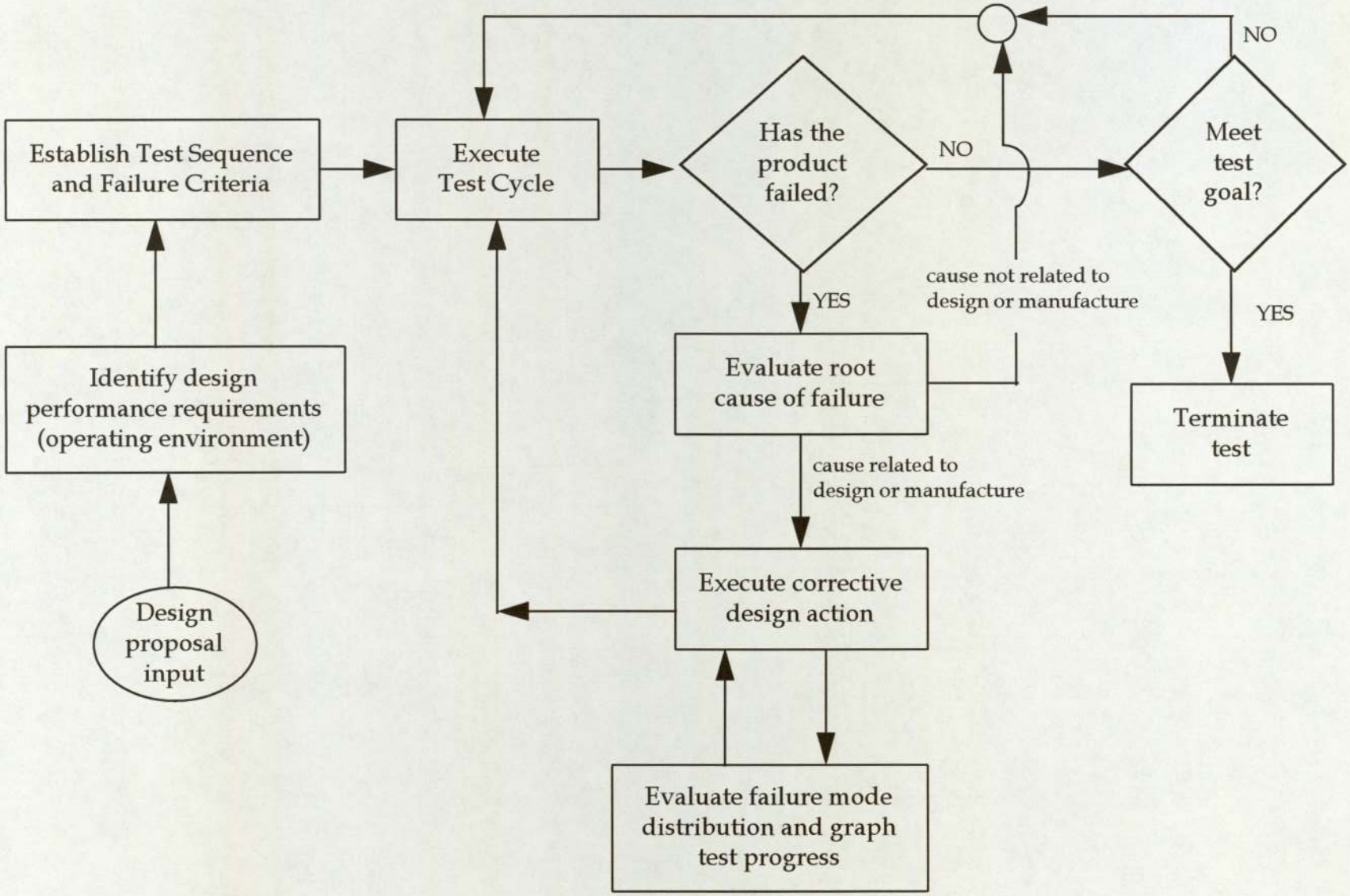
- A fixed number of environmental cycles with the last '*n*' cycles failure free.
- A fixed number of failure free test hours.
- A fixed number of failure free test hours with an upper limit on the cumulative number of test hours.
- A pre-determined minimum number of failures per a fixed number of cycles or hours.
- Testing an additional number of machines when failures reached a very high level.

The basic principle or criteria that was followed was that one machine would be put on cycle and expected to perform a fixed number of failure free test hours. A 400 hour failure free test was then determined to be a suitable figure. Therefore, dependent on the number failures that occurs, the reliability growth test may take a minimum of 400 hours or a significant greater amount of cumulative time to complete. Although no upper limit on the cumulative number of test hours was specified, the assumption was that if a satisfactory number of cumulative test hours was achieved (for example 2000 hours) then the test would be terminated. This avoided prolonging the reliability growth test for too long. Through a closed feedback loop, every failure would be further investigated and where needed design improvements would be incorporated. Figure 7.6 illustrates the basic principles of the test. This 'Duane' type of reliability growth testing has been observed to be a useful tool for both evaluating design reliability and identifying and correcting design deficiencies.

### 7.6.3 Reducing the Need for Reliability Evaluation Through Technological Advancement

As stated above, CM recognise the advantages of reliability oriented engineering activities to the achievement of product reliability. While these engineering activities aid in the process of appraising reliability, the overall aim is to:

Figure 7.6: Reliability Growth Test Process For New Product Design



- Reduce the amount of reliability evaluation needed during the design process.
- Reduce engineering uncertainty.

A number methodologies and techniques are used to achieve this objective and is detailed in Table 7.1.

Table 7.1: Use of Design Techniques and Principles

| **Description of Technique** |
|---|
| Re-use of design knowledge and experience |
| Standardisation of design |
| Modular design concepts |
| Familiarity with both existing and anticipated future designs |
| Use of latest and proven technology |
| Reduce the need for unnecessary design features (i.e. over design) |
| Reduce the number of parts and process steps |
| Incorporate sub-system design of existing products |

The application of the methodologies detailed in Table 7.1 has seen growing acceptance as effective means of assuring reliability during the design process. For example, the discipline of designing machine tool products with minimal number of parts, design features and process steps to assemble the final machine tool product has significant effects on design and process simplification. In consultation with manufacturing and service, machine tool products are designed with minimal parts and process steps to reduce unnecessary complexity. This inevitably leads to an enhancement of reliability and reduction of failures in the field.

Where feasible, various new designs are based on (1) re-use of design knowledge and experience, (2) familiarity with both existing and anticipated future designs and (3) incorporation of sub-system design of existing products. This type of approach to the design of products and sub-systems has significant benefits on the following areas:

- Reduce the need for development testing because the design has already been proven in the field.
- Reductions in reliability related problems during the product introduction process and more importantly fewer failures during field use.
- Reduce reliability uncertainty since sub-system design have been proven in the field.
- Reduce the need for design for manufacture considerations since production methods are already established.

The advancement of technology has paved the way for mechanical, electrical, electronic and control design simplification of machine tool products. The use of latest proven technology has minimised the need for maintenance and improved reliability substantially. Similarly, the use of modular design concepts and standardisation of parts allows for better spare parts planning, improved maintainability and accessibility and simplification of design.

### 7.6.4 Use of Reliability-based Methods During the Design and Manufacture Process

There is now a considerable literature extant on the different techniques for analysing and appraising product reliability. For example, chapter 4 has reviewed the application of FMEA, QFD and Taguchi Methods in the area of product reliability. Despite the existence of this large body of literature on tools and techniques to be used for reliability assessment, there is evidence to suggest that little use of such analytical techniques are being made by CM. Managers may often disregard the use of such techniques in their actual decision making process.

Little use of formal techniques were made by the design engineers both on a individual or multi-disciplinary team basis. In the various design projects examined in detail during the course of the longitudinal study there was a marked absence of evidence that such techniques had been used. To this extent

it can be concluded that formal tools and techniques are not among the systems used by either the design engineering or the manufacturing group in aiding in the problem solving process. Three main barriers to the acceptance and use of reliability-based methods were identified:

*Resource Constraint*: The most significant barrier to effective use of techniques is the demand on resources by the use of dedicated teams. This often cannot be sustained for long, even in a comparatively large company.

*Time Constraints*: There is considerable pressure to reduce the time from new product design to eventual production release. The use of reliability-based techniques tend to increase this time by the addition of more activity within the design and manufacture framework.

*Cost-Effectiveness*: In evaluating the cost-effectiveness of any analytical effort, the relevancy and criticality of application must be taken into consideration. For example, those techniques, predominantly of an analytical or test nature, are more controversial in terms of their benefit to a particular application. These are the techniques whose benefit may have to be proven in order to justify the investment in time, resources and capital. As previously discussed, much of the critical reliability tasks are already carried out by equipment and parts manufacturers. This leaves little scope for a specialised route to be adopted for the evaluation of machine tool reliability during the design, development and manufacturing process.

The general consensus on the use and application appears to be that reliability-based methods can simply be considered to be good management and design practices, rather than tasks unique to the design and manufacture process. The aim of reliability-based methods as one senior design engineer explained (using FMEA as an example), is to formalise much of the good design practices that is already being carried out in one form or another within the CM organisation:

> "although FMEA is not used as a formal technique for reliability analysis, failure and failure mode analysis is carried out throughout the

evolution of the product design process...my understanding of the application of FMEA is to formalise, structure and document what we already do on an informal basis."

Essentially, it can be concluded that despite the low usage, the basic principles of the reliability-based techniques are practised in some form or another. Table 7.2 provides examples of the design and manufacturing practices within CM that can be regarded as being an alternative means of using formal techniques in problem solving, engineering decision making or design analysis.

One of the significant findings of the study was that those analytical methods characterised as being procedural, laborious and require the use of documentation aids (i.e. significant paperwork) receive less well. However, those techniques that do not advocate any explicit procedure or documentation are more widely applied. For example, both value engineering and value analysis are widely used within the CM organisation for reducing unnecessary costs and design features that neither lead to quality nor reliability. However, the effective use of such techniques are heavily dependent on the judgement and experience of the design engineers.

### 7.6.5 Beta Testing and Its Utility to Reliability Improvement

Involvement of users is viewed as a crucial element in the latter stages of the design and development process, not least because of the need to establish the functional performance prior to market introduction. The main vehicle deployed within the CM organisation for user involvement is beta testing. This entails a sample of machines to be tested in a 'real world' production environment. Beta testing is effective for design because it allows the final product to be tested at the customer's facility, directly observe use and obtain on-line customer feedback on problems.

The two key questions in this thesis are: (1) What value can a beta test provide in the reliability improvement process and (2) How is the programme designed and managed to maximise that value. The study concentrated on two areas:

Table 7.2: Example of Engineering Practices Equivalent to the Use of Reliability-based Techniques

| Description of Technique | Equivalent Engineering Practice at CM |
|---|---|
| Failure Mode and Effects Analysis (FMEA) | Failure and failure mode analysis is conducted on an informal basis<br>This is primarily conducted on the judgement and experience of the engineer. |
| Value Engineering and Analysis | Value engineering is conducted on an incremental basis<br>More emphasis is given on value analysis |
| Design for Simplicity and Assembly (DFS/A) | Where feasible design principles listed in Table 7.1 are used to achieve standardisation, simplicity and reduction of assembly steps |
| Taguchi Methods and Design of Experiments (DoE) | Variables within a process or design is evaluated or optimised before full production runs begins<br>This is primarily conducted through vetting or through design-manufacture liason |

*Beta Programme Design.* This included the main purpose of beta, product development activities prior to beta and functional area involvement.

*Beta Programme Management*: This included the criterion used for selecting beta sites, the approximate number of sites used, the management of information flows, the nature of interaction with beta sites and utilisation of beta site feedback.

The concepts of beta testing within the CM UK organisation was introduced late 1994, as a means of validating the basic functioning of new products prior to market penetration. Although, beta testing can also be used for the purposes of marketing and initial sales promotion, CM do not pursue either of these benefits. In working towards the operation of beta test concepts, CM is not trying only to validate the functioning of the product, but also to ensure that the product meets with market needs and expectations in performing its intended functions. The formalisation of the beta testing process during 1995 came as a direct result of its effectiveness in the area of functional testing within a production environment.

In addition to the basic function check, data is also obtained pertaining to desired refinements of the product and/or added features. However, most major design change ideas surfaced by a beta test are passed on to design engineering for incorporation in the next design milestone. Time to market pressure usually restricts further development efforts to incorporate ideas and concepts.

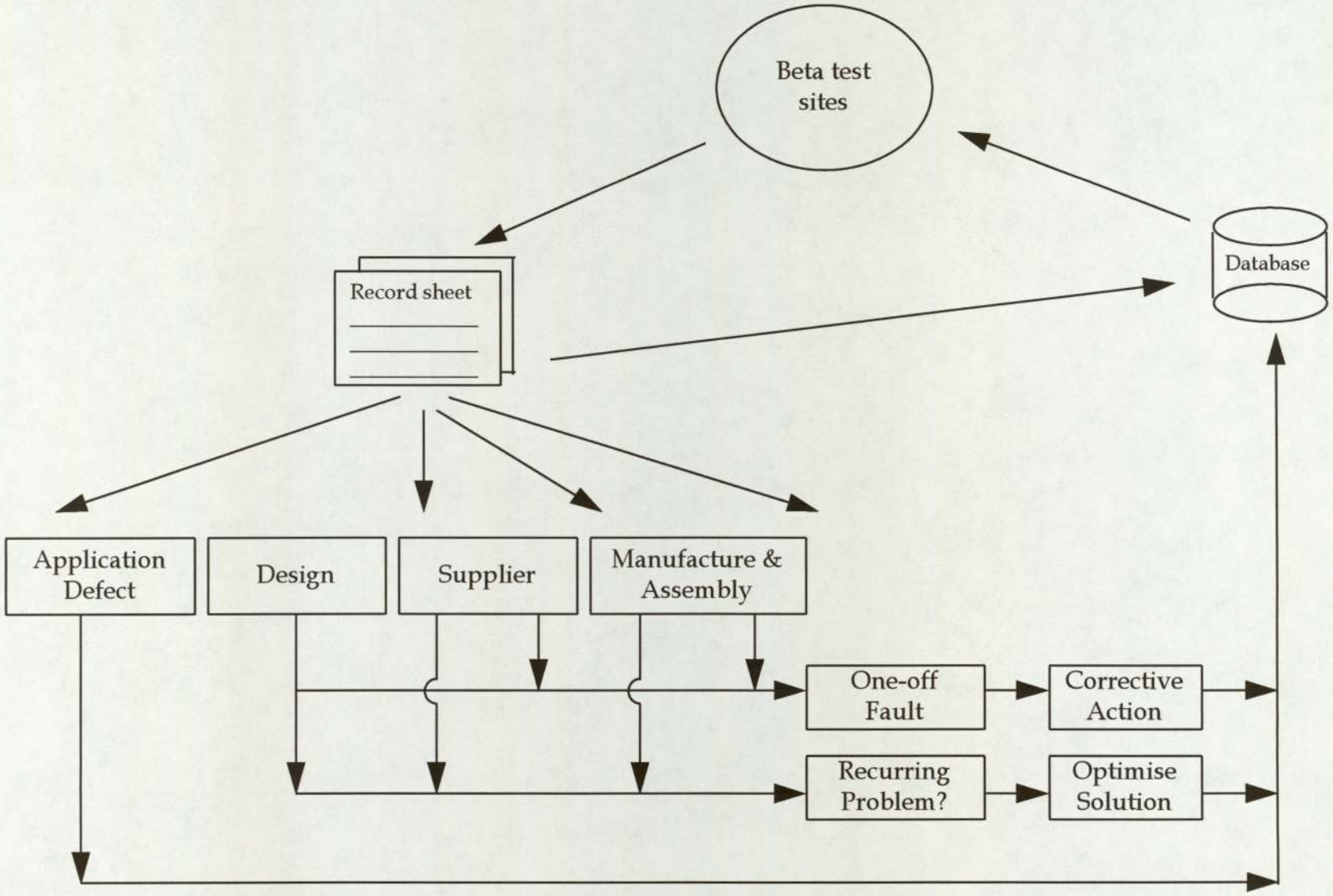
Prior to the introduction of beta testing principles, no formal tool existed for the evaluation of product design under normal production environment. More reliance was given on alpha testing and the initial build process for identifying possible design and manufacturing flaws. However, while extensive alpha testing is done, the demands put on the system by external users cannot be always anticipated and, even if anticipated, realistically simulated in-house. The introduction of beta testing made this type of testing possible.

Despite the small sample sizes commonly used in beta tests, the performance data acquired can provide an useful means of measuring the initial reliability in terms of mean time between failure (MTBF) or failure rate. This is of importance since it provides first indications of the anticipated field reliability performance during the initial market introduction process. Essentially, product complexity and cost limits the sample size of beta tests. Typically, the sample size range from 4 - 6 customers. In discussions with managers, it became clear that they tended to use the domestic customer much more extensively than the overseas one in beta testing. Having a customer who was close at hand allowed easier contact and communication and quick and periodic feedback of problems. However, with the aid of the parent company, a number of machines are also tested in the USA.

Due to the diverse nature of machine tool applications, beta test sites are selected on a heterogeneous basis. When selecting customers, an even balance is maintained between customers employing machine tool products in continuous high volume, batch-related manufacturing and customers who use the products in a tool-room for a variety of machining applications. This enables technical attributes such as reliability, accuracy and speed of operation to be evaluated for batch type manufacturing. Where the machine is tested in a tool-room production environment, technical attributes such as flexibility, accuracy and maximum size of workpiece can be evaluated.

Figure 7.7 details the communication and information flows of the beta testing process. Each customer selected as a beta test site is given a document for recording any observations of any kind with regard to the use and performance of the product. The recorded observations typically include aspects such as the machine's accuracy, reliability, ergonomics, maintainability, accessibility, flexibility and durability as well as general faults and failures observed throughout the duration of the beta tests. This completed document is collected on a periodic basis by a CM management personnel. All observations are investigated further and appropriate actions

Figure 7.7: Information Flows and Feedback of the Beta Testing Process



are taken by relevant functional areas. A computer database is kept of all observations made by the customer for archival and monitoring purposes.

Monitoring of beta product performance is carried out on a regular basis. First the relationship with beta test customers is such that the sites will take the initiative in immediately reporting any application problems or failures to the Customer Service and the Product Quality Manager. Customer Service then play a major part in rectifying the problem and putting the machine back into normal operation. Second, periodic contact with beta test customers is maintained by the Product Quality Manager. This regular contact helps account relationships, review beta test performance and can indicate quickly whether the test should be terminated or expanded.

### 7.6.6 Key Observations

There are no formal programmes for appraising or analysing the reliability of new product design, although the following reliability related engineering processes are used for this purpose:

- The concurrent engineering process.
- The Project Review Board.
- Design analysis activities such as design sensitivity analysis and design reviews.
- Reliance on supplier parts reliability and quality.
- Development and product testing.
- Involvement of functional areas (particularly manufacturing) during the conceptual stages of the product introduction process.

CM shows signs of having progressed along the organisational learning curve for the introduction of the CE process. Full integration of service, manufacturing and design personnel has yet to be achieved throughout the stages of the product introduction process. However, particular efforts are

being made to learn from previous experience and formalise the process for future developments.

The 'vetting' procedure which evaluates manufacturing issues of engineering changes and new designs has some bearing on enhancing product reliability.

Direct user involvement at the latter stages of product development is considered desirable and beneficial for the enhancement of product reliability. To this end, increasing reliance is given on the application of beta testing for evaluating the operational reliability and performance of machine tool products prior to market introduction.

A 400 hour reliability growth test is carried out on every new product which undergoes a substantial change in design. Normally, an upper limit of 2000 hours is specified on the cumulative number of test hours. This 'Duane' type reliability growth monitoring which is deployed during the latter stages of product development has proved to be useful in identifying and correcting any design deficiencies prior to beta tests.

The application the following design methodologies within the CM organisation reduces the need for reliability evaluation and also reduces reliability uncertainty:

- Standardisation of design.
- Re-use of design knowledge.
- Modular design.
- Use of latest and proven technology.
- Reduce unnecessary design features.
- Reduce number of parts and process steps.

No use of any reliability-based methods (e.g. FMEA) are made during any stage of the product introduction process, although the general design engineering activities such as stress/life analysis, design and environmental

sensitivity analysis, and general failure analysis are constantly being used as an alternative. These informal methods of reliability evaluation provides some form of assessment. Because the results are not documented on a regular basis, reporting of the fragmented findings is a difficult exercise in practice. Furthermore, these activities are carried out on a subjective basis and are based on the engineer's own judgement and experience.

## 7.7 Reliability in Manufacture

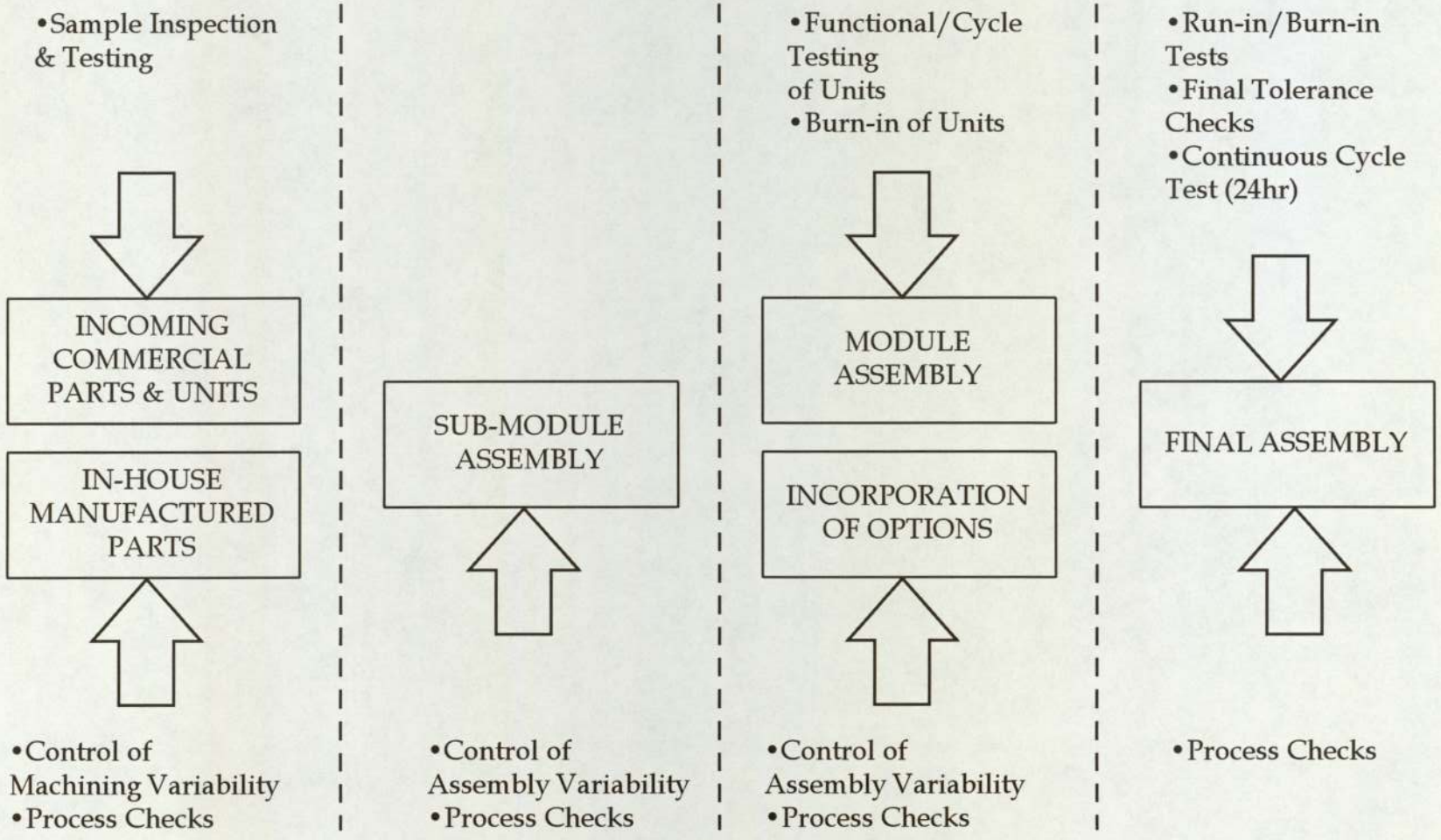
It is common knowledge that a well-designed product can be unreliable in service because of poor quality of production. Control of outgoing production quality is therefore an indispensable aspect of an effective reliability programme. This involves controlling and minimising variability and identifying and solving problems. While a significant amount of reliability effort during the design and development process is analytical, much of the effort to control production quality involves the use functional testing, fixed number of cycle tests and burn-in type tests.

This section briefly describes the main methods used within the manufacturing and assembly process to control quality of production and minimise the effects of manufacturing variability. Figure 7.8 aims to fundamentally describe the main processes and activities of controlling the outgoing production quality in Cincinnati Milacron.

### 7.7.1 Control of Production Variability

One of the primary functions of the overall reliability management system is to control the variability inherent in processes and products. This also applies to variability inherent in bought-in components. Although no form of statistical process control (SPC) is applied to measure and identify variability, sample inspection and testing of precision parts, components and sub-assemblies is carried out where relevant. However, in the majority of cases the sample inspection is not applied to commercial bought-in parts. This is particular so for electrical and electronic parts and equipment. Defective commercial parts is

Figure 7.8: Control of Production-induced Unreliability



therefore only identified during particular stages of the assembly process. Reliance is given on the quality and reliability of supplier parts and any defective parts are credited through a supplier warranty clause. Much of the sample inspection is carried out by the quality engineering department who essentially act as a service to the assembly and machining function.

Considering the nature of the machine tool build process, control of variability is mainly carried out on-line. The majority of the sub-assembly build stages go through a process check against a pre-determined standard. Fundamentally, these activities primarily involve the checking of engineering tolerances and logging the results in a test documentation for each machine built. This activity ensures manufacturing consistency and reduces the likelihood of encountering assembly-related problems downstream in the build process and more importantly during field operation.

### 7.7.2 Internal Failure Reporting and Corrective Action (FRACA)

Under the whole assembly process, the internal FRACA concept is extremely decentralised and fragmented. This commonly causes duplication of effort throughout the organisation, where more than one person is investigating the same problem. It is important to highlight that due to the organisational structure for reliability, the internal FRACA system operates separate from the field FRACA system. However, operation of one common FRACA system has several advantages in terms of (1) providing an effective feedback loop from in-use experience to future design and production and (2) better linking of production induced failures during field operation.

Only for the cases of defective commercial parts, a robust system is in place which ensures the return and where feasible rework of defective parts. A separate quarantine area acts as an administrator and co-ordinator for the return and rework of parts. On the other hand, failure reporting and corrective action of assembly related problems is very much decentralised and fragmented within the CM organisation. However, the recent introduction of a

'product quality' managerial position (see section 7.5.2) has had some effects in the following areas:

- Centralisation of information flows of assembly related problems.
- Better co-ordination.
- Better awareness by design engineering of assembly problems.

Under the current FRACA system, there is little systematic analysis of defective data and little monitoring of trends. Analysis of failure patterns, monitoring of trends and reporting on these is not considered to be of particular importance in the overall FRACA system. Although some fragile attempts have been made during the early 1990's to measure basic trends in assembly problems, at present the measures are used merely to give some indication of the trend, rather than a means of expanding the knowledge and experience for improving the process on a long-term basis.

It is accepted that new products, when released for production, may experience problems of a design and assembly nature. Therefore, an intensified monitoring process is adopted during the initial build stage. Shop-floor personnel are also expected to play a major role in improving design and manufacture performance following the introduction new products, as they are the people who are assembling and testing the product on a day to day basis.

### 7.7.3 Functional Testing of Sub-Assemblies: Identification and Reduction of Latent Defects

Sub-assemblies whose design and assembly is of a complex nature undergo functional testing. Essentially, relevant sub-assemblies are placed under a fixed number of test cycles to precipitate any faults or failures prior to the final assembly of the machine tool product. The specified number of cycles tend to be small. Nevertheless, the test satisfies the objective of identifying any latent defects which may be passed downstream to the assembly process. The latent defects being costly to correct downstream in the build process of a machine

tool product. The fact that sub-assemblies are designed and manufactured using modular design concepts allows tests to be carried out on a more robust scale.

Purposely designed test rigs are used and physically located within each sub-assembly cell or workstation. However, one of the limitations of test rigs is the inability to satisfy the flexibility requirements for the particular sub-assembly, product variants, product options and new product introduction. For example, due to this limitation, testing of specific sub-assemblies of new products does not happen on-line with the introduction of new products. Delays as much as 12 months is expected before new test rigs are introduced. This is primarily because of capital costs required to change or modify testing facilities. Consideration of flexibility in test rig design is therefore of particular importance.

### 7.7.4 A Description of Burn-in Models and Methods used within the Assembly Process

As detailed in figure 7.8, all products undergo a final burn-in test prior to shipment. This procedure expands on the cycle testing of sub-assemblies. The technique is particularly used to increase the quality of outgoing products delivered to the customer. Essentially, the procedure involves the setting and testing of various machine design parameters. Tests are normally conducted under alpha environmental conditions. All results are recorded on a test documentation for future consultation. Unique to the burn-in procedure is a reliability cycle test. The testing criteria used for this reliability cycle is that a fixed number of test hours needs to be achieved prior to shipment. Normally a 24 hour cycle test is conducted.

Although a text book approach is not adopted to the burn-in procedure [see Jensen and Peterson, 1982; Leemis and Beneke, 1990], the primary objective is to improve the outgoing quality of machine tool products by consuming part of their useful lifetime within the latter stages of the assembly process. In particular, the 24 hour reliability cycle addresses this issue. Within the burn-in

procedure, the disposition of failed items during the burn-in test is handled in two ways: (1) discarding the failed item and replacing with a new one and (2) repair the failed item.

In accordance with the theory of burn-in, both static and dynamic testing is used. Static burn-in involves subjecting the machine tool to alpha environmental conditions. Dynamic testing involves an alpha environment as well as making the machine perform the intended functions. A prime example of the dynamic burn-in test is the 24 hour cycle test.

### 7.7.5 Key Observations

Robust burn-in type tests and cycle testing are the main elements employed within the assembly process for the purposes of maximising the outgoing 'quality and reliability' of all machine tool products. Essentially, these burn-in tests are used for the purposes of:

- Reducing the number of latent defects being passed onto the final stages of the build process which may be costly to correct downstream in the process.
- Improving the outgoing 'reliability' by consuming part of their useful lifetime.
- Providing assurance that a failure free product has been passed onto the customer.
- Eliminating infant mortality failures of the bath-tub curve.

Sample inspection of general engineering tolerances is the main method used to control production variability of in-house manufactured parts. For commercial items, reliance is placed on suppliers to deliver parts with optimum quality and reliability.

The internal FRACA system is very much fragmented and decentralised, leading to a duplication of corrective action effort. However, there have been movements towards rationalising and centralising the FRACA system in terms

of return of defective parts, performance monitoring using conventional measures (e.g. faults per period), regular monitoring and corrective action of assembly related problems and greater involvement of shop-floor personnel.

## 7.8 Feedback of Field Failure Data

The purpose of this section is to examine the extent to which field failure data is used as a means of improving the reliability and design of CM's machine tool products. The section begins with a discussion of the structure of the field failure reporting and corrective action system and how this influences design improvement. Attention is then focused on the various performance metrics used as a measure of field reliability performance. Focusing the discussion still more precisely, attention then turns to recent developments in this critical area of the overall reliability management process.

### 7.8.1 Structure of Field Failure Reporting and Corrective Action System

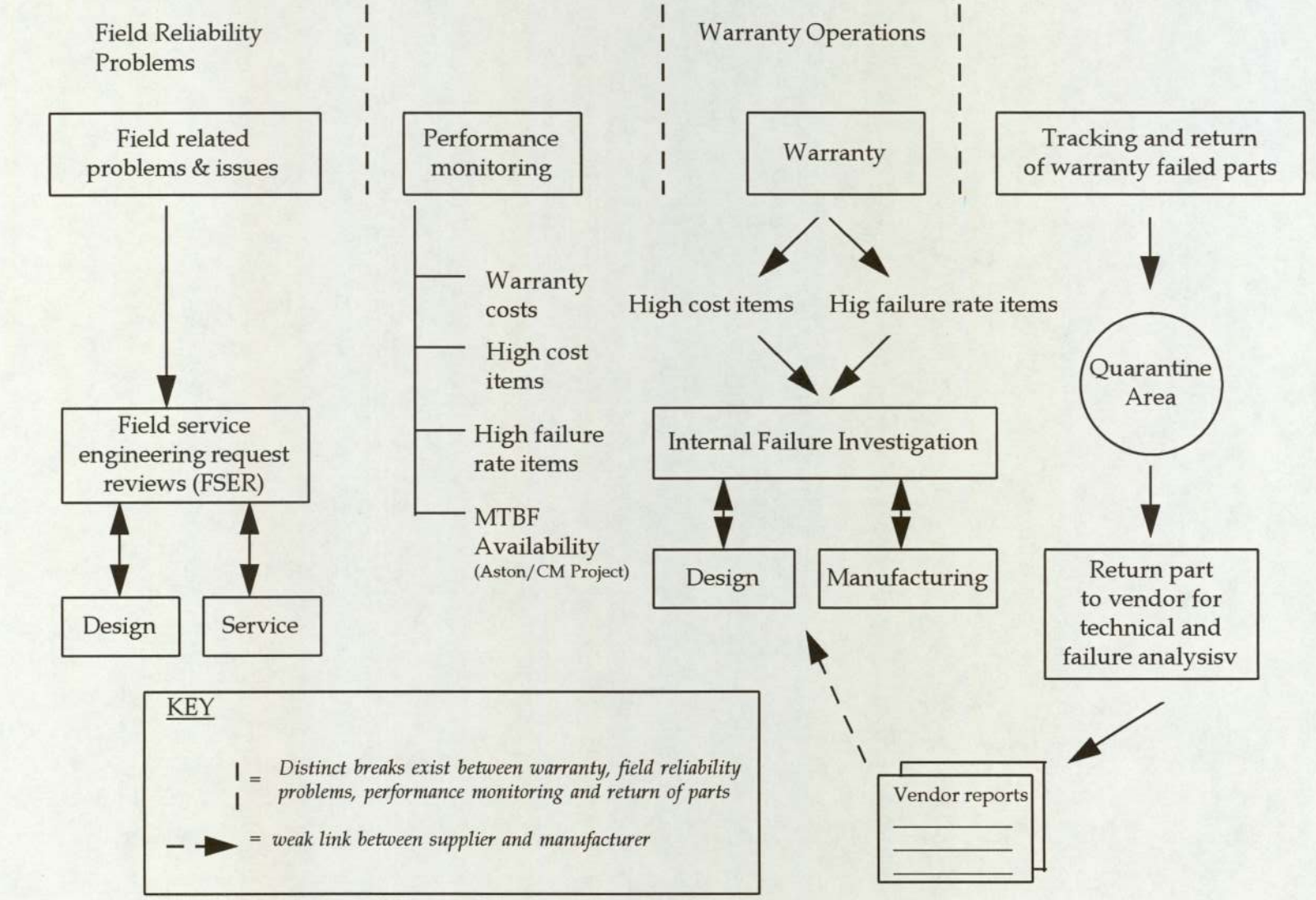
Similar to the internal FRACA system, the external FRACA is decentralised and fragmented in nature. This leads to inadequacies in:

- Co-ordinating engineering activities and effort related to field reliability issues.
- Some duplication of reliability effort.
- The use of performance metrics to monitor field reliability.

The FRACA system employed in Cincinnati Milacron is very much subjective and does not constitute any form of reliability and maintainability analysis, or monitoring field reliability performance. Figure 7.9 details the data generation and information flow of the FRACA system. Essentially, the objectives of the diversified FRACA system include:

- Addressing field related problems. This includes addressing on-going problems as well as isolated cases.

Figure 7.9: The Diversified Field FRACA System



- Feedback failure data to designers to enable them to (1) take corrective action to prevent recurring failures or (2) improve product design. However, failure data normally tends to be of a subjective nature rather than analytical and of a quantitative manner.
- Performance monitoring using conventional operational and cost metrics. For example warranty costs monitored on a periodic and year to date basis are used as indicators of field reliability performance.
- Warranty operations. This primarily includes addressing reasons for high usage of parts in the field. Investigations as to the root cause of failure is normally initiated when a specific part is deemed to have a high failure rate either in terms of cost or usage.

### 7.8.2 Addressing Field Reliability Problems: A Complex Issue

A phased approach to the review of field related problems is adopted. Using a team based approach, weekly reviews (termed 'field service engineering request' - FSER) are held on a regular basis by service and design supervisory personnel. The overall objective of this review board are to (1) review the status of existing field failure problems and (2) address new and anticipated problems. Although this team based approach exists at an operational level, rather than at a functional level, it has proven to be an effective method of ascertaining the root causes of failure and initiating design improvements where relevant. Due to the diversified nature of the field failure reporting system, aspects such as (1) high failure rate items, (2) high cost items (3) engineering problems (for example software specification errors) and (4) special requests from customers are reviewed.

Relative to the depth of failure information available, little or no reliability and maintainability analysis is conducted to support the periodic review of field reliability problems. Use of such analytical data can provide a more precise and systematic representation of the effects of the field reliability problems. However, despite the attractions of using reliability and maintainability data,

inadequacies in the recording of failure data makes the analysis less valid and ineffective. Examples of inadequacies and difficulties involved in conducting reliability and maintainability analysis are given below:

- Accuracy and integrity of recorded failure data.
- Ambiguity and insufficient detail in the numeric coding of failure data.
- Analysing failure data is a time consuming and costly exercise.
- Validity of recorded data in terms of variations in the operating performance conditions (e.g. dust, humidity, manufacturing activity and frequency of machine usage).

Recent developments in the recording of failure data has lead to the adaptation of numeric codes to record the information. The failure code is defined by three parts. The first part of the code represents the nature and type of failure, the component or sub-assembly that failed and the failure mode. The second part of the code describes the possible failure cause. The last part of the code addresses the corrective action taken.

Appendix L contains examples of alpha-numeric codes used to record failure data. As detailed in the Appendix, the codes adopted lacks detail. In particular part 2 of the numeric code is very indeterminate and provides little information on the root cause of failure (see Appendix A). In addition to the recording of failure data, information such as serial number, parts usage, date of failure, repair and logistics delay time are also recorded. Due to the cost and logistic difficulties involved, machine operating or elapsed time hours is not recorded. Appendix M illustrates an example of a service report document used to record these information.

In extreme cases, field tracking studies are deployed to monitor the effects of any design or manufacturing change(s) which resulted as direct result of a FSER inquiry. Alternatively, a field tracking study is also used to ascertain root causes of failure. This form of study involves closely monitoring the

performance of a sample of products in the field in order to (1) evaluate the impact of these changes or (2) ascertain root causes of failure. Similarly, where a particular machine has on-going reliability problems reflected by numerous service visits and constant customer complaints, a 'machine performance' document is provided to the customer to log all known problems. Appendix N details the design of the document and provides an completed example. The design of the document enables information such as machine operating hours, nature of the problem, root cause, corrective action, downtime hours and repair hours to be accurately recorded on a daily basis by the customer. These information are then analysed by service personnel to calculate basic machine availability against maximum production hours available and instigate further action to resolve the problem on a permanent basis. Availability calculations are normally performed to verify uptime guarantees which was previously specified to an individual customer.

### 7.8.3 Performance Monitoring

Measures of field performance are primarily based on costs. For example, a useful indicator of field reliability performance used by CM is the cost of warranty. This measure is monitored on a quarterly (of a year) basis which provides the basis to compare actual warranty costs with budgeted allocation. Similarly, it is also used to some extent in management decision making at a business and operational level:

- Support data for monitoring vendor performance and development.
- Evaluating the feasibility of extending the warranty clause.
- Initiating efficiency action in terms of product design, process or service improvement, if the warranty cost has exceeded a defined upper limit threshold.

The cost of warranty basically includes the cost of replacement parts in the field and excludes labour costs. However, the implementation of a computerised

service management system has enabled information and calculation of labour costs more easily accessible and predictable.

In 1994, senior and middle management felt that a more objective measure for monitoring field reliability performance was needed. Mean time between failure (MTBF) was defined as a mechanism for measuring field reliability performance. In order to do this, a joint industrial project between Aston University and CM was constructed. As stated in chapter 1, the author was recruited by CM to carry out this project.

As a result of this industrial project, MTBF is measured on a quarterly basis and communicated to a large number of interested parties at a business and operational level. The MTBF parameter merely serves as a reliability performance indicator at system and sub-system (unit) level. Considering the inadequacies in reporting failure data, MTBF of components and parts cannot be predicted. Therefore, the MTBF parameter is only used to identify inhibitors to poor reliability performance at an unit level. Furthermore, it was now possible to quote MTBF figures to customers who requested such information and can serve as a potential sales tool.

Compared to previous measures deployed within CM (e.g. faults/machine, high failure rate items), it has proved to be a more objective means of monitoring trends in field reliability performance. The diffusion of networked computer-based data bank has allowed easier access to field failure information and enabled the automatic collection and processing of data for use in MTBF calculations.

### 7.8.4 Developments in the Operation of Warranty

In 1995, senior management felt that more attention needed to be focused on the warranty aspects of the overall FRACA system. It must be emphasised that approximately 2.5 years were taken to meet the above objectives and change the way the warranty activities were operated.



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The principal factor influencing the decision of senior management to improve the system for operating warranty was as a direct result of increasing warranty costs. In order to do this, senior management suggested the use of a multi-disciplinary team to tackle this problem. The team itself consisted of representatives from design engineering, customer service, purchasing and accounts. The overall objectives were as follows:

- Reducing the overall cost of warranty which surpassed the allocated budget threshold.
- Periodically review warranty operations in terms of cost and consumption of parts.
- Review and modify procedures for the return, rework and technical analysis of replacement parts in the field.
- Creating a formalised system for investigating the root causes of field failures.

Prior to the review and development warranty operations, activities relating to the running of warranty had evolved within the CM plant in a rather ad hoc manner and concealed manner. The formalisation of the warranty operations was made necessary by the high warranty cost. In working towards the formalisation process, the following problems and solutions were found by the multi-disciplinary team:

*(I) Logistics problems encountered in the return of replacement parts:* Various logistical problems and difficulties were identified which hindered the efficiency of the warranty operations and the overall FRACA system. These were:

- Lack of customer co-operation in returning parts.
- Tracking of replacement parts within the CM organisation and in the field.
- Lack of supplier co-operation in subsequent technical analysis.

- Mechanisms for returning parts.
- Criterion used for returning parts. For example high cost items or high failure rate items.

It was therefore critical to address these logistical problems in order to improve the process of returning and analysing failed parts both internally (i.e. within the CM organisation) or externally (i.e. supplier). It became apparent to the team that efforts had to be directed towards rationalising the operations within this area in order to conform to and satisfy the initial objectives. Through a review of procedures, the return of defective parts was made possible by the customer service function taking more responsibility in co-ordinating and scheduling the return of failed parts from the field. Similarly, in order to eliminate the problems of tracking parts internally, a designated quarantined area was created for the storage of failed parts. As shown in Figure 7.9, this independent storage area paved the way towards:

- Better traceability of defective parts. Prior to the creation of the quarantine area, defective parts returned from the field were relocated in the main stores. This caused difficulties in tracking the physical location of defective parts.
- Defective parts were returned to the vendor on a more consistent basis for evaluation as to the cause of failure.
- A PC database was also developed to allow records to be kept of every returned parts to CM.

*(II) Little consistency in investigating root causes of high failure rate and high cost items:* Despite the existent of a FRACA system, it was realised that investigations into the reasons for (i) high failure rate items and (ii) high cost items needed to be carried out on a more regular basis. Relative to this activity, high failure rate and high cost items were monitored on a periodically and year to date basis, using Pareto techniques. A new procedure was created for reviewing warranty failures. Figure 7.10 details this procedure. Where

Figure 7.10: Procedure Adopted for the Review of Failed Parts Under Warranty (flow chart 1)

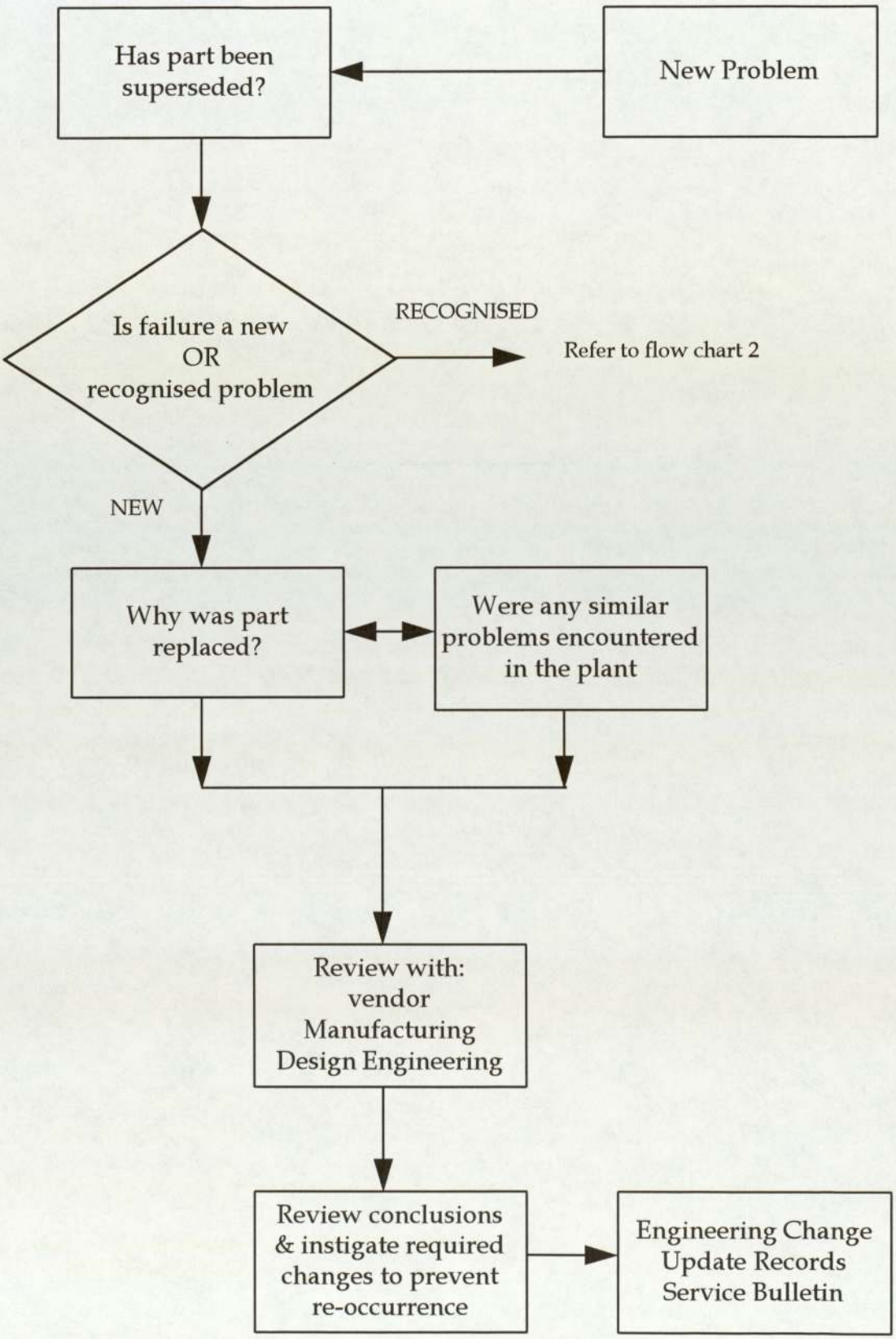
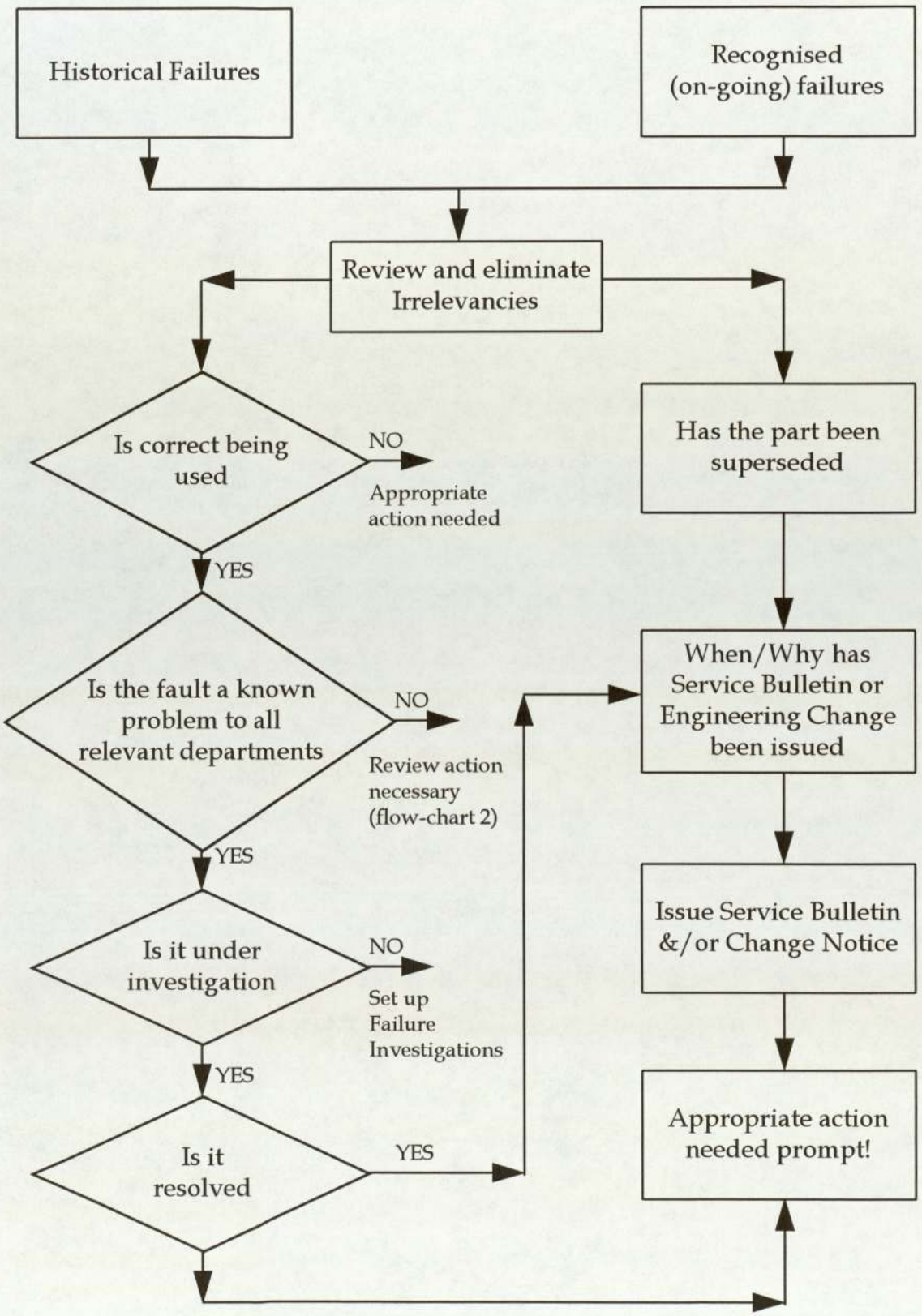


Figure 7.10: Procedure Adopted for the Review of Failed Parts Under Warranty (flow chart 2)



relevant vendors were made more accountable and invited to furnish data in the investigation process.

The above developments has allowed a better means of running the various aspects of the warranty operations. Although little reductions in the cost warranty was observed, the following intangible benefits were achieved through the review of warranty operations:

- Better co-ordination and tracking of defective parts.
- Greater vendor involvement in the failure investigation process.
- Greater accountability of vendors.
- High failure rate and high cost items addressed on a more consistent basis.
- Better feedback of field failure data when needed.
- Effective monitoring of replacement parts.
- A structured approach to investigating high failure rate items.
- Greater involvement of key functional personnel in the failure investigation process.

### 7.8.5 Key Observations

Although the overall FRACA system was observed to be decentralised and fragmented, recent reviews and developments in warranty operations and the overall FRACA system has allowed a more effective means of monitoring and improving the reliability of machine tool products. In particular, consistency and a more objective approach to the review and subsequent failure investigation of failed parts within the warranty period was achieved.

Reliability monitoring is performed using measures derived from warranty data (high failure rate items, high cost items, warranty cost by product line and overall warranty cost). However, recent developments in the area of performance monitoring enabled a more objective reliability measure to be

adopted. Monitoring of reliability performance is now primarily based on the MTBF parameter.

Inadequacies in the reporting of failure data (e.g. integrity and accuracy of data) inhibits reliability and maintainability analysis to be conducted and used as a support tool for failure investigations. Due to these inadequacies any reliability and maintainability analysis data is of less significance and invalid.

### 7.9 Concluding Summary

Using 'action research' methodologies, this chapter has provided a longitudinal account of the reliability management process at Cincinnati Milacron. The study itself focused on the design, manufacture and service aspects of the reliability management process. The overall aim of the study was to ascertain and evaluate on the key mechanisms used by CM to appraise and improve reliability throughout the life cycle phases of the machine tool product. Key conclusions of this longitudinal study are as follows:

- Product reliability is seen as an important variable within other competitive factors such as price and delivery performance.
- Given the nature of the machine tool design and manufacturing process, there is no independent management structure or a programme for reliability appraisal or improvement.
- The application of CE has had some bearing on the upstream consideration of manufacturing and service issues, thereby reducing the risk of downstream failures and problems. However, the basic principles of CE is only adopted within the conceptual design phase of the product introduction process.
- Appraisal of reliability during the design stage is predominantly subjective. Informal techniques such as design sensitivity analysis and stress/life analysis provides the main platform for analysing and evaluating reliability issues during design stage. Alternatively, to reduce the amount of reliability evaluation needed, design techniques

such as re-use of design knowledge, use of proven technology and modular design concepts are adopted.

- Supplier involvement and integration is minimal, but are consulted outside the product introduction forum. Although vendor evaluation criteria addressed reliability and quality aspects of vendor supplied parts, often, price is the dominant issue in the selection of suppliers.
- Increasing reliance is given to alpha and beta testing concepts for evaluating reliability. Unique to the evaluation of design reliability is the recent introduction of a reliability growth test.
- Burn-in type and cycle tests forms the main platform of reliability assessment during the assembly process. Sample inspection is carried out on critical parts, but for commercial parts reliance is given to
- Increases in the cost of warranty or field unreliability mainly influences the need for reliability improvement. Recent developments in the FRACA system has allowed a more objective means of monitoring and improving the reliability of machine tool products.

Based on the survey data, the next three chapters provides a generalised evaluation of reliability management practices within the UK machine tool industry.

## 8. Reliability Practices During the Product Design and Development Process

### 8.1 Introduction

This chapter is concerned with the analysis and evaluation of reliability engineering and management practices adopted by machine tool manufacturers during the introduction of new products. Based on the results of the survey, it examines the broader concepts behind product reliability optimisation during new product introduction, outlining factors which may have an influence on reliability improvement.

The chapter begins with a general discussion on the reliability assurance systems of machine tool manufacturers and the degree of application and formality. Attention is then focused on customer influences on new product design and development, with particular emphasis on the application and role of beta testing methods in improving machine tool reliability.

Focusing the discussion more precisely, attention then turns to (1) evaluating the effects of concurrent engineering on product reliability optimisation, (2) design methods used to address product reliability issues and their degree of application and (3) vendor evaluation criteria and perceived business performance. Each of these aspects studied forms an important part of the context within which reliability decisions are taken. The chapter ends with some broad conclusions on product reliability improvement during the introduction of new products.

### 8.2 Status and Structure of Reliability Management

The success of any reliability improvement effort in an organisation depends on the status and organisation of the reliability management function and the importance placed on it by senior management. In answer to the question, *'Does your company have a systematic reliability assurance system providing an effective and economic means of controlling and improving the reliability of your*

*products?'*, nine out of the seventeen (53%) companies answered 'No'. Additionally, these companies were asked how they contemplate reliability assessment and improvement of their machine tool products, given that they did not adopt to a formal reliability system. Figure 8.1 presents the average results to this question.

The most common means of assessing and improving the reliability of machine tool products is through addressing field and in-house failures. As indicated by Figure 8.1, little reliance is placed on engineering and development activities or the control of production quality in addressing machine tool reliability. It is evidently clear from this analysis, that machine tool companies adopt a 'corrective' philosophy to the improvement of reliability, rather than a 'preventive or a 'proactive' one.

Of the remaining eight companies who did claim to have a structured reliability system all said that the system encompassed the basic areas of product engineering and design (including product development), purchasing of commercial parts, manufacturing and assembly (including control of production quality) and service and support. However, on closer examination, the patterns of concentration, in terms of coverage, differ considerably from one functional area to another. Indeed, one of the most pronounced differences evident from the findings was the importance given to service and support (i.e. field performance data) as a means of improving machine tool reliability. It appears from the findings that the service and support function form the "pinnacle" of the reliability assurance system adopted by machine tool manufacturing organisations (see Figure 8.2).

Regardless of whether a machine tool manufacturer adopts a structured or a non-structured route to tackling reliability related problems it is evident from the results of this analysis that little or no emphasis is given to designing or building-in reliability upstream in the product life cycle (i.e. during the design and development phase). Clearly, UK manufacturers are placing more reliance on the use of field failure data to improve the overall reliability of their

Figure 8.1: Application of Engineering Activities as a Means of Reliability Improvement.

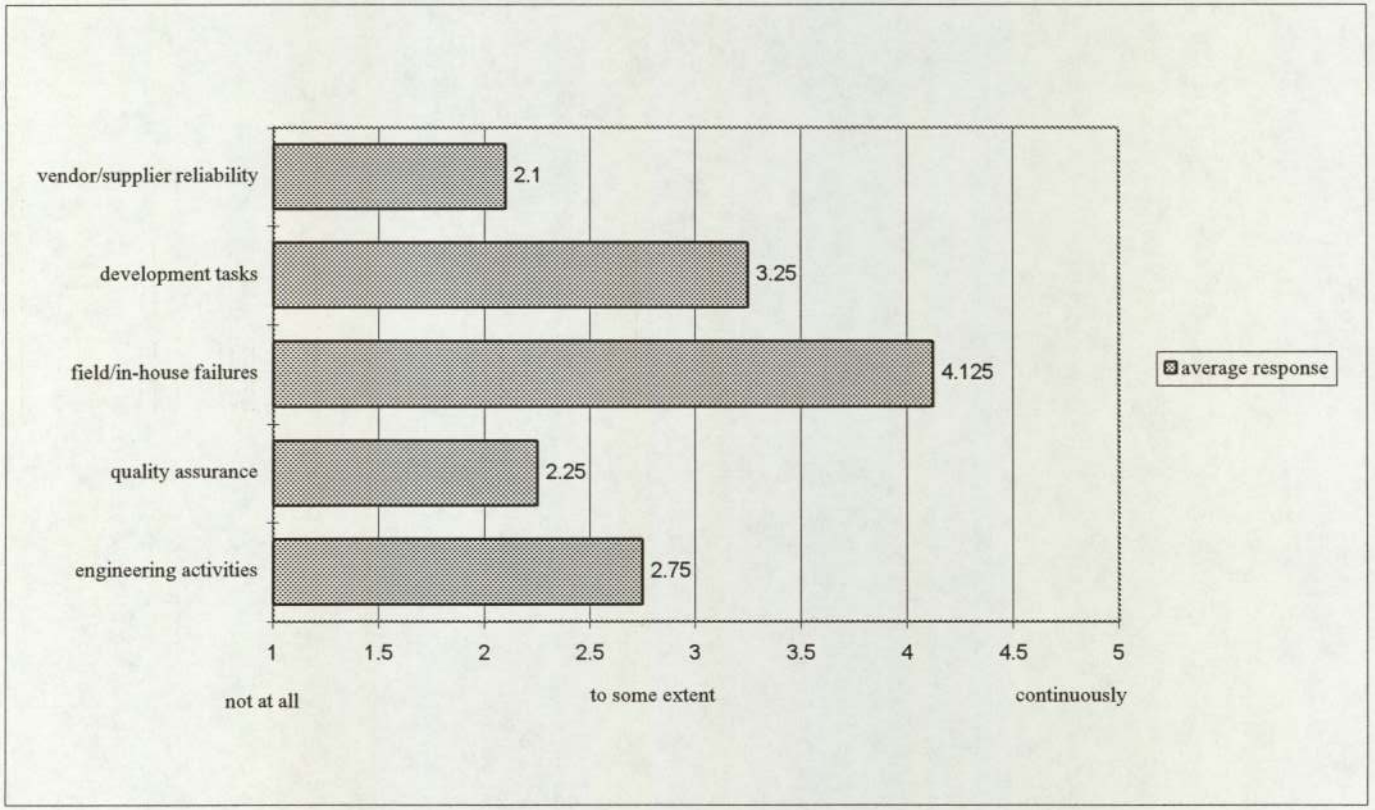
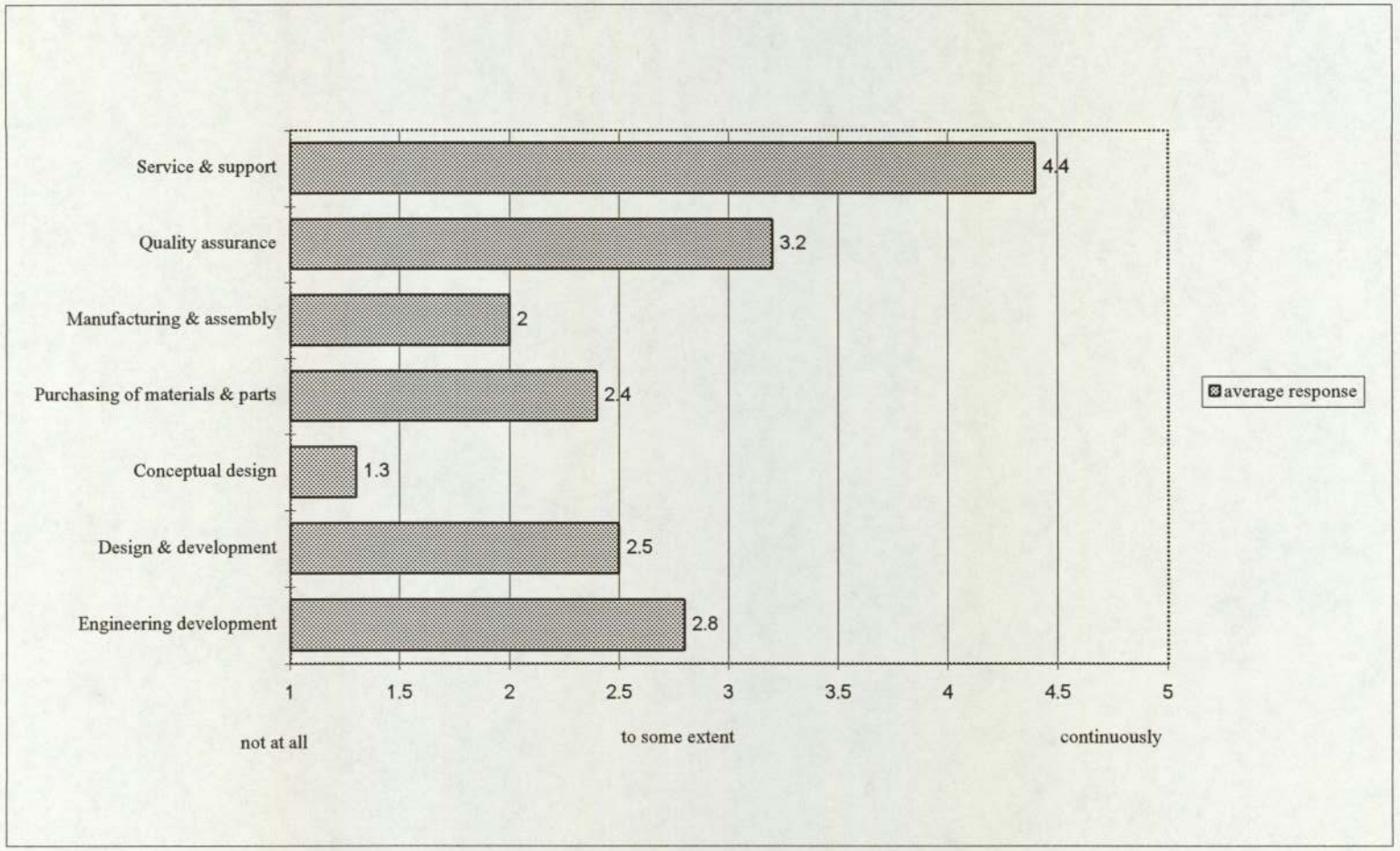


Figure 8.2: Reliability Systems and Degree of Functional Coverage



products. Although this outcome is consistent with the many models of product reliability improvement which stresses the importance of using field data for improving the reliability of products, it is apparent that all reliability improvement models stress this as secondary to the design and manufacture factor. In other words, field data becomes a determinant factor in choice only when assurance can be given that all reliability variables and constraints have been considered and proven during the design, development and manufacturing phase.

### 8.2.1 Degree of Formality

In attempting to measure the predominant style in which reliability issues and information are considered and communicated, companies were asked how frequently they communicated information relating to product reliability, the management style adopted and, finally, how they communicated the information through functional areas. The analysis revealed (see Figure 8.3) that the management style was on average 'mostly informal,' the frequency of communication of product reliability issues was 'seldom regular' and communication of reliability information 'seldom in writing.' These practices were broad indicators of the nature of the reliability improvement system itself - less formal and less systematic.

The methods, engineering activities and documentation used in the overall reliability assurance system are central to studying the status and structure of reliability management practices. Closer interrogation of the reliability assurance system revealed a less systematic and less explicit approach to the achievement and improvement of machine tool reliability. There was little evidence of any of the reliability activities or documentation listed in Table 8.1, being fully incorporated in the overall reliability assurance system. However, according to the review of the literature in Part 1 of this thesis, these activities form the pinnacle of any reliability assurance system. In this context, the reliability systems employed by manufacturers can be said to have little substance or structure.

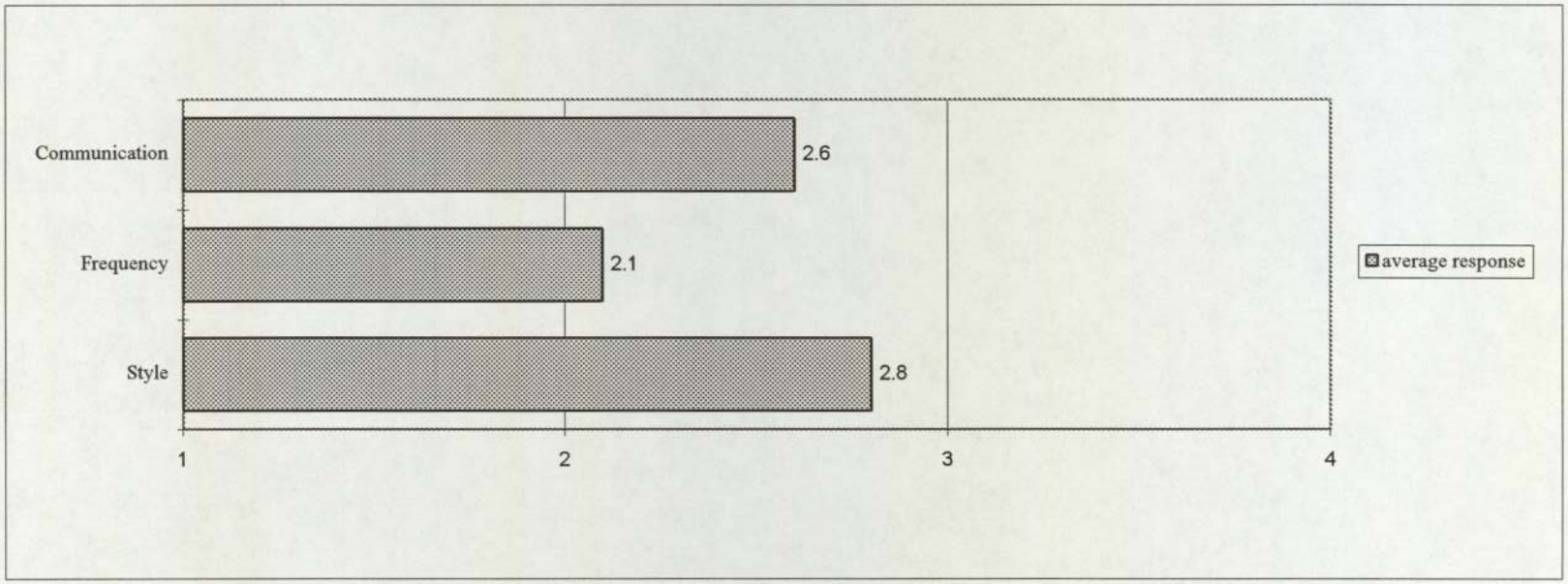
Table 8.1: Examples of Reliability Activities, Methods and Documentation of a Reliability Assurance System

| Reliability Activity | Brief Description |
|---|---|
| Reliability Instruction or Guideline Manual | Manuals normally should contain all relevant reliability activities (together with guidelines on how to perfom these activities) that needs to be conducted during the design and development stages of a machine tool product. |
| Periodic Warranty Review | Warranty reviews should normally form the basis for initiating investigations on high failure rate items and high cost items on a periodic basis. Reviews of warranty also covers areas such as design ofwarranty clauses, reclaiming and reduction of warranty costs, return and technical analysis of commercial and in-house parts. |
| Reliability Testing | Reliability related tests which encompasses development and assembly Particular tests that are applicable from a reliability perspective are growth or cyclic type testing, burn-in or run-in. |

Table 8.1: Examples of Reliability Activities, Methods and Documentation Aids of a Reliability Assurance System

| Reliability Activity | Brief Description |
|---|---|
| Reliability Analysis and Measurement (Statistical) | This activity is concerned with analysing and measuring reliability concerns using failure data. |
| Design Reliability and Maintainability Assurance | This activity is concerned with design and maintainability analysis in terms of reliability appraisal during the design process. |
| Reliability Evaluation of Parts | The reliability of commercial and in-house designed parts should be continuously evaluated in terms reliability/cost trade-off. Use of failure data is normally used to substantiate such evaluation. |
| Design Reviews | Formal design reviews conducted at various design milestones forms an effective means of reliability appraisal. This activity should normally be conducted at a functional rather than a operational level. |
| Life Cycle Costing | Life cycle cost (LCC) is the total cost of ownership of a machine tool during its operational life. Normally this activity is conducted from the request of customers or as a sales promotion tool. |

Figure 8.3: Degree of Formality in the Communication of Reliability Information




KEY

| Scale | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| **Style** | very informal | mostly formal | mostly formal | very formal |
| **Frequency** | complete ad-hoc | seldom regular | mostly regular | very regular |
| **Communication** | never in writing | seldom in writing | mostly in writing | always in writing |

As shown in Figure 8.4, reviews of cost associated with the operation of warranty and reliability related testing formed a significant part of the overall reliability assurance system. However, there was little evidence which indicated the use of warranty and failure data in the area of (1) reliability analysis and measurement, (2) reliability evaluation of commercial parts or (3) life cycle costing (LCC). There was no reliability instruction or procedural manual deployed by any of the surveyed companies within their reliability assurance system. Such documents normally provide a list of reliability activities to be performed during the design and development stages of machine tool products. Reliability and maintainability analysis of the evolving design and formal design reviews were less widely practised as a means of reliability appraisal.

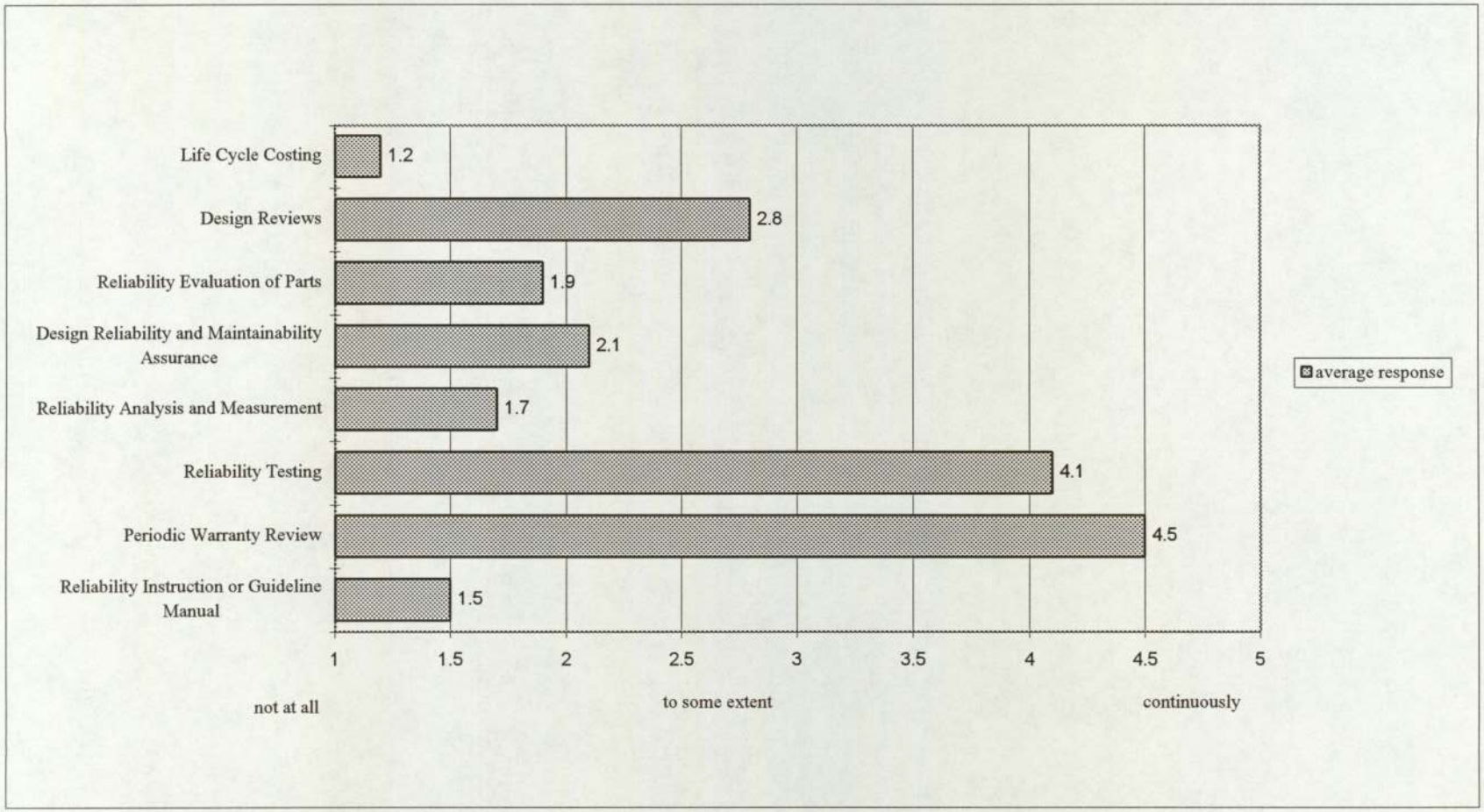
There was considerable evidence that the reliability improvement process was not prone to extensive written rules and procedures. Furthermore, a lack of planning and co-ordination of reliability improvement activities was also evident. However, the degree of formality required in the reliability improvement process depended heavily on the volume of manufacture and the resources available (as many companies commented).

### 8.2.2 Use of Warranty Data in Design Improvement

During the course of the field research it became apparent that decisions to improve machine tool reliability were precipitated by two major factors. Either the cost of warranty had passed a defined threshold or, by the identification of high failure rate items. The principal factor influencing the decision to improve reliability generally was increases in warranty costs. The importance of this factor clearly depends on the extent to which individual companies collect and use information on the warranty costs of existing machine tool products.

Although, a less systematic approach was adopted to the review of warranty, UK machine tool companies were significantly more likely to collect and assess the cost of warranty of individual machine tool products and associated parts and components on a regular basis. By doing so they were more likely to

Figure 8.4: Application of Reliability Activities, Methods and Documentation Aids in Reliability Assurance Systems



identify unacceptable changes in the warranty costs of their machine tool products through increased unreliability. The cost-based stimulus for engineering changes appeared to be more likely to drive improvements in product reliability. However, the limitation is that low cost items with a high failure rate will receive less attention. The consequence of this is that the overall reliability of machine tool products will remain at a low level.

Figure 8.5 illustrates the main types of warranty cost information used by the majority of machine tool companies and the extent of use for (1) general management decision making and for (2) effecting design improvement. There were some significant differences in the types of warranty cost information used, as Figure 8.5 indicates. 88% of the total sample quantified losses arising from the cost of supplying replacement parts and used this to some extent in management decision making. These quantified figures included both field and shop-floor replacements. 35% of the sample predicted the cost of warranty labour costs. None of the companies in the sample of 17 quantified production and inventory costs for warranty support. It appears that machine tool companies are more concerned with warranty parts cost rather than both parts and labour costs. Arguably the latter will give a cost-based stimulus for change in both product reliability and maintainability.

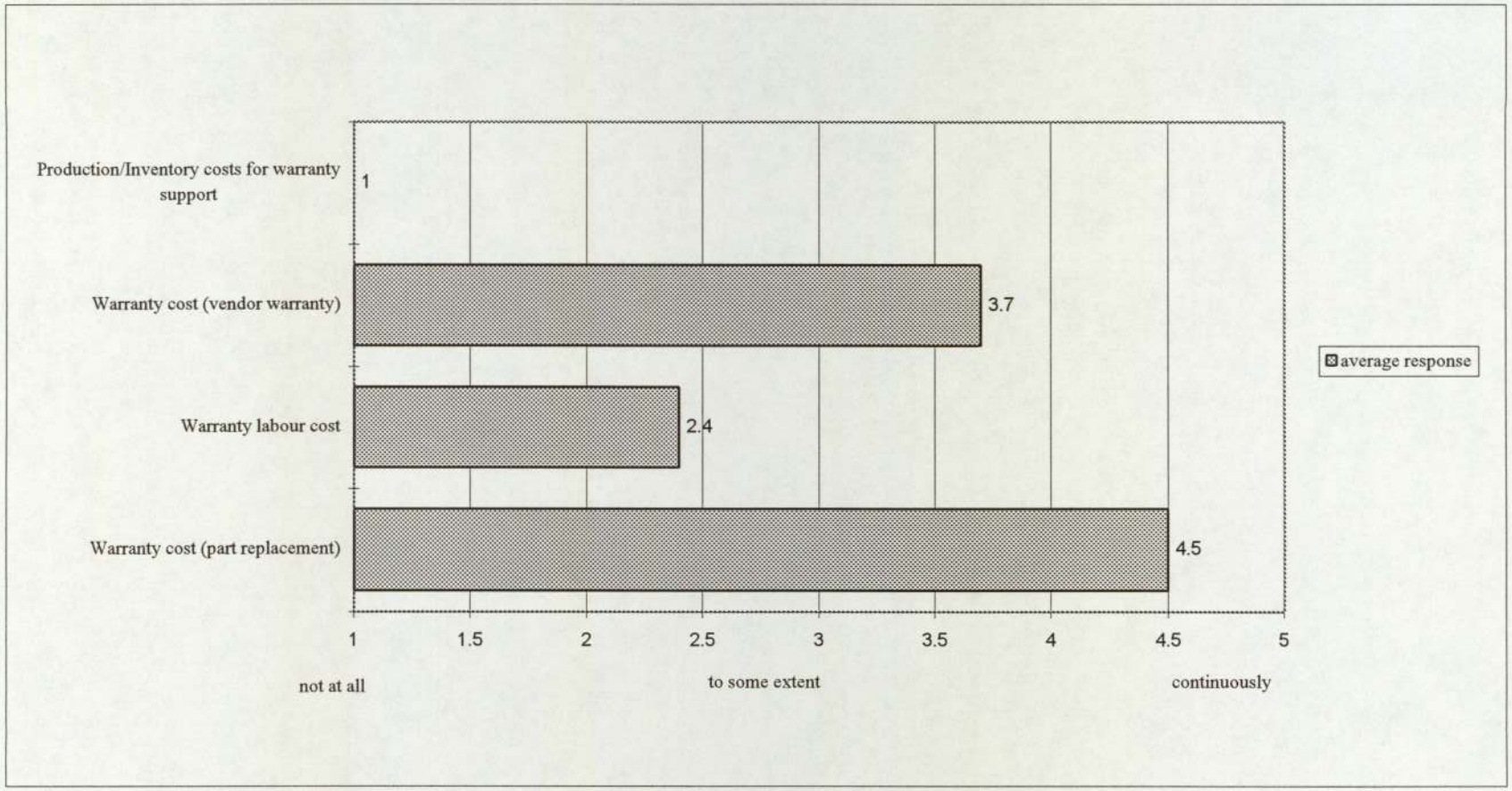
### 8.2.3 Key Observations

Analysis of the survey data suggests that no formal programme of reliability assessment and improvement exists in the machine tool industry. In particular, a less formal and less systematic approach is adopted.

Reliability appraisal during the product introduction process is conducted through normal design engineering activities like cycle testing.

The pinnacle of the reliability assurance system is the feedback of failure data for effecting design and reliability improvement. Warranty cost data is the main component used to effect reliability improvement.

Figure 8.5: Use of Warranty Data in the Area of Management Decision Making on Reliability Improvement



### 8.3 Buyer-Seller Interaction in New Product Development

There is already some evidence in the literature, supported by the results of the last chapter, that the customer can frequently play an active role in initiating change in a supplier's product. Furthermore, the customer can influence the development of engineering changes during the latter stages of the development process. If the customer plays an active role in the latter stages of the development process then the importance given to different product features such as reliability, durability and overall functional performance is clearly crucial information for a manufacturer. The last chapter has shown how Cincinnati Milacron involve customers indirectly with the machine tool development process. This is achieved primarily through the deployment of beta testing methods. This reflected a positive attitude on the part of Cincinnati Milacron to customer involvement in the development of their range of machine tool products.

There was considerable evidence which indicated that UK machine tool manufacturers are more likely to use domestic customers than overseas customers in product development work. Clearly it could be argued that manufacturers have access to all potential customers whether domestic or overseas. However, in the discussion with manufacturers, it became clear that they tended to use the domestic customer much more extensively than the overseas one in product development work. Managers spoke of having a customer who was close at hand for ease of contact and communication, providing quick and periodic feedback on the overall performance of the products. Problems of language and geographical distance tended to preclude reference to overseas customers.

#### 8.3.1 Differences in the Needs of Machine Tool Users: A Manufacturers View

The relative importance of technical and economic factors in the machine tool purchasing decision is at the centre of this inquiry. Studies of the process of purchasing decisions have traditionally been customer-orientated, in that they

have concentrated on characteristics of the customer company and its approach to purchasing decisions of machine tool products. These type of studies can frequently yield useful generalisations about the importance given to reliability by customers compared to other technical attributes. For example, if the customer plays an active role in the development process then the importance given to different product features such as reliability, cost and accuracy is clearly crucial information for a supplier. These features can be distinguished from other essential 'supplier-related' factors such as 'after sales service' or 'delivery reliability' which are not specific to an individual product.

However, a study of the approach of the customer's importance given to technical factors during the purchasing process is deficient to the extent that it ignores the potential views on this important subject held by machine tool manufacturers. This inquiry attempts to assess the manufacturers view on this area. In the context of this inquiry, respondents were asked to indicate the level of importance which they believed a customer would give to a series of machine tool attributes in the final evaluation of the machine tool buying process.

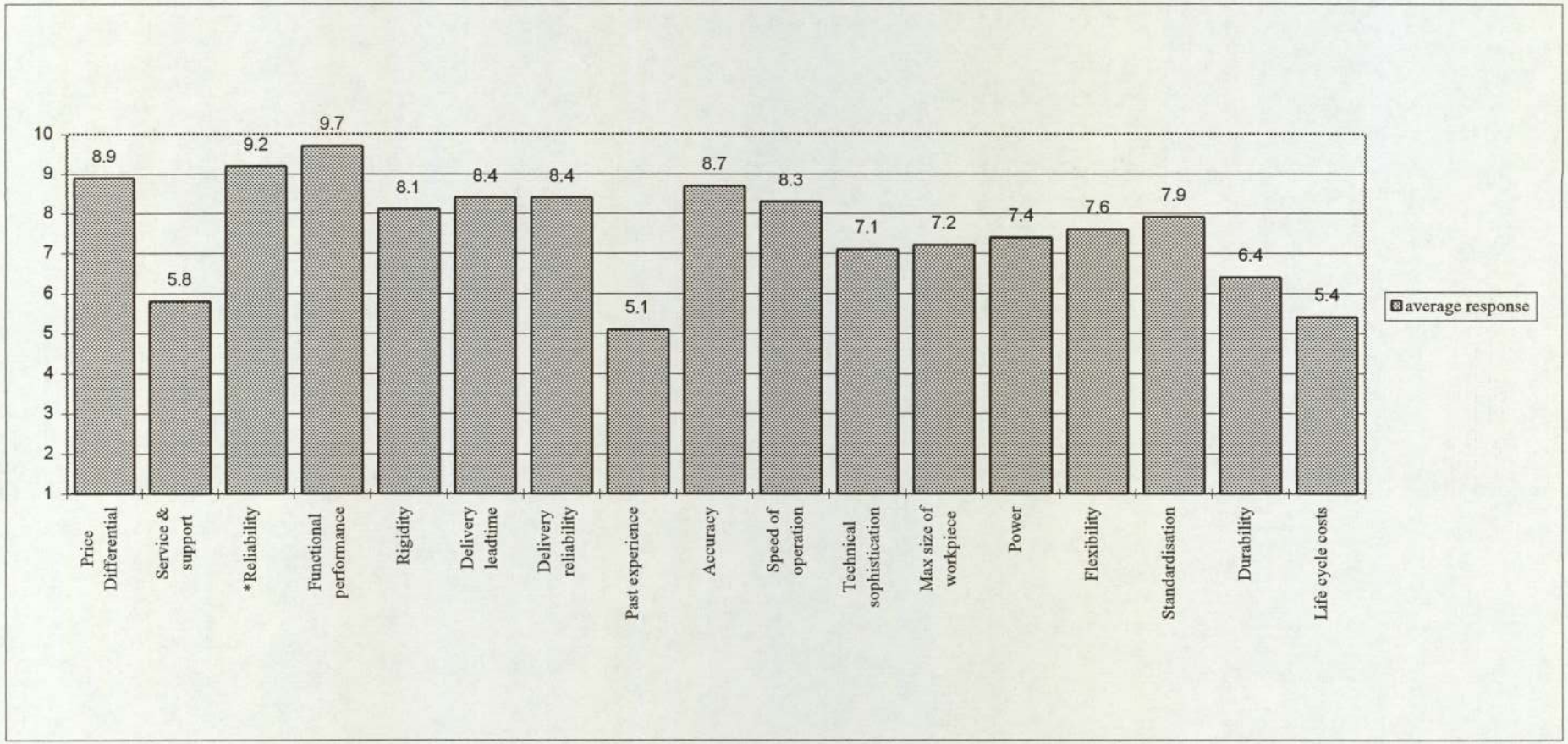
If the elements of the machine tool buying process is referred to, it can be recalled that, at the final stage, the machine tool buyer is in the process of evaluation and negotiation. The buyer would have completed his search of potential suppliers and excluded those which did not meet the technical specifications. The potential suppliers on the short list, normally not exceeding three or four in number, will then be evaluated against a set of factors before a buying decision is finally arrived at. Often, because the suppliers in the short list have satisfied the broad requirements on machine performance and price, there will be little to choose between them, and the factors against which the suppliers are evaluated tend to be more subjective than quantitative in nature. It is against this background that the respondents in the survey were asked to rate the buying factors.

Figure 8.6 illustrates the overall rating of importance given to a series of technical, non-technical and economic attributes by respondents. Clearly, the rating of an individual machine attribute could vary depending on the type of machine tool market the manufacturer is catering for. For example, if the respondent primarily manufactures production machine tools to be used in continuous high volume, batch-related manufacturing, then the attributes of reliability, accuracy and speed of operation would be likely to be most important. On the other hand, if the respondent was engaged in the manufacture of special purpose machine tools or workshop machines which would be used in a tool-room on a variety of applications, then the attributes of flexibility, accuracy, and maximum size of workpiece could be expected to be of greater importance.

Acknowledging these problems of interpretation the question still allows a general comparison to be made between the manufacturers perception of the relative importance of reliability and other related technical and economic factors. In this respect the study is significantly different from earlier ones which have tended to take the viewpoint of the researcher and define important innovations in terms of the researcher's own perception of importance rather than that of the manufacturer.

From Figure 8.6, it is clear that reliability among other technical attributes of the machine including accuracy, rigidity, speed of operation and overall functional performance were seen as important by the majority of respondents. Statistically, little variance was observed between the individual ratings, clarifying the importance of all these technical attributes. Other technical attributes including flexibility, technical sophistication, power, maximum size of workpiece, standardisation of parts and product durability were viewed with varying degrees of importance by different respondents, some rating these attributes highly, others less so. Price and delivery (leadtime and reliability), the two economic product attributes included in this listing, were also viewed with varying degrees of importance, but with an overall high rating.

Figure 8.6: Overall Rating of Product Attributes




The mean value of each attribute is provided on the assumption that the scale has interval properties

* To be read: On average respondents believed that reliability was an important factor, rating 9.2 on a scale from '10: very important' to '1: not important,' in the machine tool buying process.

In some cases respondents rated product reliability, functional performance and accuracy as being equally important to the customer.

Another economic attribute 'life cycle cost' (LCC) was rated moderately overall, but with varying degrees of importance by each of the respondents. In some cases, no rating was given to this attribute. This may have been because of the interpretation difficulties with the word 'life cycle cost' and understanding the meaning of this term. However, this was not apparent during the piloting of the questionnaire.

The attributes 'after sales and support' and 'past experience with company' was again rated moderately. Little degrees of variance was observed between each of the individual ratings, clarifying the overall effectiveness of the results.

The results of this analysis are consistent with those reported in other broad based studies of machine tool reliability and purchasing decisions adopted by machine tool buyers [e.g. Parkinson, 1984; Yong, 1981]. It is apparent that technical product attributes (in particular product reliability from the perspective of this study) are rated more importantly than economic ones by the majority of respondents. In particular, reliability, accuracy and functional performance of machine tools are rated more importantly than price.

From informal discussions with some machine tool users it was clear that this outcome was consistent with a model of the machine tool purchasing decision which stressed the importance of the ability of a machine tool to perform to the requirements stated by the manufacturers, rather than the importance of price. Price becomes a determinant factor in choice only when the suitability of the machine tool product has been proved.

The analysis has also shown that UK manufacturers understand the needs of the markets more precisely than in previous decades. In this perspective, the analysis overrides traditional views that British machine tool manufacturers are not as competent as their overseas competitors in meeting the needs of the market in that they have traditionally concentrated on price.

These data suggest that a decision to concentrate on price alone rather than considering improvements in product reliability as the basis for competition will lead to problems in this market. On average, respondents assigned a greater importance to technical product attributes of a machine tool of relatively standard design. However, although manufacturers understand the importance of product reliability from a customer's perspective, this is not reflected or consistent with their reliability assurance systems (the findings of which have been reported in the previous sections of this chapter).

Why is the reliability of the machine tool such a crucial factor to buyers, as seen from a manufacturer's perspective? Two main reasons were cited through the progress of the research and from the comments in the questionnaire. Firstly, because of the high capital cost of machine tools, it is essential that users try and achieve a high 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 production system.

Clearly, this is an area where a manufacturer can capitalise during selling. A manufacturer assuming greater responsibility in this field can in fact help to increase the reliability of their line of machine tool products.

### 8.3.2 Customer Influences in Product Design

As highlighted earlier, the comparative importance given to different technical features such as reliability, accuracy, power and functional performance by potential customers is clearly crucial information to the manufacturer. Direct customer involvement in the product development process is therefore significant in obtaining such information. This involvement can be measured in a variety of ways, for example by a count of the number of visits to potential customers made by the manufacturer and the level and extent of contact between different management functions (in particular design engineering) over time. It can also be measured in terms of the number of joint programmes between manufacturer and customer when new technologies have been

required to solve specific customer requirements. This measure would, however, give a biased and unrealistic view of customer involvement.

However, in this study only one simple measure of customer involvement in product development was devised. This measure asked the machine tool manufacturers in the sample to indicate the extent to which they, as manufacturers, involved customers in three types of product development work:

1. The development of a completely new type of machine tool of relatively standard design (i.e. involvement in the product introduction process).

2. Continuous minor development of machine tools (small scale incremental engineering improvement or adaptation of new technology, for example CNC hardware).

3. The development of special purpose machine tools built to the customer's own specification.

The degree of customer involvement during the evolution of each of the above categories of product design was also measured. This was indicated by the response to a question asking respondents to indicate at which stages of the product design process customer involvement and interaction was greatest. With reference to category 1, three stages of product design and development work were used: (1) concept design, (2) design/development, (3) final product testing. For category 2, two stages of the design process were used (1) evaluating and modifying the design as it is being developed, (2) evaluating and modifying the final design. In addition to the two stages used for category 2, a further category entitled 'suggesting the original idea' was used for category 3.

Table 8.2 provides a measure of the extent to which manufacturers involve and interact with customers in the design and development process, for the

Table 8.2: Customer Involvement in Product Design and Development

| | Standard Design | Continuous Design/Development | Special Purpose |
|---|---|---|---|
| **Concept Design** | 2.9 | N/A | N/A |
| **Design/Development** | 1.4 | N/A | N/A |
| ***Product Testing** | 4.1 | N/A | N/A |
| **In suggesting the original idea** | N/A | 2.5 | 4.5 |
| **In evaluating & modifying the design as it is being developed** | N/A | 1.2 | 2.5 |
| **In evaluating and modifying the final design** | N/A | 1.4 | 1.5 |

*To be read: On average respondents indicated that they involve customers to a great extent during the product testing stages.
A Likert scale rating system of '5: continuously' to '1: not at all' was used.

purposes of enhancing both the reliability and overall technical quality of the machine tool product. The response to this question suggests that there is considerable variation in customer involvement and interaction between different types of product design and development work. In particular, further analysis indicates that there are significant variations in customer involvement during specific stages of the design and development cycle.

As would be expected, customer involvement is clearly greatest for the development of special purpose machine tools built to the customer's own specification. The degree of customer involvement was greatest during the early conceptual phases of the design process. Customers played a significant role in suggesting the original idea and specification of the product design. However, manufacturers were reluctant to involve customers in suggesting a technical solution to the manufacturing problem and modifying the product design as it developed.

Where new machine tool products and technological innovations were supplier specified and supplier driven, little or no customer involvement (excluding marketing/sales customer surveys) is observed during the conceptual phases. In effect the customer was playing a passive role in the development of new products. However, the customer has a much greater role to play during the development and final beta testing phases of the product introduction process. Feedback and assessments of the product's functional performance, technical incapability and design/manufacturing inadequacies are provided by the customer to the manufacturer.

As was expected, customers have little role to play in suggesting technical solutions or voicing opinions on overall functional performance in small scale incremental engineering improvements. Such types of engineering innovations are most likely to only be tested and proved through initial alpha testing and during preliminary service introduction.

### 8.3.3 The Extent of Use and Application of Beta Testing Methods

There is already some evidence in the literature, supported by the results of the longitudinal case study, that beta testing may frequently provide an effective means of enhancing the reliability of machine tool products. Through influencing minor design changes during the course of beta testing, this not only ensures that design and manufacturing deficiencies have been eliminated, but also leads to an enhancement of product reliability. It is also an effective means of measuring the initial field reliability of machine tools. The longitudinal case study has shown that a positive attitude on the part of Cincinnati Milacron is shown on the effective use and application of beta testing. There was some evidence in the case study of a greater degree of formality in the design and subsequent management of beta tests.

The overall objective of beta tests is to eliminate any functional performance problems and eradicate any minor design and manufacturing deficiencies which were not surfaced during alpha testing. In effect, this form of testing ensures that the optimum functional performance of the product is proved and an enhancement in the reliability of the product is achieved. As outlined above, it is clear that customer influences are greatest at the latter stages of the product development cycle, particularly during the product testing and initial market introduction phase. This provided an indication that the majority of the machine tool manufacturers in the sample adopted some form of beta testing method.

However, the results of this analysis show that only 41% of the sample of 17 machine tool manufacturers adopt some of form beta testing method for all new product designs. It may be that beta testing is not the main method used for customer involvement in the latter stages of the product development cycle. It may be that 'usability' testing is done by customers at the manufacturer's facility as an input to the design process. Like beta testing, usability testing is effective for design of the product because user testing at the manufacturer's site allows the manufacturer to control the operating conditions, directly

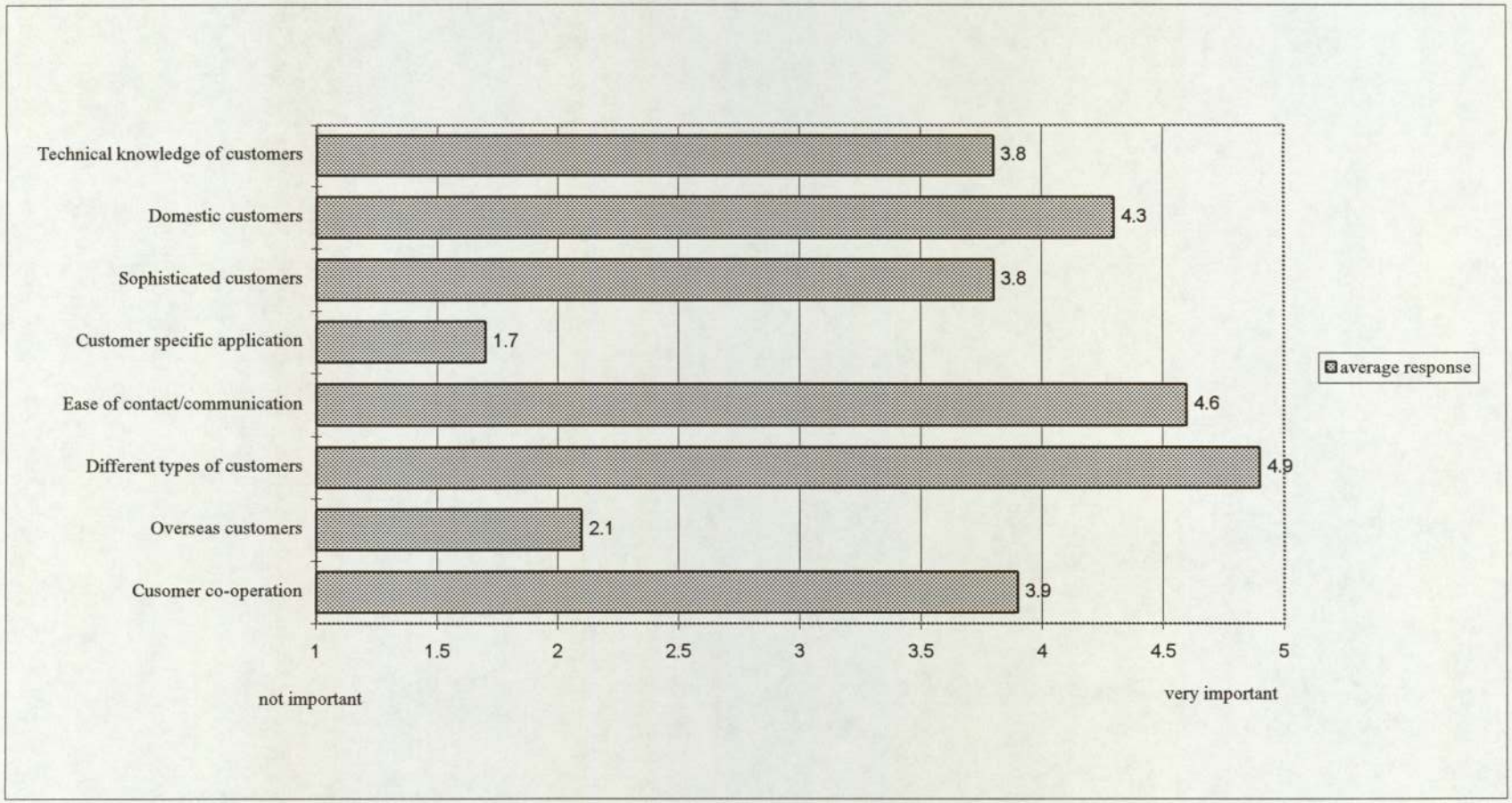
observe prototype use, and obtain real-time customer feedback. However, beta testing is a far greater method of assessing the operating performance and functionality of the product, since it augments these procedures by moving testing out to the users actual environments for a 'real-world' test.

The criteria used by manufacturers in evaluating the general suitability of customers for beta testing purposes are detailed in Figure 8.7 together with ratings of importance which respondents gave to each criterion. From this analysis it is clear that the most important factor was different types of customers. This is not surprising, since the potential user base of modern machine tool products is diverse and alpha testing could not adequately simulate use under the full variety of environmental and operating conditions which may be experienced in the field. If the majority of the selected beta test sites are homogeneous, then beta testing would not be effective in simulating all possible conditions of the newly designed product.

Ease of contact and communication was the next factor of importance, followed by domestic customers. This gives a broad indication of the need for effective and regular feedback to be achieved between a beta test site and the manufacturer. In order that the manufacturer can be in regular contact with each site, ease of contact and communication, together with the selection of domestic customers rather than overseas is a necessity if this is to be achieved.

Customer co-operation was again rated quite highly as a criteria for selection. Alongside this criteria, manufacturers also indicated the importance of the beta test customer to have a significant technical knowledge and experience in the application of machine tools and the need to select sophisticated customers who view beta testing very highly. Having beta test sites which have significant technical experience in the use of machine tools will enable a manufacturer to receive a more influential assessment and feedback of the basic functional of the product. In particular, comments were made by the individual respondents concerning the importance of establishing good relationships with beta test

Figure 8.7: Criteria Used by Manufacturers as the Basis for Selecting Beta Test Sites



sites. These ratings are similar to the guidelines given in the literature for selecting customer sites for beta testing:

1. Sites should collectively represent a broad portfolio of applications.
2. A site should show likelihood of delivering an influential assessment of the product's operating and functional performance.
3. A site should have previous positive experience as a beta.

The number of beta sites used by an individual manufacturer varied considerably and was dependent on the size and status of the company. The range of sample sizes commonly found in beta tests of machine tool products amounted to 2 - 12 sites. The significant variation in this figure is also dependent on the type of machine tool product being tested in the user environment. For example, a smaller number of beta sites would be selected for CNC drilling and sawing machines compared to CNC machining centres. This is because the user base of sawing and milling machines would be significantly less diverse than the user base of machining centres.

Similarly, the duration of the beta testing process varied significantly. A typical length of beta testing adopted by all the manufacturers in the sample could not be defined from the data received. Again, this was conditional on the type of machine tool product being tested. For complex, high technological content machine tools, the typical length of beta testing can be defined as being 6 - 10 months. Whereas for other less complicated products, the typical length can be defined as being 2 - 4 months. However, given the small size of the sample, no generalisations can be made on this particular issue.

### 8.3.4 Key Observations

The majority of the manufacturers view reliability as a critical attribute in the final stages of the machine tool buying process. However, this is not reflected in their reliability assurance improvement systems.

Customer involvement tends to be greatest for the development of special purpose machine tools. Similarly, for the development of standard machine tools, customer involvement is greatest during the alpha and beta testing phases.

According to the majority of machine tool manufacturers, beta testing is a useful tool for enhancing product reliability. The number of beta sites and the length of testing varies and is dependent on the type of machine tools.

### 8.4 Concurrent Engineering Evaluation: The Perceived Impacts to Product Reliability

Concurrent Engineering (CE), as reviewed in Part I of this thesis, is a philosophical method for attaining four key business objectives:

1. Reducing time to market.
2. Improving product quality and reliability.
3. Improving the product introduction process.
4. Lowering product design and development costs.

This is accomplished by integrating engineering, manufacturing and where relevant service operations to promote early and substantive interaction. Cross-functional integration and communication assure that issues of manufacturability and maintainability are considered in the earliest possible stage of the product development process. This enables design, manufacturing and service inadequacies to be identified early in the product introduction process. Thus, this eliminates the need for costly modifications downstream in the process. As highlighted in the review of the literature, the use of CE, therefore breaks up the sequential nature of the conventional serial approach to the design of products.

The objective of this inquiry is to assess whether the use of CE leads to any improvements in product reliability as prescribed in the literature, or does it merely provide the platform for the free-flow of information and interaction

between product design and manufacturing. Although much attention has been given on the beneficial aspects of CE, little empirical research has been conducted to validate the perceived benefits of CE from an industrial perspective.

### 8.4.1 Problem Areas Associated with the Development of New Products

Initially, the analysis of the literature provided the foundation for establishing key problem areas associated with the development of new products, which was supported by the researcher's experience of working in the case study firm, Cincinnati Milacron. Difficulties encountered during the product introduction process can be categorised into two major areas:

1. Integration of design, manufacturing and service during the product development process.
2. Reliability related problems downstream in the product introduction process.

Six features of the product introduction process had been cited as being difficulties associated with the integration of design, manufacturing and service functions early in the product introduction process (see Table 8.3). Two of the features addressed the degree of feedback between manufacturing and design. A further feature defined the degree of commitment between the two functions. The fifth feature cited was the difficulty associated with integrating design and manufacturing activities during new product introduction. Supplier involvement and integration was taken to be the fifth difficulty. This feature was considered to be a critical measure given that 95% of the constituent parts of a machine tool product are commercial. A further feature defined the degree of involvement and integration of service early in the design process.

As detailed in Table 8.3, a further six features defined as being difficulties related to reliability problems encountered during the product introduction process were identified. Four features addressed engineering changes (1) prior to production release, (2) post-production release, (3) during initial market

Table 8.3: Key Problem Areas Associated with the Serial Design Approach to New Product Introduction

| Design for Manufacture Interface | Reliability-related Interface |
|---|---|
| Design interface with manufacture and assembly | Engineering changes prior to production release |
| New product engineering feedback to production | Engineering changes post-production release |
| Production feedback to product engineering | Engineering changes during beta testing |
| Production commitment to product engineering | Engineering changes during initial warranty |
| Supplier involvement and integration early in the design process | Consideration of key reliability-related attributes early in the process |
| Service involvement and integration early in the design process | Reduction of design complexity and improved maintainability |

Key:

Production refers to manufacture and assembly

Engineering changes refer to changes carried out as a result of inherent reliability problems

introduction (i.e. beta testing phase) and (4) during initial warranty period. A fifth feature addressed whether CE had any effects to the consideration and appraisal of reliability-related attributes early in the design process. Similarly, the sixth feature was concerned with the degree of part reduction achieved through the deployment of the CE philosophy. Here, part reduction also included design complexity and machine maintainability.

The questionnaire focused on obtaining data which enabled an assessment of CE to be conducted from the point of view of the difficulties experienced by firms during the product introduction process. The difficulties defined in Table 8.3 were used in the questionnaire as the basis of obtaining the data. Respondents were initially queried on the extent of CE operationalisation within their company, the reasons for implementing CE and the extent to which reliability was considered in the CE process.

Based on a modified Likert-type scale, respondents were directed to indicate the 'problematic' nature of the 12 product introduction features, relative to each other. To assess the perceived benefits of CE, respondents were asked to indicate the degree to which the 12 features were improved as a result of adopting to CE principles and techniques. To determine whether any significant differences exist between a firm's use of CE and non-use (i.e. conventional serial engineering), respondents were asked to base their rating against the following two criterion:

1. Prior to implementing CE (i.e. sequential development of products).
2. After implementation of CE.

The Likert scale went from 1 for 'no problems' to 5 for 'significantly problematic.' In other words, a rating of 1 was taken to indicate that the area posed no significant problems, where as a score of 5 indicated that the feature was a key problem area.

### 8.4.2 Degree of CE Application

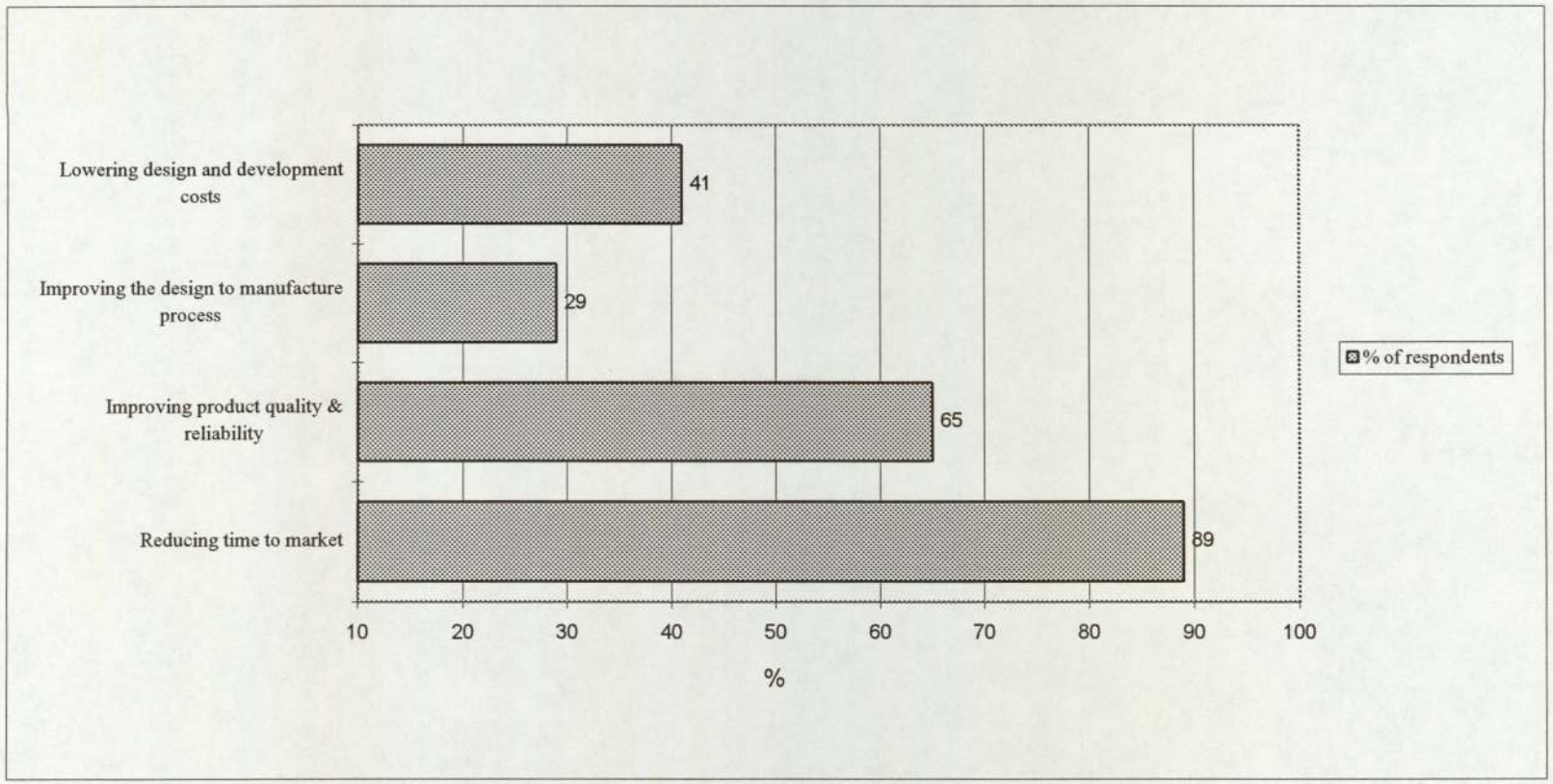
The desire to cut product development time, thereby shortening the time taken to market the product was the key driving factor for introducing CE among machine tool firms. Among the many suggestions given for implementing the basic concepts of CE, this factor was by far the most common reason given (see Figure 8.8). It is possible to conclude from this analysis that machine tool firms perceive CE as a mechanism for reducing time to market, rather than a combination of this factor, improved product reliability and reduction of design and development costs.

It is indicative that for many firms, competitive pressures and the urgency for accelerated product development were such that sequential design and development had become a bottleneck. CE was the only route to eliminating this bottleneck which caused delays in bringing the product into the market. Further to this, accelerated development was seen as being the main tangible benefit of CE. Similarly, reduction of cost and improved reliability was seen as being intangible benefits.

The degree of CE operationlisation within machine tool firms is also far from being complete. As detailed in Figure 8.9, of the seventeen machine tool firms, ten firms stated that CE was more than 50% operational. However, this was only in terms of design and production integration; a basic notion of CE. There was no evidence to suggest that machine tool firms were working towards full CE implementation in terms of (1) engineering process initiatives and (2) the application of formal methods of reliability appraisal. Given the relative size structure of machine tool firms compared to say the automotive firms, it is possible to conclude that only the basic foundation of CE is adopted (i.e. more closer integration between design and production).

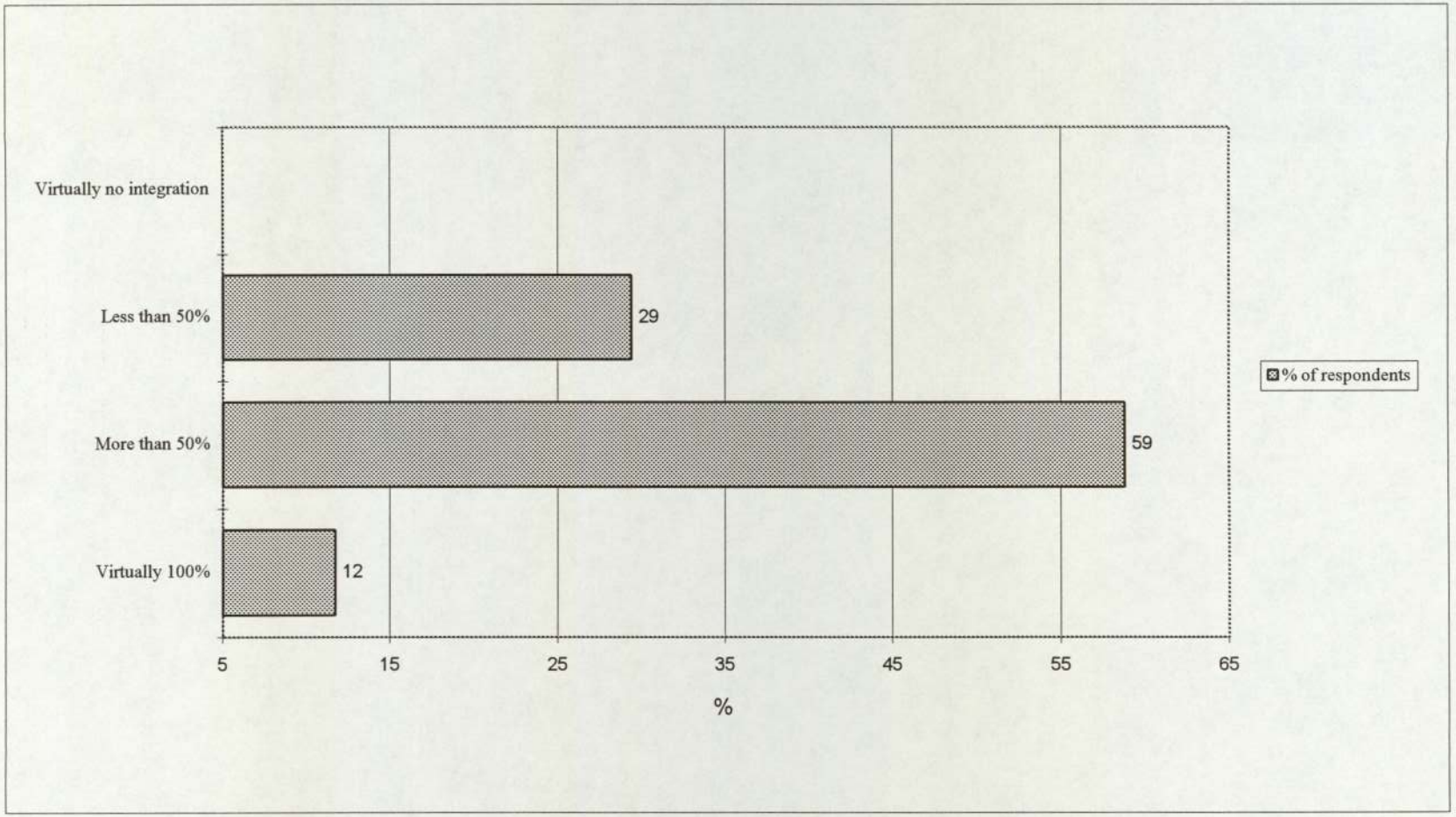
The level of reliability consideration within the new product introduction process was also evaluated to be low. Respondents were asked to indicate the degree of reliability appraisal using a Likert scale ranging from 1 for 'little consideration' to 5 for 'full consideration.' The mean of this rating was 2.5.

Figure 8.8: Common Reasons for Implementing Concurrent Engineering




Note: The sum total of the percentages in this figure exceeds 100 because the majority of manufacturers stated more than one reason

Figure 8.9: The Degree of CE Implementation



The measure of spread (variance) of the sampled data and standard deviation was relatively low. Values were calculated to be 0.5 and 0.7 respectively. This suggests that the majority of machine tool firms give little or no consideration to reliability issues within the CE process. There was no data to evaluate the way in which reliability was appraised during product design. However, as discussed in Chapter 7, reliability is most likely to be assessed on an informal basis. As concluded in Chapter 7, designer's are most likely to use their own experience and judgement in appraising reliability.

### 8.4.3 The Effects of CE on Product Reliability

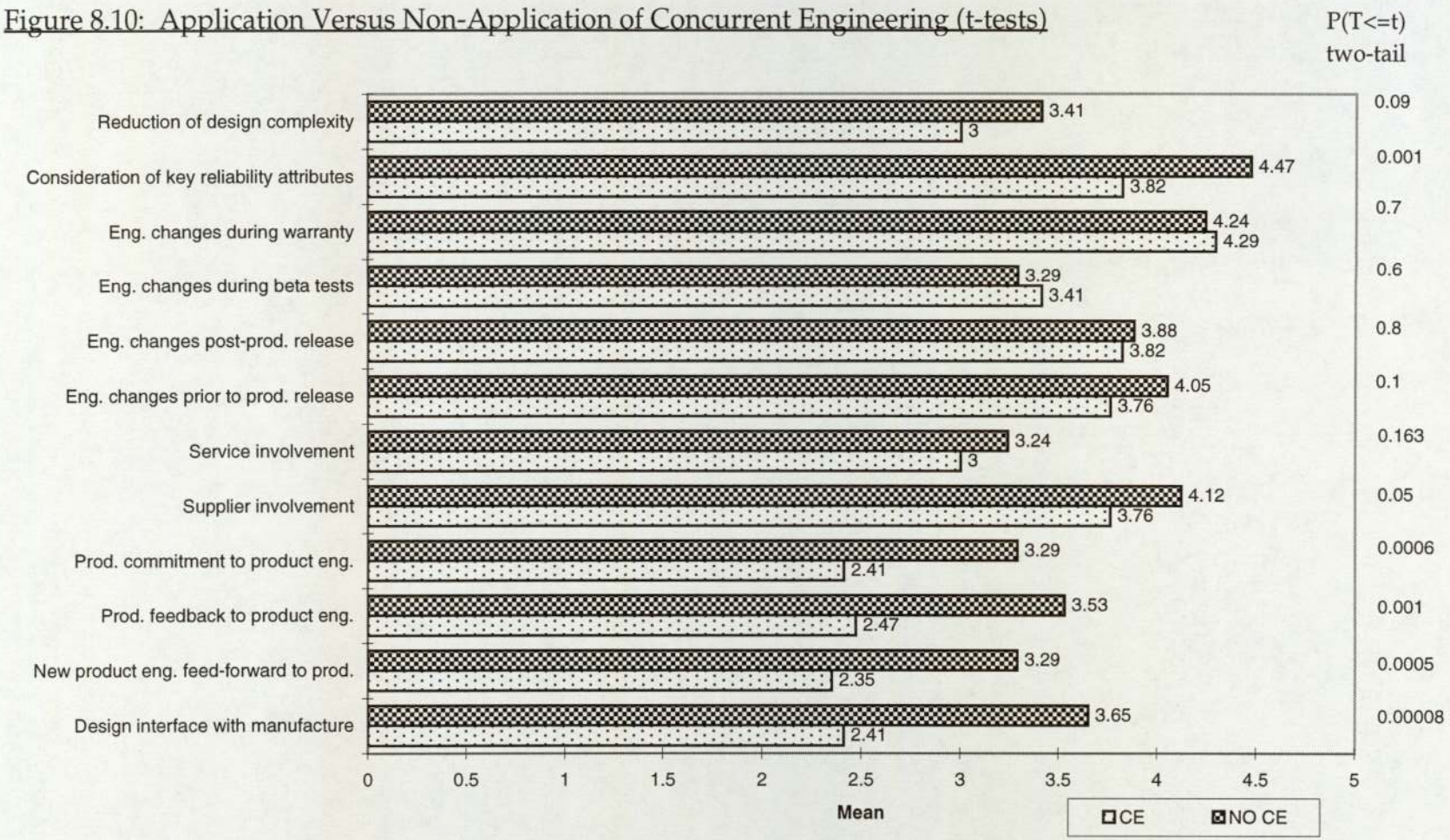
In order to assess whether any significant differences existed between a firm's use and non-use of CE, the questionnaire data was analysed using design of experiments. As defined in Table 8.3, the analysis was conducted with respect to problems experienced during the design and development process.

The first step in the analysis was to examine the significance of the survey results. Statistical significance tests were performed using the t-test procedure. This particular t-test did not assume that the variances of both populations from which the data sets are drawn are equal or unequal. As an expansion to the t-tests, one way analysis of variance (ANOVA) was used as the design of experiment (DoE) for comparative purposes. The dependent variables in this study was the 13 key features defined as being difficulties associated with the product development process (see Table 8.3). The two independent variables were 'use of CE' and 'non use of CE.' A 5% confidence level was used in this experiment.

Figure 8.10 summarises the results of the t-tests. Table 8.4 summarises the results of the ANOVA experiment. Full details of the t-tests and ANOVA experiment can be found in Appendix P.

Overall, the use of CE had the most positive effect on the integration of design and manufacturing functions (see Figure 8.10 and Table 8.4). Findings showed that CE was more effective than the serial engineering approach in areas such

Figure 8.10: Application Versus Non-Application of Concurrent Engineering (t-tests)




P(T<=t) = Significance Level - The lower the value the higher the significance

Table 8.4: Results of the ANOVA Experiment on the Effects of CE on Reliability

| Variable | Average Rating | | Variance | | Mean Square | F-Observed | P-Value |
|---|---|---|---|---|---|---|---|
| | CE | NO CE | CE | NO CE | | | |
| Design interface with manufacture and assembly | 2.412 | 3.647 | 0.382 | 0.993 | 12.971 | 18.866 | 0.000132 |
| New product engineering feedback to production | 2.353 | 3.294 | 0.243 | 1.096 | 7.529 | 11.253 | 0.002058 |
| Production feedback to product engineering | 2.471 | 3.529 | 0.390 | 1.515 | 9.529 | 10.008 | 0.003406 |
| Production commitment to product engineering | 2.412 | 3.294 | 0.382 | 1.096 | 6.618 | 8.955 | 0.005295 |
| Supplier involvement and integration early in the design process | 3.765 | 4.118 | 0.816 | 0.735 | 1.059 | 1.365 | 0.251316 |
| Service involvement and integration early in the design process | 3.000 | 3.235 | 0.375 | 0.816 | 0.471 | 0.790 | 0.380696 |

*F Critical = 4.149

**df* = 1 ( between groups) and 32 (within groups)

Table 8.4: Results of the ANOVA Experiment on the Effects of CE on Reliability

| Variable | Average Rating | | Variance | | Mean Square | F-Observed | P-Value |
|---|---|---|---|---|---|---|---|
| | CE | NO CE | CE | NO CE | | | |
| Engineering changes prior to production release | 3.765 | 4.059 | 0.441 | 0.684 | 0.735 | 1.307 | 0.261386 |
| Engineering changes post-production release | 3.824 | 3.882 | 1.154 | 0.360 | 0.029 | 0.039 | 0.845022 |
| Engineering changes during beta testing | 3.412 | 3.294 | 0.632 | 0.221 | 0.118 | 0.276 | 0.603047 |
| Engineering changes during initial warranty | 4.294 | 4.235 | 0.221 | 0.316 | 0.029 | 0.110 | 0.742771 |
| Consideration of key reliability-related attributes early in the process | 3.824 | 4.471 | 0.529 | 0.640 | 3.559 | 6.088 | 0.019146 |
| Reduction of design complexity and improved maintainability | 3.000 | 3.412 | 0.500 | 0.632 | 1.441 | 2.545 | 0.120442 |

*F Critical = 4.149

**df* = 1 ( between groups) and 32 (within groups)

early consideration of manufacturability issues, better communication of design information to production, feedback of manufacturing and assembly problems to design engineering and production commitment to product design. From this analysis it is clear that CE has a major influence on the appraisal of manufacturing and assembly issues up-front in the design process. Furthermore, the findings would suggest that one major benefit of adopting CE is its ability to effect change among the engineering functions. In particular, it seems that CE is more conducive to the streamlining of information flow between design and production.

Secondly, it appears from the findings that the application of CE did not have a major influence on the degree of service and supplier involvement during the design process. This may be due to the fact that the majority of machine tool companies perceive CE as a mechanism for integrating design and manufacturing activities only. In this context, little effort is placed on involving the service personnel early in the design process. As discussed in Chapter 7, the level of trust and commitment shown by manufacturers to their suppliers depends heavily upon the value the supplier's component adds to the machine tool product. This in turn affects the degree of supplier involvement in the design process.

One of the significant findings of this ANOVA experiment was that the application of CE did not have much of an effect in reducing reliability-related problems. The results suggest that the serial engineering approach is as effective in some aspects of this particular area. In some cases, the serial approach proved to be more effective in reducing reliability-related problems (see Figure 8.10 and Table 8.4). In other words CE was seen as having a negative impact in some aspects of this area. Particularly, it was evaluated that the adoption of CE did not have a major influence on the reduction of engineering changes during specific phases of the product introduction process ($t= -0.25$, $p= 0.8$ for post-production release, $t= 0.57$, $p= 0.6$ for the beta testing phase and $t= 0.44$, $p= 0.7$ for the initial warranty phase).

However, there is some evidence to suggest that CE does have a relative influence on the following aspects of reliability-related problems experienced during the product introduction process:

- Reducing the number of engineering changes prior to production release (t= -1.77, $p$= 0.1).
- Increasing the assurance and the extent to which reliability-related attributes were appraised during the early phases of the development process (t= -3.8, $p$= 0.001).
- Reducing the complexity of design and improving the overall maintainability of the product (t= -1.81, $p$= 0.09).

However, while it is tempting to conclude that the adoption of CE entails major reduction in engineering changes prior to production release, there was no overwhelming statistical support for this conclusion (see Table 8.4 and Appendix P). Similarly, the results of the ANOVA experiment also indicate that there is no overwhelming statistical evidence to suggest that CE leads to major reductions in design complexity and improved maintainability through early consideration of reliability-related attributes.

### 8.4.4 Key Observations

The desire to cut product development time was the main reason for manufacturers adopting to concurrent engineering principles and practices. The level of reliability appraisal within the CE process is significantly low.

The data reported confirms that many benefits exist as a result of adopting a CE approach. In particular, the flow of information between product design, process design and manufacturing were all areas of considerable improvements. However, there was considerable evidence from the ANOVA experiment that CE is not perceived to be effective in the area of reliability improvement. This is reflected by the fact that CE does not have any major influence on the reduction of engineering changes during the various stages of

the product introduction process (for example during the initial warranty period).

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 that many machine tool firms had only recently introduced CE to their organisation and therefore few had the opportunity to assess the benefits across a full product life cycle.

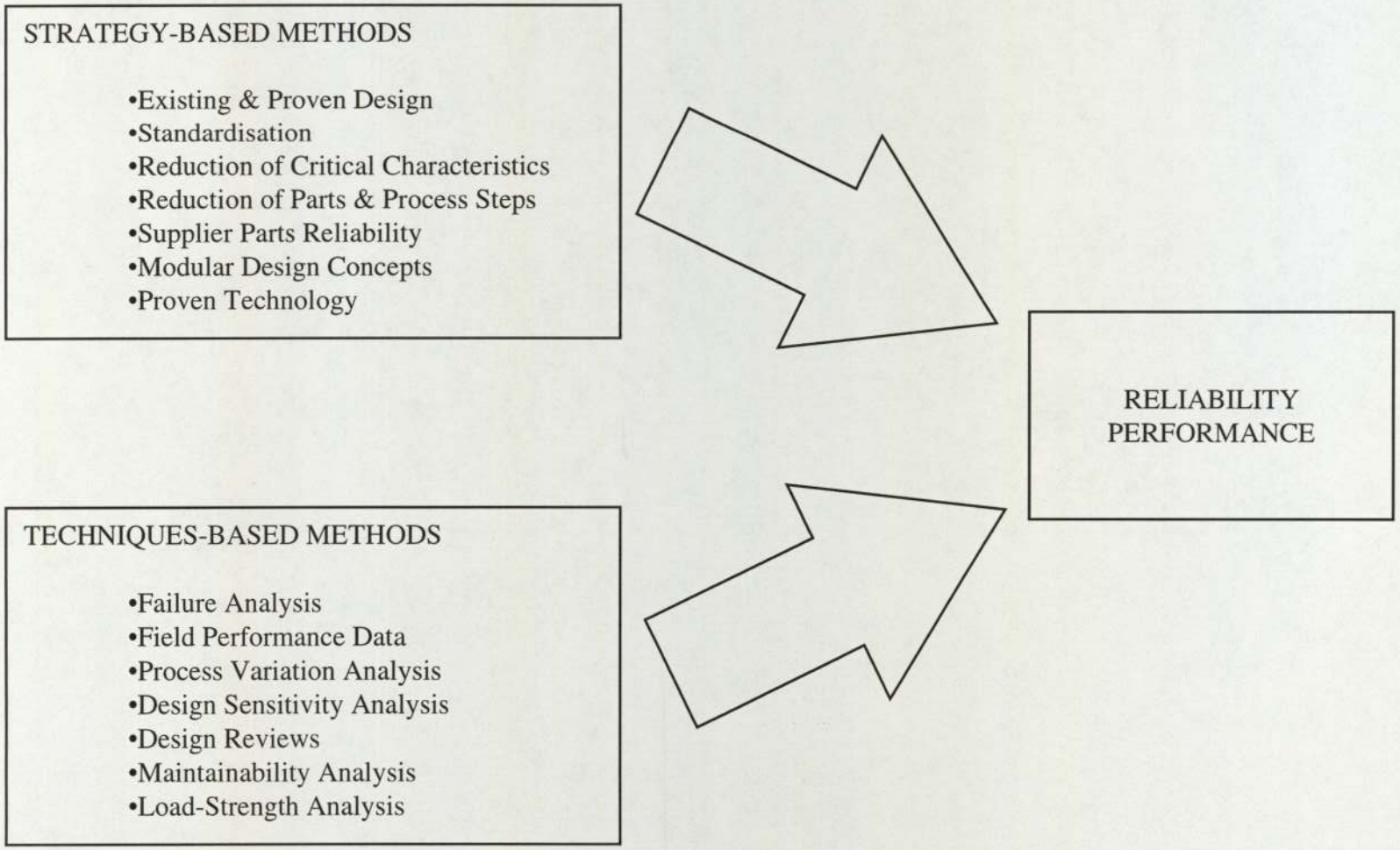
## 8.5 Techniques Used to Appraise and Improve the Reliability of Product Design

The hypothesis (H1) that manufacturers are more likely to use strategy-based methods for minimising reliability uncertainty, and are less likely to apply techniques for appraising reliability was tested. As discussed in Chapter 5, examples of strategy-based methods are modular design concepts, use of proven technology or the reliance on supplier part reliability. These methods ensure that the amount of reliability appraisal needed during the design of a product is minimised.

Techniques on the other hand is based on a detail analysis of the product design for the purposes of reducing engineering or reliability uncertainty. Results from the analysis is interpreted for the purposes of improving reliability. These types of methods do not rely upon the use of technological concepts to achieve reliability. Examples of technique-based methods are failure analysis, design sensitivity analysis or use of design reviews.

Figure 8.11 details a model of the methods that can be used to appraise and improve product reliability. In the next two sections, the differences between the techniques and strategy-based methods are elaborated.

Figure 8.11: A Model of Techniques and Strategy-Based Methods Affecting Reliability Performance



### 8.5.1 Strategies

There are numerous strategy-based methods that can be used to minimise the amount of reliability analysis and assessment needed during the evolution of a product design. For the purposes of this inquiry seven methods have been cited: (1) use of existing and proven design, (2) standardisation of parts and units, (3) reducing the number of critical characteristics of a product, (4) reducing the number of parts and process steps, (5) reliance on supplier parts reliability, (6) use of modular design concepts, (7) use of proven or advanced technology.

*1) Existing and Proven Design:* The re-use of design knowledge and experience and where feasible the use of proven design reduces the need to carry out various aspects of the reliability appraisal process. For example, because the design has already been functionally proven in the field:

- Little development testing will be required.
- Fewer reliability related problems will occur during the design process and initial field operation.
- Engineering uncertainty will be minimised.

Furthermore, the need for reliability assessment will also be minimised or eliminated. Similarly, design for manufacture considerations will be minimised since production methods have already been established.

*2) Standardisation of Parts and Sub-Assemblies:* The concept of standardisation of parts and assemblies across a range of product lines minimises the amount of reliability appraisal needed. As there will be fewer sub-assemblies with different design, assessing various aspects of reliability will be more effective and resourceful. Furthermore reducing the variety of parts reduces complexity of production and design organisation.

*3) Reduction of Critical Characteristics:* Reducing the number of design characteristics minimises the design being over-engineered. Furthermore, simplicity of design is also achieved.

*4) Reduction of Number of Parts and Process Steps:* The use of both these concepts reduces the complexity of assembly. This in turn reduces the probability of assembly defects being passed on to the customer.

*5) Supplier Parts Reliability:* The concept of using suppliers who have retrospectively proven the reliability of their product substantially reduces the need to assess the impacts of commercial parts on the overall reliability of the product. Furthermore, engineering uncertainty is reduced to some degree.

*6) Modular Design Concepts:* In addition to the advantages of cost reduction in development and realisation of economies of scale, the use of modular design concepts allows more product variants to be manufactured without the added reliability uncertainty. This design concept also improves overall product maintainability.

*7) Proven Technology:* Many companies now rely upon the use of advanced technology to improve the reliability and eliminate maintenance needs of a machine tool product. This is particular so in the field of control systems aspects of machine tool design.

### 8.5.2 Techniques

While strategy-based methods are used to assure reliability and reduce engineering uncertainty, technique-based methods on the other hand, provides the means for identifying this engineering uncertainty and reliability-related problems. The results of the analysis can then be interpreted to aid in design improvement. As with the selection of strategy-based methods, seven techniques which can be defined as being analytical have been selected: (1) failure analysis, (2) use of field performance data, (3) process variation analysis, (4) design sensitivity analysis, (5) design reviews, (6) maintainability analysis

and (7) load-strength analysis. A brief description of these techniques is given below:

*1) Failure Analysis:* The use of failure analysis to identify potential modes of failure and their causes provides the scope for modifying the design to eliminate some of the causes. It is expected that a subjective and qualitative approach will be adopted.

*2) Use of Field Performance Data:* Retrospective field failure data is a useful means of identifying reliability problems and addressing them in the design of new products.

*3) Process Variation Analysis:* The effects of random variation of manufacturing processes and environments are evaluated, to determine whether the design of the product and the production processes can be further optimised.

*4) Design Sensitivity Analysis:* This method defines the effect of variations in design on system and component performance. It compliments the design by showing which design characteristics should be modified to most effectively improve performance, solve technical problems and improve reliability. In some cases environmental differences in the operation of the machine tool will also be evaluated through design sensitivity analysis.

*5) Design Reviews:* The purpose of a design review is to use techniques such as failure analysis, design sensitivity analysis or maintainability analysis for the purposes of optimising the design of the product. Design reviews are normally carried out on a team basis and are carried out on a phased basis.

*6) Maintainability Analysis:* Analysis of the ability of maintenance personnel to remove and replace parts of a mechanical system with ease and minimum of downtime.

*7) Load-Strength Analysis:* Analysis of dynamic performance and loads and stresses that act on components of mechanical and electrical systems of machine tool products.

### 8.5.3 A Comparison of the Effects of Techniques-based Methods and Strategy-based Methods on Product Reliability

The first step in the analysis was to examine the inter-correlations between the methods. The dependent variable in this study was 'reliability performance.' The independent or controlled variables were the 14 techniques and strategy-based methods. Table 8.5 details the correlation matrix and inter-correlations.

The majority of the strategy-based methods were strongly correlated to reliability performance. First, the degree of modular design concepts and the use of proven technology were seen to be effective in improving reliability performance ($r$ =0.65 and $r$ =0.64 respectively). Furthermore, both these methods were highly correlated ($r$ =0.41). Thus, it appears in our sample that those firms that were most likely to use modular design concepts also relied to some degree on the application of technology. Similarly, the application of design standardisation was highly correlated to reliability performance and modular design concepts ($r$ =0.64 and $r$ =0.41 respectively). It appears that manufacturers perceive design standardisation as a means of reducing reliability uncertainty and degree of reliability appraisal needed.

Compared to the above three strategy-based methods, the concepts of using existing design and reducing the number of unnecessary design characteristics were less well received by manufacturers as a means of improving reliability performance of their machine tool products ($r$ = 0.47 and $r$ =0.4 respectively). As discussed above, the use of existing design knowledge significantly reduces the amount of reliability appraisal required, as the design has already been proved in the field. However, due to the rapid advancement of mechanical, electrical and control systems technology, it is not always feasible to incorporate existing design into new products.

The reliance on the product quality and reliability of a supplier did not show a strong relationship with reliability performance improvement ($r$ = 0.21). Furthermore, manufacturers did not perceive reducing the number of parts and

Table 8.5: Correlation Analysis of the Effects of Techniques and Strategy-Based Methods on Reliability Performance

| | *Existing Design* | *Standardisation* | *Critical Characteristics* | *Parts/Process Steps* | *Supplier Reliability* | *Modular Design* | *Proven Technology* | *Failure Analysis* | *Maintainability Analysis* | *Field Performance Data* | *Process Variation* | *Design Sensitivity Analysis* | *Design Reviews* | *Load_Strength Analysis* | *Reliability Performance* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Existing Design | 1.000 | | | | | | | | | | | | | | |
| Standardisation | 0.389 | 1.000 | | | | | | | | | | | | | |
| Critical Characteristics | 0.431 | 0.481 | 1.000 | | | | | | | | | | | | |
| Parts/Process Steps | -0.419 | -0.010 | -0.074 | 1.000 | | | | | | | | | | | |
| Supplier Reliability | -0.283 | 0.161 | -0.321 | 0.378 | 1.000 | | | | | | | | | | |
| Modular Design | -0.098 | 0.410 | -0.048 | 0.061 | 0.351 | 1.000 | | | | | | | | | |
| Proven Technology | 0.389 | 1.000 | 0.481 | -0.010 | 0.161 | 0.410 | 1.000 | | | | | | | | |
| Failure Analysis | -0.369 | -0.052 | -0.159 | 0.062 | 0.249 | 0.106 | -0.052 | 1.000 | | | | | | | |
| Maintainability Analysis | -0.181 | -0.385 | 0.127 | -0.289 | -0.403 | -0.090 | -0.385 | 0.324 | 1.000 | | | | | | |
| Field Performance Data | 0.275 | 0.251 | 0.397 | -0.009 | -0.417 | -0.012 | 0.251 | -0.123 | -0.093 | 1.000 | | | | | |
| Process Variation | -0.605 | -0.091 | -0.065 | 0.456 | 0.236 | -0.040 | -0.091 | 0.089 | -0.008 | -0.222 | 1.000 | | | | |
| Design Sensitivity Analysis | 0.086 | -0.268 | 0.031 | 0.056 | -0.494 | -0.375 | -0.268 | -0.503 | 0.072 | 0.597 | 0.010 | 1.000 | | | |
| Design Reviews | 0.213 | 0.306 | 0.248 | 0.028 | 0.149 | 0.124 | 0.306 | -0.205 | -0.314 | 0.450 | 0.245 | 0.159 | 1.000 | | |
| Load_Strength Analysis | 0.459 | 0.296 | 0.193 | -0.043 | -0.059 | 0.120 | 0.296 | 0.159 | -0.129 | 0.546 | -0.328 | 0.002 | 0.562 | 1.000 | |
| Reliability Performance | 0.471 | 0.636 | 0.405 | -0.042 | 0.209 | 0.650 | 0.636 | 0.026 | -0.057 | 0.357 | -0.330 | -0.141 | 0.436 | 0.537 | 1.000 |

Significance Level = 5%

process steps as a means of improving reliability ($r$ = -0.04). However, comments were made that products with fewer parts and process steps typically had fewer assembly problems.

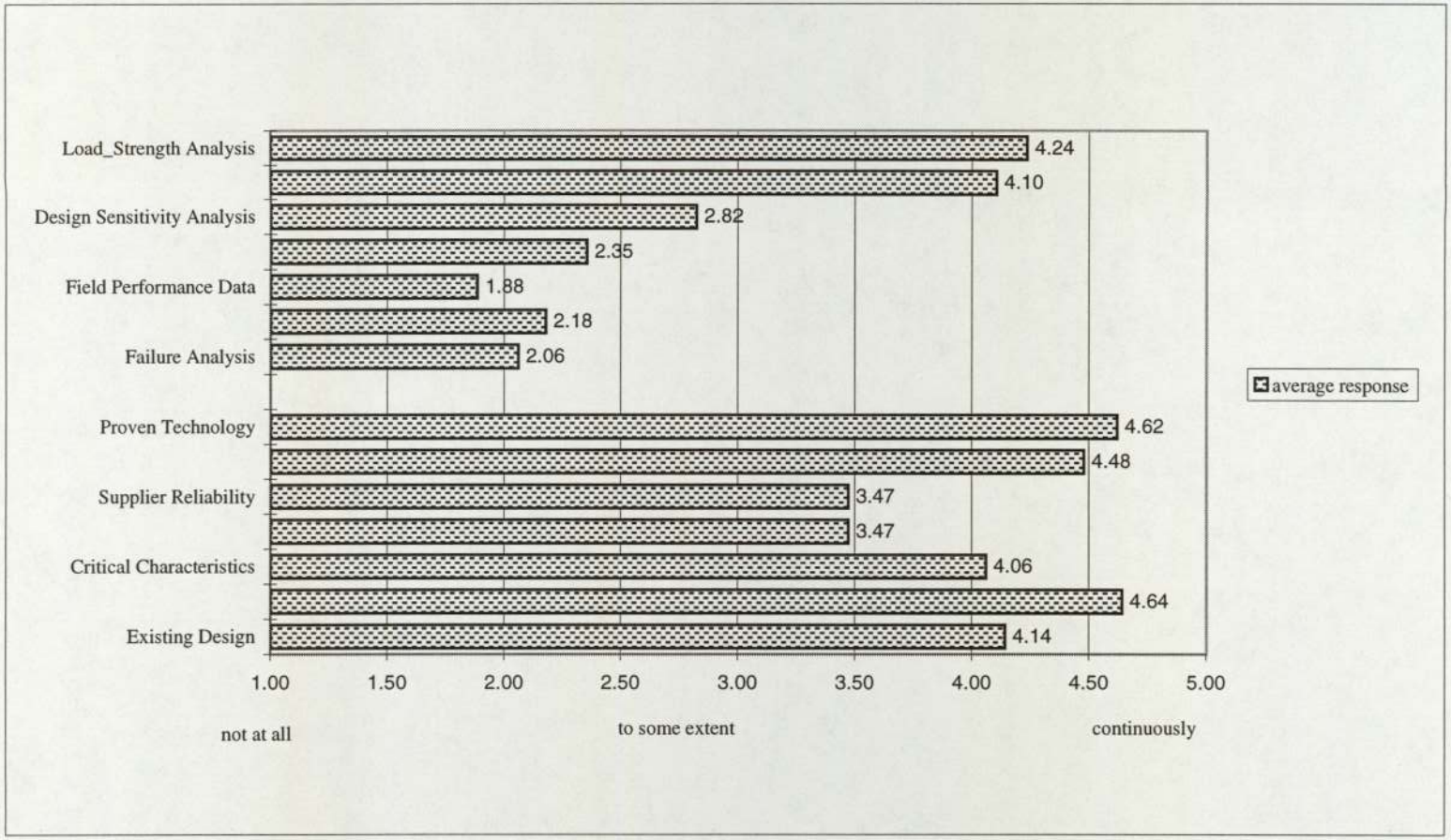
Essentially, techniques-based methods had the least significant relationship with reliability performance. Only design reviews and load-strength analysis was observed to have a strong correlation ($r$ = 0.44 and $r$ = 0.54 respectively). It was most likely that design reviews would provide the basis for conducting activities such as design sensitivity and failure analysis. Similarly, manufacturers perceived the use of field performance data as a means of improving reliability ($r$ =0.36). Analysing field failure data can provide insights into possible means of design improvement of existing and future designs.

Failure and maintainability analysis did not have much influence in reliability improvement ($r$ = 0.03 and $r$ = -0.06 respectively). According to the correlation analysis conducted, reducing process variation and the use of design sensitivity analysis was perceived to have a negative impact on reliability performance ($r$= -0.33 and $r$ = -0.14). This is most likely reflected by the low usage of these methods compared to design reviews or load-strength analysis.

Finally, compared to the application of techniques-based methods, a high usage of strategy based methods was observed (see Figure 8.12). This is particularly reflected by the occurrence of some negative correlations (see Table 8.5) for the techniques-based methods. For example, failure analysis and maintainability analysis were negatively correlated to the use of existing and standardisation of design ($r$ = -0.37 and $r$ = -0.38 respectively). According to the correlation matrix, manufacturers also heavily depend on strategy-based methods for improving reliability performance, rather than the use of techniques.

The lack of significance of techniques-based techniques is surprising to the extent that numerous literary material have highlighted the value of these techniques in the area of reliability achievement and design improvement. However, few of these literary material have addressed either the limitations or

Figure 8.12: Application of Strategy-Based Methods Versus Techniques-Based Methods



contradictory effects these techniques potentially have on each other and organisational issues.

A fundamental explanation why manufacturers perceive strategy-based methods as a means of improving reliability performance rather than techniques-based methods is most likely due to the high usage of the former methods among machine tool firms (see Figure 8.12). Therefore, as machine tool firms have the greatest experience of strategy-based methods, they are more likely to place greater value to them. However, efficiently achieving reliability requires co-ordination of a network of techniques and strategy-based methods. Addressing a random subset of these methods, instead of addressing the entire set of methods that are applicable within an organisation leads to little or no improvement in product reliability.

Another potential explanation for the lack of a significant relationship between many of the technqiues-based methods and reliability performance is that machine tool firms must learn how best to implement the former. These techniques can be difficult to use successfully as they require changes in organisational structures and engineering processes. For example, failure analysis and design sensitivity analysis require major changes in the product introduction process. Similarly, these techniques involve conducting analytical investigations from a cross-functional perspective. New methods of design and reliability analysis for reducing reliability uncertainty 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. Furthermore, adaptation to new ways of analysing designs and reducing reliability uncertainty often takes time as members experiment with their new roles, responsibilities and authority.

The next step in the analysis was to conduct a multiple regression analysis using reliability performance as the dependent variable. This analysis was necessary to substantiate the correlation analysis. The overall hypothesis was tested using a backward regression technique and confidence level of 95%. The results which were highly significant account for 66% of the variance associated

with reliability performance. Appendix Q details the full results of this multiple regression analysis. This shows that 4 of the strategy-based methods were significantly related to reliability performance. Less surprisingly, only two of the techniques-based methods were related to reliability performance. Table 8.6 details the reliability performance regression model, relative to the usage of techniques. This model substantiates the results and conclusions obtained from the correlation analysis.

### 8.5.4 Key Observations

According to the analysis of survey data, strategy-based methods appear to have the greatest impact on product reliability performance. Reliability uncertainties and the need for reliability appraisal is greatly reduced by the use of modular design concepts, advanced technology and the standardisation of design. This high significance is reflected by the high usage of these methods.

Techniques-based methods, although a significant factor, were less received by machine tool manufacturers as a means of improving reliability performance. Although design reviews, load-strength analysis and the use of failure data was perceived to have some impact on reliability performance, on an overall basis, analytical-based methods were negatively correlated to reliability performance. This is probably a reflection of the low usage of these methods compared to strategy-based methods.

## 8.6 Vendor Evaluation Criteria and Perceived Business Performance

To assess the perceived benefits of vendor evaluation criteria to business performance, respondents were queried about various criteria used to select vendors. The questions were developed using two stages. Based on a review of the literature, over 60 criteria relating to vendor evaluation and 15 factors relating to business performance were identified. An initial draft of the questionnaire was reviewed by operational managers from Cincinnati Milacron. Where possible comments were received from a small sample of CM's first tier suppliers. Furthermore, informal discussion were also held with

Table 8.6: Reliability Performance Regression Model

| Technique (Independent Variable) | Coefficients | Standard Error | t Stat |
|---|---|---|---|
| Modular Design Concepts | 0.557 | 0.162 | 3.427 |
| Proven Technology | 0.348 | 2.966 | -0.117 |
| Standardisation of Parts and Sub-Assemblies | 0.693 | 3.305 | 0.210 |
| Exsiting and Proven Design | 0.312 | 0.208 | 1.500 |
| Design Reviews | 0.445 | 0.400 | 1.113 |
| Load-Strength Analysis | 0.271 | 0.856 | -0.316 |



REGRESSION TABLE

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.988356 |
| R Square | 0.976847 |
| Adjusted R Square | 0.814777 |

ANOVA TABLE

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 14 | 2.439 | 0.174 | 6.027 | 0.151 |
| Residual | 2 | 0.058 | 0.029 | | |
| Total | 16 | 2.497 | | | |

managers from other machine tool manufacturers. This was conducted through attending trade shows and through the help of the MTTA and AMTRI. Each managers were asked to comment about these factors and rank them in terms of their importance. Their suggestions were incorporated into a revised questionnaire which was then reviewed by the same managers. This quasi-Delphi method was used until 19 vendor evaluation criteria and 11 factors relating to business performance was identified. After completion of this pilot study, a revised questionnaire containing eight vendor evaluation criteria and three basic business performance measures were used.

The eight criteria in the survey can be categorised as representing common views of Japanese vendor evaluation criteria such as "product reliability" and views of Western firms such as "price" [e.g. Deming, 1982]. Table 8.7 shows the list of the criteria used. Of the eight criteria, six dealt with the various aspects of the supplier's ability to design, manufacture and ship parts with high reliability (see Table 8.7). These criteria were defined as supplier's reliability. The remaining two criteria used in the survey were price and on-time delivery. These were treated as single item indicators. The analysis, then, was performed based on three factors: two single item variables (price and on-time delivery) and one multi-item variable (supplier's reliability). Using a five point Likert scale ranging from "not important at all" to "extremely important," respondents were asked to rate the importance of each criteria as a means of selecting and assessing vendors.

To evaluate the perceived benefits of vendor evaluation criteria the respondents were asked to indicate the degree to which three basic business performance indicators were improved as a result of using vendor evaluation criteria. These were (1) Productivity, (2) Costs and (3) Market Share. These indicators were defined as Business Performance. A five point Likert scale ranging from "not improved at all" to " extremely improved" was used.

The hypothesis (H3) that machine tool manufacturers were more likely to emphasise price and on-time delivery than product reliability as a criterion for

Table 8.7: Vendor Evaluation Criteria

| **Criteria for Supplier's Reliability** | **Single item Criteria** |
|---|---|
| Product quality | Price |
| Field reliability performance of vendor parts | On-time delivery |
| Technical design capability | |
| Reliability management system | |
| Functional performance | |
| Technological Progress | |

evaluating vendors was tested by eight one-way analysis of variance (ANOVA). Price, on-time delivery and the six supplier's reliability measures were used as the variables for the analysis.

Eight sets of multiple regressions were used to test the perceived link between organisation performance and vendor evaluation criteria (H4). One set of hierarchical multiple regression analysis was used for each vendor evaluation criterion. Price (Y1), on-time delivery (Y2) and the six supplier's reliability (Y3abcdef) measures were the dependent variables. The business performances measures, market share (X1), productivity (X2) and costs (X3) were defined as being the independent variables. As a result, the following equations were estimated:

$$Y1 = m1X1 + m2X2 + m3X3 + C$$

$$Y2 = m1X1 + m2X2 + m3X3 + C$$

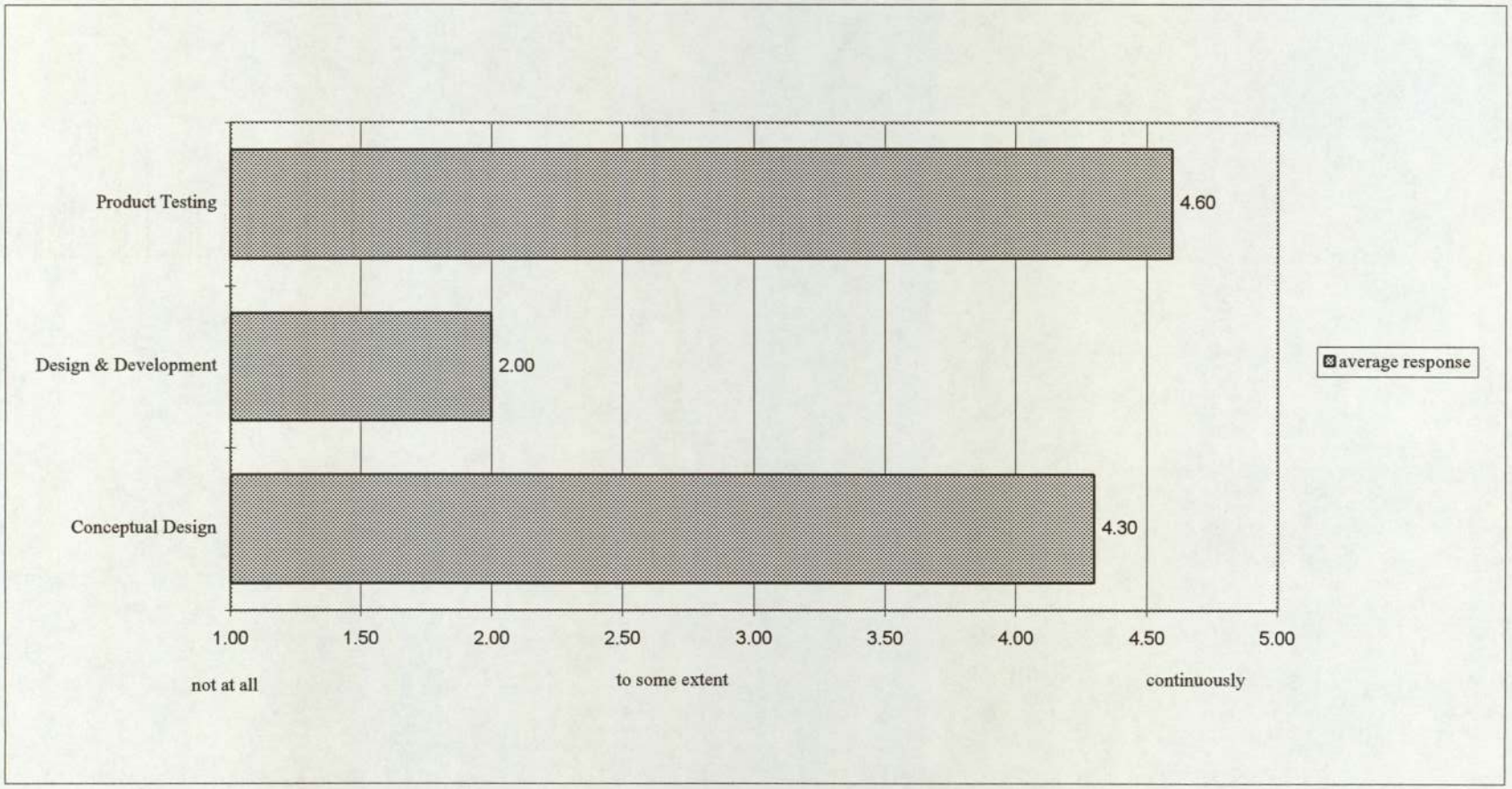
$$Y3abcedf = m1X1 + m2X2 + m3X3 + C$$

Analyses of these multiple regressions indicated the degree to which each dependent variable (vendor evaluation criterion) was determined by the perceived business performance link. Using significant tests (t test) a comparison of the performance slopes for each of the vendor evaluation criteria were conducted. This analysis showed whether any significant differences exist when performance slopes of each dependent variable are compared.

### 8.6.1 Extent of Supplier Involvement

As reviewed in Chapter 7, the level of supplier involvement and integration during the design process depends heavily upon the value the supplier's component adds to the machine tool product. This in turn affects the type of relationship and involvement in the design process. Figure 8.13 details the level of supplier involvement during the design process. As can be seen from Figure 8.13, the degree of supplier involvement is greatest during the concept design and product testing phase of the design process. It is most likely that

Figure 8.13: Degree of Supplier Involvement During the Product Introduction Process



potential suppliers intensify their involvement during the conceptual stages to provide a technical solution to a specified design specification. Similarly, suppliers are more likely to interact with design and development engineers to iron out any performance problems which may have been the cause of vendor supplied parts. In this perspective, suppliers act as a supportive role on the latter stages of the development cycle.

The results of the survey data suggests that many machine tool firms are not able acquire reliability data for vendor supplied parts. This is primarily because the majority of machine tool equipment suppliers do not hold such information. Only a relatively few suppliers hold reliability-related data and these tend to be electrical, electronic and control equipment suppliers (see Figure 8.14). Where a manufacturer makes the effort to collect reliability data for design analysis purposes, only data on critical machine tool parts will be acquired.

### 8.6.2 The Degree of Reliability Appraisal During the Vendor Selection Process

The results of the eight sets of ANOVA experiments indicated some profound significance in the criteria used by manufacturers in the selection and evaluation of suppliers. Table 8.8 details the results of the ANOVA experiment between variables dealing with supplier's reliability and price. Similarly, Table 8.9 details the results of the experiment between on-time delivery and variables dealing with supplier's reliability. Full details of the ANOVA experiment can be found in Appendix R.

As detailed in Table 8.8 and Table 8.9, manufacturers are more likely to emphasise price and on-time delivery when assessing the suitability of a supplier. In this respect, manufacturers were less likely to emphasise reliability aspects of the vendor supplied parts. The findings of the study contradicted some of the prevailing views and perceptions often expressed in the quality and reliability management literature. In addition there was considerable evidence from the ANOVA experiment (see Table 8.8) that manufacturers are

Table 8.8: Summary of ANOVA Experiment Between Supplier's Reliability and Price

| Variable | Average Rating | Variance | Mean Square | F-Observed | P-Value |
|---|---|---|---|---|---|
| Product Quality | 2.294 | 0.846 | 42.471 | 76.503 | 5.39E-10 |
| Field Reliability Performance | 2.471 | 0.515 | 36.029 | 92.453 | 5.87E-11 |
| Technical Design Capability | 2.941 | 0.559 | 21.441 | 52.071 | 3.39E-08 |
| Reliability Management | 1.824 | 0.404 | 62.235 | 186.022 | 6.99E-15 |
| Functional Performance | 3.588 | 0.507 | 7.529 | 19.505 | 1.07E-04 |
| Technological Progress | 4.059 | 0.559 | 1.882 | 4.571 | 4.02E-02 |
| On-time Delivery | 4.176 | 0.529 | 1.059 | 2.667 | 1.12E-01 |

*F Critical = 4.149
**df* = 1 ( between groups) and 32 (within groups)

more likely to emphasise price as opposed to product quality, field performance, technical design capability, on-time delivery, functional performance and technology progress of vendor supplied parts. Although on-time delivery was more prevalent in the supplier selection process, there was little statistical difference observed between this variable and the six variables dealing with the supplier's ability to ship high reliability parts (see Table 8.9).

However, although price and on-time delivery are the highest weighted vendor evaluation criteria, this does not necessarily indicate that the reliability aspects of a vendor supplied part are completely ignored. As Table 8.8 and Table 8.9 indicates, manufacturers also appreciate the need to assess aspects dealing with supplier's reliability. In particular, manufacturers emphasise technical design capability, functional performance and technological progress of a supplier to some varying degrees of importance.

Why price and on-time delivery are more important to machine tool manufacturers is a matter of conjecture. A likely explanation has to do with managerial philosophy. For example, Deming [1982] and Juran [1981] state that a particular quality practice is to establish acceptable quality levels (AQL). Therefore, in the context of this thesis, as long as a supplier's reliability meets these levels then this criterion is fulfilled. Assuming that suppliers are meeting the AQL then supplier reliability would not be a major criterion. This quality practice therefore is most likely to be adopted by machine tool manufacturers which leads them to emphasise price and on-time delivery more frequently.

However, as highlighted in the quality and reliability circles [e.g. Deming 1982], supplier reliability is always an important issue and should remain a key criterion for any firm striving to improve product reliability. As 40 per cent of all quality problems are caused by vendors [Leonard, 1983], it is clear that emphasising and demanding high reliability parts from suppliers can play a major role in improving the reliability of machine tool products.

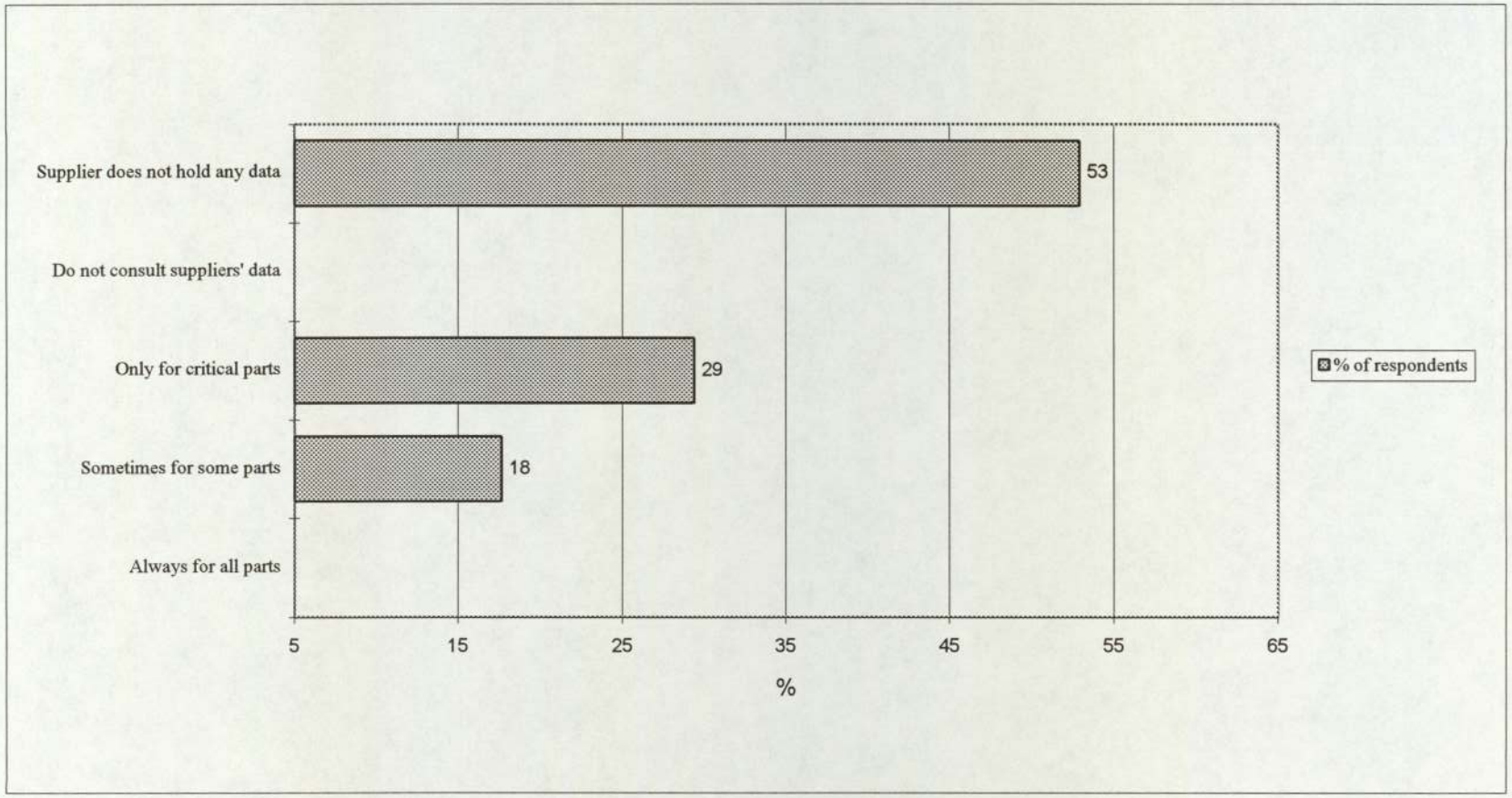
Table 8.9: Summary of ANOVA Experiment Between Supplier's Reliability and On-time Delivery

| Variable | Average Rating | Variance | Mean Square | F-Observed | P-Value |
|---|---|---|---|---|---|
| Product Quality | 2.294 | 0.846 | 30.118 | 43.807 | 1.83E-07 |
| Field Reliability Performance | 2.471 | 0.515 | 24.735 | 47.380 | 8.65E-08 |
| Technical Design Capability | 2.941 | 0.559 | 12.971 | 23.838 | 2.80E-05 |
| Reliability Management | 1.824 | 0.404 | 47.059 | 100.787 | 2.06E-11 |
| Functional Performance | 3.588 | 0.507 | 2.941 | 5.674 | 2.33E-02 |
| Technological Progress | 4.059 | 0.559 | 1.882 | 4.571 | 4.02E-02 |
| Price | 4.529 | 0.265 | 1.059 | 2.667 | 1.12E-01 |

*F Critical = 4.149

**df* = 1 ( between groups) and 32 (within groups)

Figure 8.14: Use of Supplier's Reliability Data



### 8.6.3 The Link Between Vendor Evaluation Criteria and Perceived Business Performance

The second hypothesis dealing with the vendor selection process was concerned with measuring the link between vendor evaluation criteria and perceived business performance. Table 8.10 details the results of the eight sets of multiple regression analysis. Full results of the multiple regression analysis can be found in Appendix R.

Generally, manufacturers perceive a significant strong link between vendor evaluation criteria and general business performance. In particular manufacturers perceive a strong link between productivity and costs and their established vendor evaluation criteria. However, there was little significance between market share of a machine tool manufacturer and the established vendor evaluation criteria.

When analysing the link between individual vendor evaluation criterion and perceived business performance, there was pronounced differences between each of the variables. As expected, price was viewed as having a significant positive impact on perceived business performance. This was followed by on-time delivery. Some of the variables dealing with supplier's reliability (for example, product quality and technical design capability) were viewed by manufacturers as having some positive impacts on business performance. However, on an overall scale, manufacturers viewed supplier's reliability as having little or no impact on either the productivity, costs or market share of the business organisation.

The results of the tests suggest that machine tool manufacturers would seek to improve business performance through the selection vendors with the lowest price. Secondary to this, manufacturers would emphasise on-time delivery as a means of improving business performance measures. This will show some 'short term' business performance improvements. The fact remains, however, that vendor price is not a significant factor for improving business performance on a long term horizon. Actively seeking to attract low-cost vendors with low

Table 8.10: Summary of Multiple Regression Analysis on Vendor Evaluation Criteria and Perceived Business Performance

| Vendor Evaluation Criteria | Correlation Coefficient | Coefficient of Determination | Standard Error | t Stat | F Stat |
|---|---|---|---|---|---|
| Product quality | 0.421 | 0.177 | 0.925 | 1.458 | 0.932 |
| Field reliability performance of vendor parts | 0.480 | 0.231 | 0.698 | 1.003 | 1.300 |
| Technical design capability | 0.434 | 0.189 | 0.747 | 2.401 | 1.008 |
| Reliability management system | 0.298 | 0.089 | 0.673 | 3.408 | 0.424 |
| Functional performance | 0.502 | 0.252 | 0.684 | 2.549 | 1.457 |
| Technological Progress | 0.402 | 0.161 | 0.759 | 0.613 | 0.834 |
| Price | 0.719 | 0.517 | 0.397 | -0.709 | 4.633 |
| On-time delivery | 0.493 | 0.243 | 0.702 | 0.368 | 1.391 |

*t-critical = 3.411
*F-critical = 2.353

levels of reliability will increase warranty and related costs, increase production and design problems on the long term. Similarly, support costs such as spares inventory overheads will also increase. This will be reflected on the long -term performance of the business organisation. Manufacturers should emphasise the long term impacts of vendor supplied parts, like overall 'life cycle costs.' This can only be done through addressing aspects associated with the vendors ability to design, manufacture and ship parts with high reliability.

### 8.6.4 Key Observations

In this particular study, an examination of the various vendor evaluation criteria viewed as important by machine tool manufacturers was conducted. The initial analysis of vendor evaluation criterion grouped them into three major factors (variables) of price, on-time delivery and supplier's reliability. Six variables dealt with the suppliers ability to design and manufacture parts with optimum reliability.

The results of this study demonstrated that manufacturers were more likely to emphasise price and on-time delivery in their established vendor evaluation, rather than supplier's reliability. However, variables dealing with supplier's reliability were viewed with varying degrees of importance. For example, technical design capability, functional performance and technological progress were rated more highly than field performance, vendor's reliability management and product quality.

The findings concerning the second hypothesis suggest that all machine tool firms perceive a link between vendor evaluation criteria and general business performance. In addition, it seems that manufacturers perceive a strong link between price and general business performance. In particular, tests indicated strong links with productivity and costs. Although manufacturers perceive some significant link between supplier's reliability and general business performance, this was not as strong as the link with price.

## 8.7 Summary

This chapter has evaluated key aspects of the product design process which has a bearing on reliability appraisal and improvement. It sought to evaluate how machine tool manufacturers achieve reliability throughout the design cycle. In this context, the following key design aspects of the overall reliability management process were discussed in varying degrees of depth and detail:

- The overall reliability assurance system.
- The extent to which reliability issues are assessed during the design process.
- The use and perceived effectiveness of concurrent engineering.
- The type of methods used to appraise and improve reliability during the design process.
- Vendor evaluation criteria and perceived business performance.

Key observations and conclusions were concisely discussed at each sections of this chapter. The next chapter soughts to evaluate the degree to which formal reliability management techniques are applied during the design and manufacture process.

# 9. Application of Reliability Management Techniques in UK Machine Tool Industry

## 9.1 Introduction

In this chapter emphasis changes from understanding the reliability practices adopted during the design and development process, to examining the degree to which reliability-based methods are used during this process. The basis for this investigation is to test a series of hypothesis (hypothesis H9) put forward in chapter 5. These hypothesis relate to the usage of reliability-based techniques in the machine tool industry.

This chapter concentrates on the degree of application and barriers preventing companies from introducing reliability-based methods as the focal point for discussion. However, it is clear from discussions in chapter 4 that there is an urgent need to increase the awareness and knowledge of reliability techniques in the general manufacturing industry.

Discussion on these findings will not be repeated in detail in this chapter. It will, however, be tested as to whether this is also the case for the machine tool industry. Further to this, attention will focus on measuring the effectiveness of reliability-based methods as a tool for product reliability improvement. These differences appear fundamental and help to explain some of the problems encountered by the industry in the application of these methods.

In addition to the above, an examination was conducted to ascertain the following:

- Whether or not issues and difficulties are unique to an individual technique or are found across all reliability-based methods.
- The benefits of reliability-based methods at an operational level and whether they significantly differ across the range of techniques available.

The relative importance and difficulties associated with the use and application of reliability-based techniques during the design and manufacture of a product is at the centre of this inquiry. There is already some evidence in the literature, supported by empirical evidence reported in chapter 4, that the use of such techniques can enhance the reliability of a product. For example, the use of value engineering and analysis will lead to the identification and reduction of unnecessary design features. This will inevitably leads to a more simplified but robust product design.

## 9.2 Degree of Application and Issues Associated with Reliability-based Methods

In the review of the technical literature reported in chapter 4, numerous examples of successful implementation of individual techniques such as failure mode and effects analysis (FMEA) [see, for example Dale et al., 1991] and Quality Function Deployment (QFD) [see, for example Griffin, 1992] across different industries were cited. Similarly, there are examples of specific application of complex techniques such as Design of Experiments (in particular Taguchi Methods) [see, for example Taguchi, 1984].

Empirical evidence available regarding the application and use is confined to specific techniques and does not indicate whether or not the same principles of application apply to all of the techniques or what the practical or theoretical basis for effective use of reliability methods is. Furthermore, conclusive evidence is most frequently based on the general manufacturing industry, rather than emphasising the problems and experiences to a specific industry or size of firms.

### 9.2.1 Identification and Classification of Difficulties Associated with Use

Significant analysis of the literature detailed in chapter 4 indicated that a variety of issues and difficulties existed with the use and application of specific methods. Such issues can be defined as 'barriers' undermining the successful application and acceptance of reliability-based methods in the manufacturing

industry. They can be broadly classified as (1) a lack of senior management support, (2) a lack of knowledge and understanding of the technique, (3) a lack of planning with regard to training and implementation, (4) time constraints, (5) resistant to change (i.e. successful without using these techniques) and (6) lack of resources. The intention of this survey was to measure and evaluate the extent to which these problems existed in the use and application of reliability-based methods within the UK machine tool industry.

To test the validity of the above literary findings, a number of semi-structured interviews were conducted with professionals in design engineering, manufacturing, customer service and purchasing in Cincinnati Milacron. The framework of the semi-structured interviews was flexible enough to allow a greater or lesser exploration of issues, depending on the interviewees, their job function and their position within the Cincinnati Milacron organisation structure. The exercise proved that the above issues are critical to the successful application of reliability-based methods, thereby validating the above findings.

However, informal information obtained through the interviews suggested other 'specific' issues were involved, which had to be considered in the design of the questionnaire. It was possible to conclude that these issues were specific to the individual techniques rather than relating to the organisation or operational issues of the firm. For example, those techniques that were mathematically more complex and employed explicit procedures was more difficult to implement. This is an important consideration since problems surrounding the usefulness and effectiveness of a technique are not always addressed to the satisfaction of the companies using them. Such knowledge would aid the smooth introduction of additional techniques and consequently facilitate the reliability improvement process.

In view of the above, an additional six barriers were selected. These barriers can be broadly described as:

1. Explicit and formal procedures prevents the pragmatic application of techniques.
2. The successful application of many techniques require the use of multi-functional teams. Therefore there is the tendency of diverting away from the main design and development activities.
3. The application of some techniques does not justify small volume manufacture.
4. Some techniques are not seen to be effective in improving design quality or reliability.
5. The more mathematically complex the technique, the more difficult it becomes to implement.
6. Some techniques are seen to be irrelevant and therefore unproductive.

Table 9.1 summarises the barriers selected for use in the questionnaire. The existence and the degree to which these barriers were considered to be contributing factors impeding the application of techniques in the machine tool industry was evaluated on a five point Likert-like scale.

### 9.2.2 Degree of Application

The number of proven techniques and concepts that can be used by manufacturing organisations in product reliability improvement is very large, with both specialist and universal applications. However, it would have been impracticable to include every one of these in an open-ended questionnaire. Therefore, research in this thesis has identified the most commonly used methods of growing popularity in both the academic and industrial sectors:

- Value Engineering & Analysis.
- Quality Function Deployment.
- Failure Mode and Effects Analysis.
- Taguchi's Robust Design Methods.

Table 9.1: Barriers to the Application of Reliability-Based Techniques

| **Technical Barriers** | **Organisational Barriers** |
|---|---|
| Techniques employ lengthy procedures (too formal) | Resistant to change management (i.e. successful without using formal techniques |
| Distracts attention away from nominal design and development activities | Lack of senior management support or commitment |
| Does not justify small volume manufacture | Lack of resources |
| Techniques not effective or productive | Lack of knowledge, understanding and experience in the use of techniques |
| Purpose of application (i.e. relevancy) | Lack of planning in training and impelementation |
| Level of complexity | Time constraints |

- Design of Experiments (DoE).
- Fault Tree Analysis (FTA).
- Design for Simplicity (DFS).
- Design for Assembly (DFA).

Table 9.2 provides a list of the techniques selected for use in this research, together with brief definitions. A more detailed explanation of each and every one of the techniques can be found in Chapter 4 of this thesis.

In a view to ascertaining the level of application of reliability-based techniques in the machine tool industry, respondents were asked to rate, on a scale from 1 (not at all) to 5 (continuously), the extent to which their organisations used the reliability-based techniques listed in the questionnaire. Figure 9.1 details the extent to which individual techniques are used during the design and manufacture process.

Of the eight methods studied in the survey, it is clear that value engineering, design for ease of assembly and design for simplicity were seen as effective techniques for design and process optimisation by machine tool manufacturers. This is reflected by the fact that these techniques fared slightly better in application, with 13 out the 17 machine tool firms (76%) confirming that they adopt the practice of value engineering and analysis. Similarly 60 per cent of the surveyed sample confirmed that they adopt the techniques, design for assembly and design for simplicity. Usage values of 4 to 5 were reported for these three techniques (see Figure 9.1).

The high level of usage can be explained by the fact that there are no explicit procedures, recording of analysis, documentation and operational complexity associated with the use of these three techniques. Previous research findings reviewed in Chapter 4 has shown that such aspects can hinder the application of reliability-based techniques. Using the basic principles of the three techniques, a multi-disciplinary team (i.e. manufacturing, engineering and service personnel) use their own judgement and experience to optimise the

Table 9.2: Commonly Used Reliability-based Techniques

| Reliability-based Technique | Brief Description |
|---|---|
| Value Engineering & Analysis | Organised functional approach for 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. |
| Quality Function Deployment | A quality-assurance system that ensures that the 'voice of the customer' (the specific needs and desires) is clearly defined, heard and followed in the design and development of a product. |
| Failure Mode & Effects Analysis | Objective method for analysing designs in order to identify modes of failures, the effect of failure and to identify priorities for eliminating or reducing the scope of failure. |
| Taguchi's Robust Design Methods<br>Design of Experiments | A comprehensive design methodology for optimising the functional performance of a product so that it is insensitive to noise factors.<br>(i.e. manufacturing factors that cannot easily be controlled, or factors which one has little control, such as extreme environmental conditions) |
| Fault Tree Analysis | A reliability/safety design analysis technique which starts from consideration of system failure effects, referred to as 'top events.' The analysis proceeds by determining how these can be caused by individual or combined lower level failures. Standard symbols are used in constructing the FTA to describe events and logical connections. |
| Design for Simplicity<br>Design for Assembly | These techniques use a set of design rules to optimise the design in terms of simplicity and reduced assembly and process steps. |

design of a product from the perspective of reducing engineering cost, reducing unnecessary design features and where feasible simplifying the design as much as possible for ease of assembly and reliability.

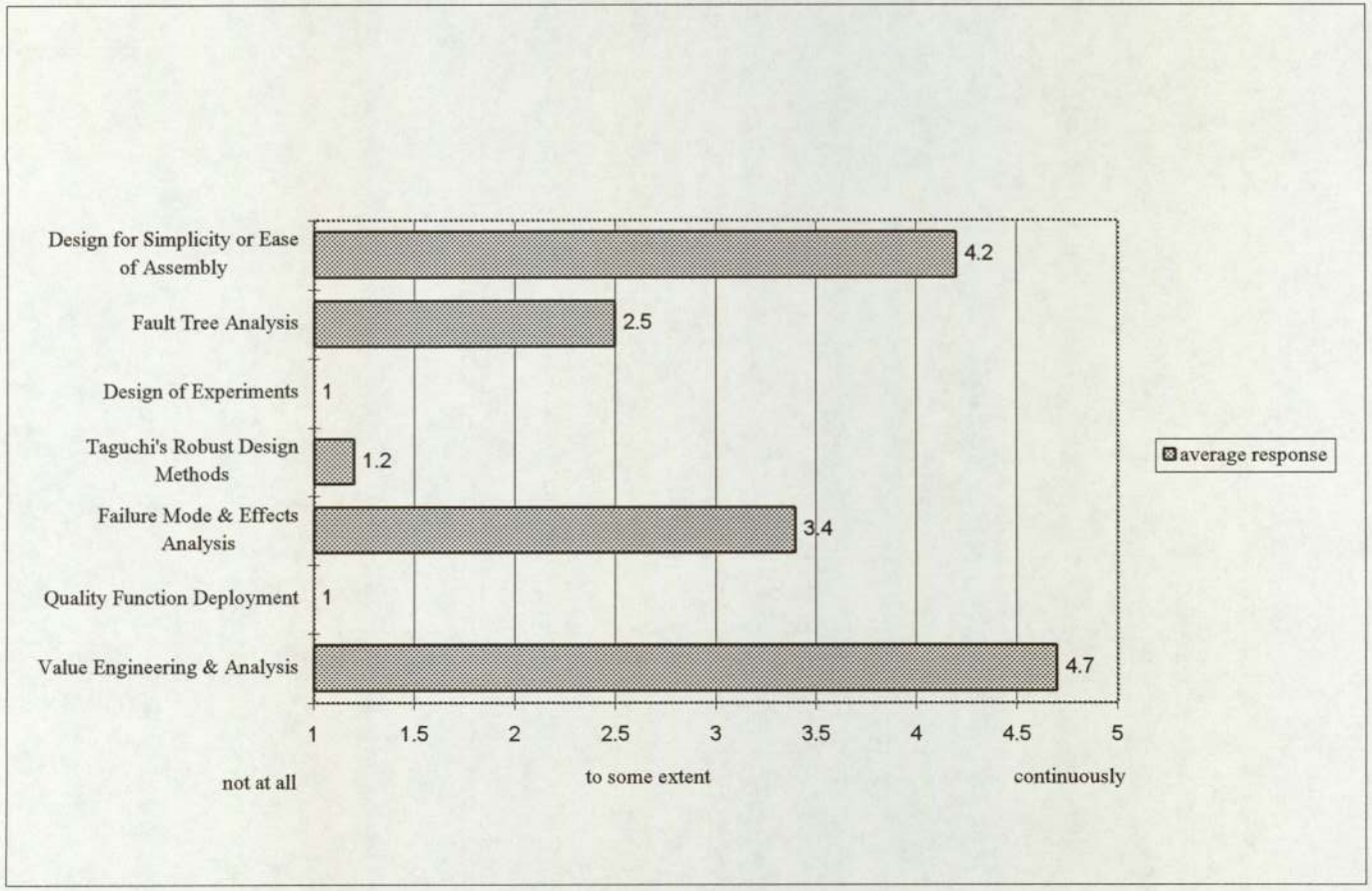
The application of the other five techniques including QFD, DoE, FTA, Taguchi Methods and FMEA were significantly lower compared to the usage of the value engineering, DFS and DFA techniques. An average usage value of approximately 1 was received for the techniques QFD, DoE and Taguchi methods, suggesting little or no application. It can also be concluded that the majority of the respondents are unlikely to be aware of the existent of these techniques, lack the understanding and knowledge required to use such techniques and are unaware of the potential benefits of using such techniques.

Furthermore, these techniques require the use of dedicated project teams, resources and employ more complex mathematical and operational procedures which may hinder the application of such techniques in medium sized enterprises. The validity of this assumption are consistent with those reported in the broadly based study on the general application of reliability-based techniques. For example, the application and diffusion of Taguchi Methods and QFD relate primarily to larger sized firms and multi-nationals [e.g. McElroy, 1987; Taguchi, 1984]. An explanation for this may be that larger sized companies have the necessary resources and time to adopt these methods on a regular basis. In many cases, they are able to create departments and groups which are primarily responsible for reliability improvement and who provide the necessary impetus for continuous use of the methods. One respondent from the survey expressed this viewpoint:

> The use of techniques during any stage of the design process tends to be minimal within our organisation because we do not have the necessary capacity... I think these techniques are more useful for larger sized firms (involved in high volume manufacture or safety critical items), where they are able to justify the use of these techniques.

The application of FMEA and FTA were also significantly low, but fared slightly better with an average usage value of 3. FMEAs and FTAs are

Figure 9.1: Application of Reliability-Based Techniques



considered to be laborious and time consuming activities to carry out. Engineers often view them as an unexciting activity which places additional workload to engineering staff. It is of significance that those machine tool organisations who scored 4 and 5 as the usage value were less likely to face as many difficulties in the use of FMEA and were most likely to view the technique as a continuous improvement tool. The results of this analysis suggests that machine tool companies are aware of the potential application of the technique and use it with varying degrees of application.

However, as a comparison to the automotive industry, the application of FMEA is significantly lower [see for example Dale et al., 1990]. One explanation for this huge difference is that the majority of the automotive suppliers are using FMEA only because it is a contractual requirement placed on them by major car manufacturers. In the machine tool industry, contractual requirements do not exist and the analysis of the surveyed data suggests that the implementation of FMEA is purely carried out through an internal drive for change, rather than outside influences.

### 9.2.3 Benefits of Usage

The effectiveness of reliability-based techniques can be measured by the benefits that is achieved at a functional and operational level. Ten key potential benefits which can result from the use of reliability-based techniques were cited in the literature. These benefits have been broadly categorised and defined as follows:

*Product Design and Manufacture Variables*: These include (1) reduction of engineering changes, (2) reduction of assembly problems, (3) improved reliability and maintainability, (4) reduction of number of parts and (5) reduction in time to market.

*Engineering Cost Variables*: These include (6) reduction of design cost and (7) reduction of warranty claims. Scrap and efficiency issues were also identified in the literature as potential benefits. However, this was not included in this

study since it is primarily a factor of production quality, rather than a factor of product design.

*Organisational Variables*: These include (8) structured approach to product design, (9) early involvement of field service and manufacturing personnel in the design process and (10) improvement in team-building for problem solving.

Figure 9.2 details this model. Respondents were asked to rate using a Likert scale of 1 to 5, which of the benefits were applicable to their organisation. Clearly the rating of any of the six benefits could vary depending on the degree of application. It could also relate to any individual technique which is used more than others. For example, it has already been established that value engineering is the most widely used technique and therefore the rating of the benefits may primarily relate to this particular technique. Acknowledging these problems of interpretation, the questions still allowed a general comparison to be made between the usage of techniques and the benefits gained.

Correlation analysis was used to examine the positive intercorrelations between the usage of techniques and the benefits gained. This analysis is shown in Table 9.3. The product design and manufacture variables were not strongly correlated to the usage of techniques. The degree of engineering changes, reduction of assembly problems and reduction in time to market did not show a strong relationship with the usage of techniques. However, it was observed that the use of reliability-based techniques had some impact in enhancing the reliability and maintainability of the product and reducing the number of unwanted parts and design features. Thus, it appears that the use of techniques have more of an impact on enhancing the functional robustness of the product, rather than systematically identifying design and assembly issues.

Furthermore, one of the two organisational variables which included structured approach to new product introduction also was not strongly correlated to the usage of techniques. However, it was observed that early involvement of manufacturing and field service were significantly influenced by the usage of

Figure 9.2: Benefits of Using Reliability-Based Techniques

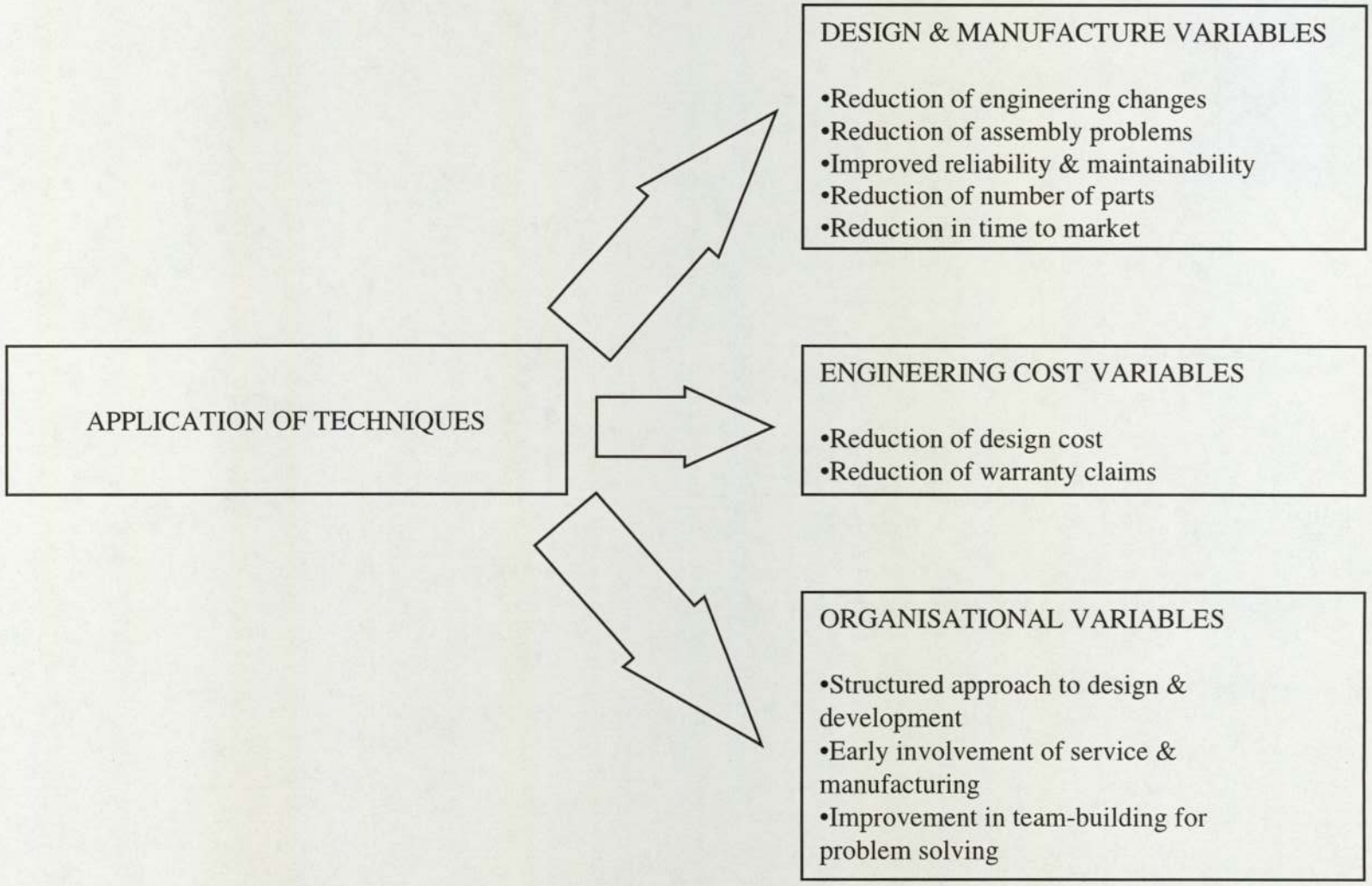


Table 9.3: Relationship Between the Application of Reliability-Based Techniques and Engineering Benefits

| | *Reduction in design changes* | *Reduction in warranty claims* | *Reduction in design costs* | *Increase in team-building* | *Reduction in time to market* | *Improved R&M* | *Reduction in assy problems* | *Reduction of number of parts* | *Structured development* | *Early involvement* | *Usage of Techniques* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reduction in design changes | 1.000 | | | | | | | | | | |
| Reduction in warranty claims | 0.212 | 1.000 | | | | | | | | | |
| Reduction in design costs | 0.146 | 0.476 | 1.000 | | | | | | | | |
| Increase in team-building | 0.148 | -0.106 | 0.554 | 1.000 | | | | | | | |
| Reduction in time to market | -0.263 | 0.288 | 0.247 | -0.226 | 1.000 | | | | | | |
| Improved R&M | -0.024 | 0.230 | 0.504 | 0.667 | 0.240 | 1.000 | | | | | |
| Reduction in assy problems | -0.031 | -0.206 | -0.089 | 0.251 | 0.193 | 0.221 | 1.000 | | | | |
| Reduction of number of parts | 0.116 | 0.483 | 0.721 | 0.364 | 0.113 | 0.487 | -0.131 | 1.000 | | | |
| Structured development | -0.253 | -0.580 | -0.176 | 0.344 | -0.498 | -0.072 | 0.324 | -0.008 | 1.000 | | |
| Early involvement | 0.236 | 0.506 | 0.887 | 0.640 | -0.065 | 0.526 | -0.049 | 0.683 | -0.005 | 1.000 | |
| Usage of Techniques | 0.281 | 0.510 | 0.936 | 0.654 | 0.123 | 0.617 | 0.026 | 0.709 | -0.057 | 0.943 | 1.000 |

reliability-based techniques. This result suggests that the use of techniques influences multi-disciplinary teamwork in organisations. This finding is not surprising, since the majority of reliability-based techniques rely on the use of multi-disciplinary teams for effective use.

Engineering cost variables had the most significant relationship with the use of techniques in this study. Both reduction of engineering cost and reduction warranty were significantly correlated to the use of techniques. It is apparent, that the majority of machine tool companies see the use of techniques as a means of achieving cost reduction.

### 9.2.4 Key Observations

The findings would suggest that the overall usage of the eight techniques studied in the survey is relatively low. This proves the hypothesis that the usage of reliability-based techniques is relatively low within the UK machine tool industry. In analysing the usage of the techniques individually, the results also suggests that value engineering, DFS and DFA were the most widely used techniques in the machine tool industry. In particular, the results also suggest that FMEA rates favourably as a technique which is used infrequently to address both reliability-related design problems.

One of the most pronounced differences evident in the study was that some methods were more acceptable than others. These methods are the ones that are not laborious, difficult to apply such as value engineering and requires little or no written rules, procedures or documentation.

In evaluating the data from the interrcorrelations and multiple regression analysis, it is tempting to conclude the benefits detailed in Table 9.3 are generally applicable to all the eight reliability-based techniques. However, although statistical tests show significant relationships with the use of the techniques and operational and engineering benefits, there were no supportive evidence for this general conclusion. The relative use of the eight techniques varied considerably. High usage of value engineering, design for assembly,

FMEA and design for simplicity were reported. Therefore, it can be concluded that these benefits are more applicable to value engineering, design for simplicity, FMEA and design for assembly.

### 9.3 A Comparative Analysis of the Effectiveness of Reliability-based Tasks

To further examine the relationship between individual techniques and tools and their efficiency in the reliability improvement process, a separate questionnaire was developed. Essentially, the objective of this research inquiry was to fulfil the following main objectives:

1. Establish the degree of application of a wide variety of proven reliability-based techniques, tasks and activities.

2. Examine the general awareness, knowledge and understanding of the techniques by the industry.

3. Measure and compare the effectiveness between individual techniques as facilitators for product reliability improvement.

4. Compare the efficiency of individual techniques against the more conventional and widely applied reliability-based tasks and activities, for example failure reporting and corrective action (FRACA).

The questionnaire incorporated an assessment matrix as an alternative to open-ended questions, as this was a better means of obtaining quantitative data of usage and effectiveness of techniques. Earlier pilot studies indicated that this type of information gathering could not be easily extracted from open-ended, semi-structured questions. The rationale for incorporating the assessment matrix was that it provided respondents the opportunity to cross compare their responses during completion of the questionnaire.

The questionnaire itself was targeted to Engineers across a wide variety of engineering disciplines. Engineers were targeted, rather than Managers, as it was observed during the evolution of the longitudinal study that Engineers are

the primary user of such techniques. Therefore, Engineers were more likely to paint a true picture of their knowledge and understanding, extent of usage as well as the perceived efficiency of the tasks and techniques. However, it was appreciated that the response rate of this particular questionnaire matrix can be strongly correlated with the recipients beliefs, understanding and activities of the subject.

In the questionnaire matrix, respondents were asked to provide their response in each of the following categories, for every technique listed in the matrix;

1. *Awareness and/or Familiarity:* The basis of this category was to conclude whether respondents were familiar with the technique or task.

2. *Knowledge and Understanding:* In order to examine the depth of knowledge and understanding of individual techniques, a modified Likert scale was used, where 1 = No Understanding and 5 = Complete Understanding.

3. *Application in Engineering:* The degree of usage of individual tasks was again measured using a modified Likert scale. A scoring method of 1 = Not at all and 5 = Continuously was devised.

4. *Effectiveness:* The main intent of the survey was to measure this variable. Respondents were asked to rate the effectiveness of individual techniques as a tool for product reliability improvement. Similarly, a modified Likert scale was devised, where 1 = Very Unproductive and 5 = Very Effective. The objective was to measure the perception of effectiveness of reliability techniques and tasks a company undertakes during the product engineering process, specifically to improve product reliability. The reported *perception* was measured due to the complexity and difficulties encountered in developing other relevant metrics for measuring effectiveness, during the course of research.

The questionnaire also addressed whether there were other tasks the respondent's company did to improve reliability. This was asked to ensure

that all activities of the respondent's company, specifically to improve product reliability, would be covered. Modified Likert type scales were used given their proven success in previous research studies [see, for example Oakland et al., 1986].

Using the literature review, a total of 22 techniques, activities and tasks were listed in the questionnaire matrix. The techniques selected for investigation were divided and grouped into the following categories:

- Common reliability-based tasks and activities.
- Reliability measuring techniques.
- Analytical methods for use during design and manufacture.
- Engineering management methods.
- Reliability-related testing.

Table 9.4 provides a list of all 22 techniques. Brief explanation of the techniques can be found in the glossary section of the thesis.

### 9.3.1 Response Rate of the Questionnaire

As a comparison to the response rate of all other questionnaires used in the survey, 33 questionnaires entitled *'Tools and Techniques for Product Reliability Improvement'* were received. This high number of questionnaires returned was as a direct result of sending approximately 100 of these questionnaires to a wide variety of Engineers, as opposed to sending it on a machine tool company perspective. A high number of these questionnaires were filled in by Engineers employed within Cincinnati Milacron. This provided a response rate of 33% of the initial mailing. For direct mail response, 33% was considered a large return from a statistical accuracy and social science perspective.

Table 9.4: List of Reliability Tasks, Activities and Techniques

| Category | Description of Task and Technique |
|---|---|
| Reliability-related Tasks and Activities | 1 Failure Reporting and Corrective Action |
| | 2 Derating |
| | 3 Worst-Case Analysis |
| | 4 Parts, Materials and Process Reviews |
| | 5 Design Reviews |
| Reliability-related Testing | 6 Product Testing |
| | 7 Durability Testing |
| | 8 Reliability Growth Test (Test-Analyse-Fix) |
| Analytical Methods | 9 Design FMEA |
| | 10 Process FMEA |
| | 11 Sneak - Circuit Analysis (SCA) |
| | 12 Design of Experiments (DoE) |
| | 13 Taguchi Methods |
| | 14 Fault Tree Analysis (FTA) |
| Engineering Management Methods | 15 Quality Function Deployment (QFD) |
| | 16 Value Engineering and Analysis |
| | 17 Design for Simplicity and Assembly (DFS/A) |
| | 18 Design for Manufacture (DFM) |
| Reliability Measuring Techniques | 19 Weibull Analysis |
| | 20 Parts Stress Reliability Prediction |
| | 21 Parts Count Reliability Prediction |
| | 22 Field Failure/Warranty Analysis |

### 9.3.2 Effectiveness of Reliability-based Tasks as a Tool for Product Reliability Improvement

Table 9.5 summarises the analysis of the surveyed data on the effectiveness of reliability-based tasks as perceived by Engineers across a number of different disciplines. The results were averaged to get the effectiveness ratings for each task.

Not all survey respondents provided effectiveness ratings for every task. Usually, respondents who were not familiar with the task did not provide an effectiveness rating. Another interesting feature of the responses is where respondents were familiar with the task, they did not rate the effectiveness. One reason for this is that respondents were familiar with task but, never applied the task in any form within their design or manufacturing process.

There is considerable evidence from this analysis that tasks which belong to the following groups or categories are applied more frequently and rated highly as a tools for improving product reliability;

- Reliability testing methods.
- Reliability-based tasks and activities.

Analytical, engineering management and reliability measurement based tasks were received less favourably by Engineers as techniques for product reliability improvement. This is probably reflected by the low usage of these techniques within the reliability management process. Similarly, Engineers had little or no knowledge and understanding of these tasks.

Product testing was rated as having the highest effect on improving product reliability, and Reliability Prediction or Measurement as having the least effect on improving product reliability. Similarly, failure reporting and corrective action (FRACA) was also regarded highly as a tool for product reliability improvement. It is therefore indicative that conventional tasks that are well

Table 9.5: Effectiveness Rating of Reliability Tasks and Techniques

| Category | Description of Task and Technique | AVERAGE RATING Knowledge & Understanding | Application in Engineering | Effectiveness |
|---|---|---|---|---|
| Reliability-related Tasks and Activities | 1 Failure Reporting and Corrective Action | 5 | 5 | 4.8 |
| | 2 Derating | 4.7 | 3.9 | 3.7 |
| | 3 Worst-Case Analysis | 3.2 | 1.5 | 2.1 |
| | 4 Parts, Materials and Process Reviews | 4.2 | 3.1 | 3.2 |
| | 5 Design Reviews | 4.6 | 2.7 | 3.5 |
| Reliability-related Testing | 6 Product Testing | 5 | 5 | 4.9 |
| | 7 Durability Testing | 5 | 3.2 | 3.4 |
| | 8 Reliability Growth Test (Test-Analyse-Fix) | NO RATING | NO RATING | NO RATING |
| Analytical Methods | 9 Design FMEA | 3.6 | 2.4 | 3.1 |
| | 10 Process FMEA | 3.2 | 2.1 | 2.8 |
| | 11 Sneak - Circuit Analysis (SCA) | NO RATING | NO RATING | NO RATING |
| | 12 Design of Experiments (DoE) | NO RATING | NO RATING | NO RATING |
| | 13 Taguchi Methods | 2.1 | 1.2 | 2.4 |
| | 14 Fault Tree Analysis (FTA) | 2.1 | 1.1 | 2.1 |

Table 9.5: Effectiveness Rating of Reliability Tasks and Techniques

| Category | Description of Task and Technique | AVERAGE RATING Knowledge & Understanding | Application in Engineering | Effectiveness |
|---|---|---|---|---|
| Engineering Management Methods | 15 Quality Function Deployment (QFD) | 2.1 | 1.4 | 2.5 |
| | 16 Value Engineering and Analysis | 4.2 | 2.8 | 3.9 |
| | 17 Design for Simplicity and Assembly (DFS/A) | 4.2 | 1.8 | 3.7 |
| | 18 Design for Manufacture (DFM) | 4.4 | 2.1 | 3.6 |
| Reliability Measuring Techniques | 19 Weibull Analysis | 2.6 | 1.6 | 1.3 |
| | 20 Parts Stress Reliability Prediction | NO RATING | NO RATING | NO RATING |
| | 21 Parts Count Reliability Prediction | 2.7 | 1.2 | 1.4 |
| | 22 Field Failure/Warranty Analysis (MTBF) | 3.9 | 2.6 | 2.1 |

KEY

Knowledge & Understanding: 1= No Understanding to 5= Complete Understanding
Application in Engineering: 1= Not at all to 5= Continuosly
Effectiveness: 1= Very Unproductive to 5= Very Effective

established in terms application and have a high level of familiarity amongst Engineers are perceived to be effective programmes for improving reliability.

Tasks with a high effectiveness rating had the lowest standard deviations and tasks with the lowest effectiveness rating had the highest standard deviation. This indicated a strong agreement amongst respondents for tasks that are seen to be effective and weak agreement amongst respondents for the lowest rated tasks.

The implication of these findings are of significance. For example, the findings can be used as a general guideline for increasing reliance on tasks which have a significant effect on improving product reliability and reduce reliance on tasks that have the least effect. In this particular study, a machine tool manufacturer would have the most immediate success by increasing time, resources and capital with product related testing (for example cyclic testing, burn-in type testing and general development testing). Similarly, a machine tool manufacturer would significantly benefit by focusing more time and effort on improving the overall Failure Reporting and Corrective Action Process. There is a high level of familiarity with the tasks and general consensus that they are effective programmes.

However, the results also suggest that increasing the reliance on reliability measurement, engineering management and analytical based tasks may have little direct impact with product reliability. Many Engineers in the machine tool industry perceive these type of techniques as having little impact on reliability improvement.

There are several limitations associated with the findings that needs to be put in perspective. First, a task that is very effective for one company may not be effective for another because of variations in applications due to different reliability management practices and organisational structures. Second, some tasks are solely intended to measure the reliability of a product and therefore do not directly enhance or improve product reliability. One respondent commented that it is easier to judge the effectiveness of tasks which measure

reliability than to assess the effectiveness of tasks which enhance or improve reliability. This questionnaire only asked respondents to rate each task on its effectiveness for improving reliability, not the effectiveness of the task in fulfilling its original purpose. Therefore, ratings for tasks which are intended to measure reliability (e.g. Weibull analysis) should not be constructed to mean that the original intentions of the task are ineffective. The ratings only address that the task is not perceived as being effective in improving product reliability.

## 9.4 Failure Mode and Effects Analysis as a Tool for Product Reliability Improvement

To further validate the questionnaire findings on the issues and difficulties encountered by machine tool companies in the application of reliability-based methods, a case study on the use and effectiveness of design failure mode and effects analysis (Design FMEA) was conducted. Cincinnati Milacron was used as the case study company.

'Experimental' action research was used as the methodology for conducting the FMEA case study [see Foster, 1972]. The application of this type of action research methodology involved the use of a controlled group, comparative treatments and measuring any outcomes.

This section describes the work carried out in developing the use of Design FMEA at Cincinnati Milacron, the difficulties encountered and the value of the technique as a tool for product reliability improvement. It forms an extension to the questionnaire findings, reported above, on the use and application of reliability-based techniques in the industry.

### 9.4.1 What is Failure Mode and Effects Analysis?

FMEA is a structured analytical tool for examining the potential of a product or process to fail to deliver it's intended functions. FMEA represents an effective and documented method for engineers to present in a structured and formalised manner their subjective thinking and experience in terms of:

- How can a device fail?
- What happens when it fails?
- What are the current design or process measures?
- How can we reduce or prevent the occurrence?

FMEA techniques forms an important part of any reliability assurance programme. The technique can be applied to a wide variety of problems which may occur in technical systems. It can be carried out in varying degrees of depth, or modified, to suit a particular application. Some of the detailed applications and benefits of FMEA are given below:

- To avoid costly modifications by the early identification of design deficiencies.
- To identify failures which when they occur alone or in combination, have unacceptable or significant effects, and to determine the failure modes which may seriously affect the expected or required operation.
- To determine the need for redundancy, design improvement, more generous stress allowances (derating), screening of items, design features that ensure that the system fails in a preferred failure mode (i.e. 'fail-safe' outcomes of failures) and selection of alternative materials, parts, devices and components.
- To identify serious failure consequences and hence the need for changes in design or operation rules.
- To ensure that the development test programme can detect potential failure modes.
- To focus upon key areas in which to concentrate quality control, inspection and manufacturing process controls.
- To assist in defining various aspects of the general maintenance strategy, such as (1) establishing the need for data recording and condition monitoring during testing and use, (2) establishing

maintenance cycles which anticipate and avoid wear-out failures and (3) selection of built-in test equipment.

- To facilitate or support the determination of test criteria, test plans and diagnostic procedures. For example, performance and reliability testing.
- To identify parts and assemblies requiring worst case analysis.
- To support the design of fault isolation sequences and to support the planning for alternative modes of operation and reconfiguration.
- To facilitate communication between (1) general and specialised engineers, (2) equipment manufacturer and his suppliers and (3) system user and the manufacturer.
- To enhance the analyst's knowledge and understanding of the behaviour of the equipment studied.
- To provide designers with an understanding of the factors which influence the reliability of the system.
- To provide a final document that is proof of the fact that (and of the extent to which) care has been taken to ensure that the design will meet its specification in service.

From an industrial practice perspective, the main two areas where FMEA is deployed are during product design and manufacturing processes. Design FMEAs assess what could, if not corrected, go wrong with the product in service and during the manufacture as a consequence of a weakness in the design. Process FMEAs are mainly concerned with the reasons for potential failure during manufacture and assembly as a result of non-compliance with the original design intent, or failure to achieve the design specification and tolerances.

This case study is only concerned with Design FMEA.

### 9.4.2 Background to the Formation of the Case Study and the Use of FMEA at Cincinnati Milacron Ltd

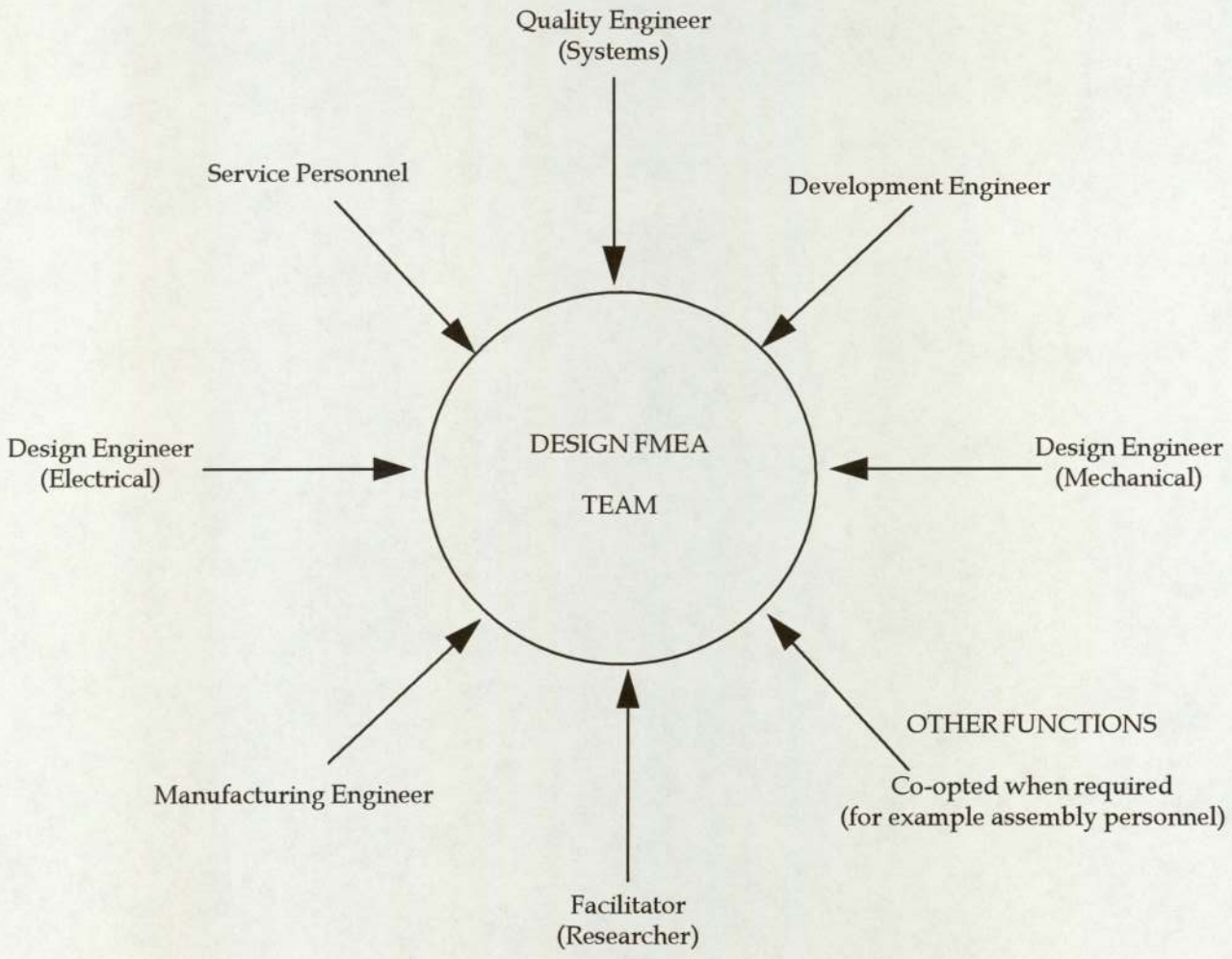
Prior to the commencement of the case study, FMEA was not practised within the UK organisation of the Cincinnati Milacron (CM) Corporation. This design analysis activity has been used only by the Plastics Machinery Division of the CM Corporation. The use was not widespread amongst the UK and USA Machine Tool Division, although the technique was recommended by the Plastic Machinery Division for use during new product design.

Within CM UK, the various FMEA material sent from the Plastics Machinery Division to aid in the implementation process was largely ignored by management. The technique was thought of as merely a window-dressing exercise, typifying what already is being carried out on an informal basis by design and development engineers. Similarly, it was viewed as being a highly resource driven design activity which aims to formalise and standardise the mental discipline an engineer normally goes through.

The introduction of FMEA at Cincinnati Milacron therefore came about as a direct result of this particular case study. The case study was initiated through joint collaboration and agreement between relevant management of CM and the researcher. CM was aware that the case study was purely theory oriented, with the objective of learning and generalising the findings. It was also recognised that the case study was of a diagnostic and experimental nature which may or may not lead to the implementation of FMEA within the CM organisation. In other words, the researcher would produce the findings which can be used to bring about change (intervention theory). The information produced having an applicability both to the CM organisation and a wider audience.

To conduct the case study, an experimental design FMEA team was created. The key members of the team are shown in Figure 9.3. As well as the normal research oriented role and contributing to the FMEA process, the researcher took the role of facilitator. This also included acting as the link for the

Figure 9.3: Structure of Design FMEA Team



administration of the FMEA. A design and development engineer formed a key member of the FMEA team. As the case study was a design oriented FMEA, it was primarily driven by these personnel. Design supervisors and quality management personnel also participated in the case study, purely from a observation perspective.

In order to exert a strong influence on design for manufacture, machining and assembly issues a manufacturing engineer formed a significant member of the team. Similarly, field service personnel were introduced to the team to raise field reliability and maintainability issues. Quality, assembly and purchasing personnel were communed with the team when required to provide data on vendor supplied parts, efficiency and scrap issues. A key factor in the preparation of the design FMEA revolved around total involvement and interaction of the overall team.

The FMEA case study was performed on the design of a new turning centre product. This product design was at the latter stages of its design and development process. Although this was not the ideal time to perform FMEA on the turning centre, the purpose was only to ascertain the effectiveness and benefits of the technique. Therefore, it was perfectly viable to conduct the FMEA. However, ideally FMEA is to be conducted during the initiation of detailed design. Weekly review meetings were held to conduct the FMEA and kept to a fixed time of approximately one hour. The length of the case study amounted to approximately 5 months. This also included initial piloting and introduction of FMEA to relevant management.

The key concepts used to conduct the FMEA case study are as follows:

- Inductive logic (i.e. bottom-up approach was adopted).
- Determine the effect of failure in terms of (1) part failure on sub-assembly operation, (2) sub-assembly failure on equipment operation and (3) equipment failure on system operation.

- Classifies the effect to determine severity of failure on system operation.
- Did not consider human errors.

### 9.4.3 The FMEA Procedure Used in the Case Study

Essentially, various procedures are documented for conducting FMEA. The most common method used in the automotive industry involves a tabular worksheet for recording the FMEA analysis and for documentation purposes [SMMT, 1989]. A similar tabular worksheet and procedure is used by the Plastics Machinery division.

The case study was conducted using the FMEA material from the Plastics Machinery division. The worksheet that was used in the case study is detailed in Figure 9.4. A ranking index of 1 to 5 for 'severity', 'likelihood of occurrence' and 'likelihood of detection' was used. Table 9.6 illustrates the ranking index employed. Having identified the part or assembly to be analysed, the principal FMEA procedure that was adopted is described below:

*Function and Specification:* The function and specification of part and assembly should be listed as concisely as possible. Where the part or assembly is likely to have numerous functions, it is to be listed separately.

*Potential Failure Mode:* This is the manner in which a part or assembly could potentially fail to meet the design intent, performance requirements or customer expectations. The potential failure mode may also be the cause of a potential failure mode in a higher level assembly, or be the effects of one in a lower level part. All possible failure modes should be listed, i.e. not whether the part or assembly will fail but how it could fail.

*Potential Effects of Failure Mode:* Describes the effects of failure in terms of what the customer may notice or experience. For each potential failure mode, consider all effects the failure would have on the overall part, assembly or product function and end user.

## Figure 9.4: FMEA Worksheet Used in the Case Study

| Cincinnati Milacron DESIGN FMEA | Part/Assembly Name: | TOOLCHANGER | Vendor Name: | CM (UK) | FMEA #: | 126956-0001 |
|---|---|---|---|---|---|---|
| | Part/Assembly No.: | 126956-0001 | | | | |
| | Prepared by: | PW, TG, JP, BB, MG, JA | Sched. Production Release Date: | 01-Jan-97 | Date: / Latest Rev. Date: | 12-Mar-96 |
| | CUSTOMER/APPLICATIONS: | SABRE 750 | | | Print Date: | 27-Aug-96 |

| Function & Specification | Potential Failure Mode | Potential Cause of Failure | LIKELIHOOD | Potential Effects of Failure Mode on End Product & User | SEVERITY | Existing Prevention or Detection Measures | EFFECT | RPN | Recommended Actions to Eliminate Cause or Help Prevention or Detection | Responsibility for Action Accepted by | LIKELIHOOD | SEVERITY | EFFECT | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | |

**SEVERITY : (Assessment of the seriousness of the effect of the failure mode)**

1 - Minor; no real effect on part or system. Probably unnoticed by customer
2 - Low; slight customer annoyance
3 - Moderate; Customer is annoyed by failure (e.g. leaks, erratic operation)
4 - High; Inoperable machine or convenience subsystem. Does not involve safety or governmental compliance
5 - Very High; potential failure affects safe equipment operation and/or governmental non-compliance.

| LIKELIHOOD | FAILURE RATE |
|---|---|
| 1 - Remote; Failure is unlikely | <1 in 10,000 |
| 2 - Low; Relatively few failures | <1 in1,000 |
| 3 - Moderate; Occasional failures | <1 in 100 |
| 4 - High; Repeated failures | <1 in 10 |
| 5 - Very High; Failure is almost inevitable | >1 in 10 |

**DEFINITION**

In the case of failure, what is the LIKELIHOOD that the "POTENTIAL CAUSE" is responsible?

**EFFECT (Likelihood of Detection by Programme)**

1 - Very High; Programme will almost certainly detect a potential design weakness.
2 - High; Programme has a good chance of detecting a potential design problem.
3 - Moderate; Programme may detect a potential design weakness.
4 - Low - Programme not likely to detect a potential design weakness.
5 - Very Low - Programme probably will not detect a potential design weakness.

*Severity:* This is an assessment of the seriousness of the effect of the failure mode. By using the ranking index (see Table 9.6), the severity for each effect of failure should be evaluated.

*Potential Cause of Failure:* This is an indication of design weakness, the consequence of which is the failure mode. Against each potential failure mode, all possible causes of failure should be listed. It is important that the list is as complete as possible so that remedial action can be directed at pertinent causes.

*Likelihood of Occurrence:* Likelihood that a specific cause will result in the failure mode. The likelihood ranking number has a meaning rather than a value. Using the likelihood ranking index (see Table 9.6), score the likelihood of occurrence for each potential cause of failure, i.e. in the case of the failure mode occurring, what is the likelihood that the potential cause is responsible?

*Planned or Existing Prevention or Detection Measures:* All existing and planned methods of prevention or detection measures should be listed. The methods listed should be directly related to the prevention or detection of specific causes.

*Likelihood of Detection (Effect):* An assessment of the ability of the proposed design programme to identify a potential design weakness before the part or assembly is released for production. Using the likelihood of detection ranking index, score the effectiveness of the prevention or detection measures to identify a potential design weakness.

*Risk Priority Number (RPN):* Calculate the Risk Priority Number (RPN) which is the product of the severity, likelihood of occurrence and likelihood of detection values. In this case study, RPN is a number between 1 and 125. The magnitude of this number could vary depending on the people making the judgement. Therefore, there is no particular significance attributed to the number other than the ranking of failure modes to give some priority of resource assignment to eliminate or reduce the potential of failures.

Table 9.6: Ranking Indexes Used in the Case Study

| Ranking | Severity of Effect | Likelihood of Occurrence | | Likelihood of Detection |
|---|---|---|---|---|
| | | Probability of Failure | Design Life Possible Failure Rates | |
| 1 | Minor: Unreasonable to expect that the minor nature of this failure would cause any real effect on the part or system performance. Customer will probably not even notice the failure. | Remote: Failure is unlikely | <1 in 10,000 | Very High: Programme will almost certainly detect a potential design weakness |
| 2 | Low: Low severity ranking due to nature of failure causing only a slight customer annoyance. Customer will probably notice a slight deterioration of the part or equipment performance. | Low: Relatively few failures | <1 in 1,000 | High: Programme has a good chance of detecting a design weakness |
| 3 | Moderate: Moderate ranking because failure causes some customer dissatisfaction. Customer is made uncomfortable or is annoyed by the failure (e.g. erratic operation, leaks, cycle interrupts). | Moderate: Occasional failures | <1 in 100 | Moderate: Programme may detect a potential design weakness |
| 4 | High: High degree of customer dissatisfaction due to the nature of the failure such as an inoperable machine or an inoperable convenience subsystem (e.g. external communications system does not work). Does not involve equipment safety or non-compliance. | High: Repeated failures | <1 in 10 | Low: Programme not likely to detect a potential design weakness |
| 5 | Very High: Very high severity ranking when a potential failure mode affects safe equipment operation and/or involves non-compliance with standards | Very High: Failure is almost inevitable | >1 in 10 | Very Low: Programme probably will not detect a potential design weakness |

*Recommended Actions:* When the failure modes have been rank ordered by the RPN, corrective action should be first directed at highest ranked concerns. The intent of any recommended action is to reduce any one or all of the severity, likelihood or detection rankings. As a general guideline, an increase in design verification actions will result in a reduction in the detection ranking only. A reduction in the likelihood ranking can only be effected by removing or controlling one or more of the causes of the failure mode through a design revision. Only a design revision can bring about a reduction in the severity ranking.

*Revise RPNs:* Revised severity, likelihood, detection and RPN associated with changes expected or demonstrated as the result of recommended action should recorded.

### 9.4.4 Potential Benefits of Design FMEA as Evaluated by the Case Study

The completion of the case study resulted in the production of several FMEA worksheets. Figure 9.5 illustrates an example of a FMEA worksheet. Overall, FMEA was perceived as a difficult, laborious and dull technique by engineers involved in the case study. This perception taken by the engineers were probably as a result of the following:

- Insufficient time to carry out the analysis on a realistic manner. The case study was purely experimental and diagnostic.
- Poor understanding of the importance of FMEA by the engineers involved.
- The first introduction of FMEA within the CM organisation and therefore little maturity effects were observed.
- The performance of design FMEA requires a resolute, analytical and inquiring mind. Furthermore, it also relies on the judgement and experience of engineers involved in the process to consider all possible modes of failures. This may have hindered the views held on FMEA.

## Figure 9.5: Example of a Completed FMEA Worksheet

| Cincinnati Milacron DESIGN FMEA | Part/Assembly Name: TOOLCHANGER | Vendor Name: CM (UK) | FMEA #: 126956-0001 |
|---|---|---|---|
| | Part/Assembly No.: 126956-0001 | | |
| | Prepared by: PW, TG, JP, BB, MG, JA | Sched. Production Release Date: 01-Jan-97 | Date: 12-Mar-96 |
| | CUSTOMER/APPLICATIONS: SABRE 750 | | Latest Rev. Date: Print Date: 27-Aug-96 |

| Function & Specification | Potential Failure Mode | Potential Cause of Failure | LIKELIHOOD | Potential Effects of Failure Mode on End Product & User | SEVERITY | Existing Prevention or Detection Measures | EFFECT | RPN | Recommended Actions to Eliminate Cause or Help Prevention or Detection | Responsibility for Action Accepted by | LIKELIHOOD | SEVERITY | EFFECT | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Index tools accurately Grip/Release tools at prescribed intervals | Pocket failure | Breakage due to fatigue | 1 | Manual tool change<br>Partial loss<br>Bed damage<br>High tooling costs<br>Loss of production | 3<br>2<br>1<br>3<br>4 | None | 5 | 15<br>10<br>5<br>15<br>20 | No Action Required | | 1 | 3<br>2<br>1<br>3<br>4 | 5 | 15<br>10<br>5<br>15<br>20 |
| | | Loose screws | 2 | Manual tool change<br>Partial loss<br>Bed damage<br>High tooling costs<br>Loss of production | 3<br>2<br>1<br>3<br>4 | Torque down | 3 | 18<br>12<br>6<br>18<br>24 | Assembly to refer to engineering drawings<br>Ensure adequate tooling | Assembly/ENG. | 1 | 3<br>2<br>1<br>3<br>4 | 2 | 6<br>4<br>2<br>6<br>8 |
| | | Incorrect mechanical set-up | 3 | Manual tool change<br>Partial loss<br>Bed damage<br>High tooling costs<br>Loss of production | 3<br>2<br>1<br>3<br>4 | Alignment checks during assembly and field | 1 | 9<br>6<br>3<br>9<br>12 | Ensure assembly & service personnel adhere to checks | Assembly/Service | 2 | 3<br>2<br>1<br>3<br>4 | 1 | 6<br>4<br>2<br>6<br>8 |

**SEVERITY**: (Assessment of the seriousness of the effect of the failure mode)

1 - Minor; no real effect on part or system. Probably unnoticed by customer
2 - Low; slight customer annoyance
3 - Moderate; Customer is annoyed by failure (e.g. leaks, erratic operation)
4 - High; inoperable machine or convenience subsystem. Does not involve safety or governmental compliance
5 - Very High; potential failure affects safe equipment operation and/or governmental non-compliance.

| LIKELIHOOD | FAILURE RATE |
|---|---|
| 1 - Remote; Failure is unlikely | <1 in 10,000 |
| 2 - Low; Relatively few failures | <1 in1,000 |
| 3 - Moderate; Occasional failures | <1 in 100 |
| 4 - High; Repeated failures | <1 in 10 |
| 5 - Very High; Failure is almost Inevitable | >1 in 10 |

**DEFINITION**

In the case of failure, what is the LIKELIHOOD that the "POTENTIAL CAUSE" is responsible?

**EFFECT** (Likelihood of Detection by Programme)

1 - Very High; Programme will almost certainly detect a potential design weakness.
2 - High; Programme has a good chance of detecting a potential design problem.
3 - Moderate; Programme may detect a potential design weakness.
4 - Low - Programme not likely to detect a potential design weakness.
5 - Very Low - Programme probably will not detect a potential design weakness.

However, a number of potential benefits were identified, which if FMEA is implemented and integrated in the design process, would be fully realised. These potential benefits were also agreed upon by the engineers involved in this case study:

*Early consideration of design variables:* FMEA promotes the up-front consideration of design, manufacturing, assembly and service issues on a systematic basis. This in effect reduces the likelihood of downstream failures. Enhancement of critical design attributes such as reliability, maintainability, accessibility and durability also results from the performance FMEA.

*Promotes cross-functional integration:* The proper use of the technique can substantially benefit cross-functional teamwork and product knowledge transfer. FMEA provides the link for manufacturing, assembly and service personnel to have a significant input in the design process.

*Application in design reviews:* Facilitates the promotion of design reviews at a functional level of the organisation. All too often design reviews are held at an operational level with no effect. Design, manufacturing and service personnel at a functional level can provide a better input as to the root causes of existing problems in the shopfloor, field or during design, manufacture and product testing phase.

*An effective 'design audit' activity:* Can be used as a 'design audit' activity. Furthermore, the final FMEA document can be used as proof of the fact that care has been taken to ensure the design will meet its specification in service. Alternatively, it can used as a future documented reference for use in (1) analysing field concerns and (2) designing new or modifying existing products.

*Common communications tool:* A FMEA can act as a common communications tool between design, reliability, development and manufacturing engineers.

### 9.4.5 The Limitations and Difficulties of Design FMEA as Evaluated by the Case Study

In addition to the potential benefits identified during the case study, a number of limitations and difficulties associated with the operation of the FMEA technique were evaluated. These are elaborated below:

*Time consuming activity:* The technique can be very time consuming. This can be overcome by working at the sub-assembly level rather than the component level, or by considering a specific point of view. The technique itself requires significant resources for its effective operation.

*FMEAs are subjective:* Opinion and bias can mean that, if two groups are given the same product, they will come up with completely different FMEAs. This is particularly true for the ranking indexes. However, this can be minimised by providing detailed guidance and by having a group instead of an individual.

*Level and detail of analysis:* Significant failure modes may be unnoticed. For instance, their is a high probability that (1) for new designs not all failure modes and causes may be covered due to insufficient data available and (2) no member of the group has experienced a specific failure mode and its causes. In the case study, engineers found difficulties in the identification of failure modes.

Another issue which caused problems in the early stages of the implementation of FMEA is the level in the product hierarchy at which the analysis is performed. This also affects the amount of time and effort required. It needs careful consideration because an analysis carried out at a high level can become too superficial, while on the other hand a lower level can become unintelligible.

The main advantages of conducting a FMEA at a low level are (1) a more detailed and focused analysis will be performed and (2) corrective design actions can be identified and targeted more effectively. However, significant

difficulties arise if the FMEA is performed at a low level of the product hierarchy. Some of these include (1) the further down the hierarchy one progresses, the more difficult it becomes to conceptualise and define performance standards, (2) at a low level, it becomes equally difficult to visualise and hence analyse failure consequences, (3) the lower the level of analysis, the more difficult it becomes to decide which components belong to which system and (4) some failure modes can cause many sub-systems to cease to function simultaneously.

The main advantages of conducting a FMEA at the top level of a product hierarchy are (1) functions and performance standards/expectations are much easier to define, (2) failure consequences are much easier to assess and (3) there is less repetition of functions and failure modes. However, starting at a top level will make the findings of the FMEA too general, superficial and meaningless from a corrective action perspective. This will not lead to any corrective design recommendations or actions.

*Validity of the findings:* In some cases the use of FMEA may lead to incorrect causes and effects being identified. Similarly, irrelevant failure modes may sometimes be given priority. However, this is purely dependent on the judgement and experience of the engineers performing the FMEA.

*Applicability of FMEA:* Instead of a detailed FMEA which answers the question how and why a product could fail to meet the customer's requirements, there is a tendency to divert away from this question. For example, the FMEA can be produced from various points of view: (1) safety, (2) mission success, (3) availability or (4) repair cost. The ratings of the severity, likelihood and detection will therefore significantly depend on the point of view. For example, a safety related FMEA may give a low severity number to a an item whose reliability seriously affects availability but is not safety critical. These points must be stated if they are specific.

*Unsupportable assumptions:* These may sometimes be made on the design, manufacturing processes and field service issues. For example, that the design

is 100% robust and 100% failure-free, that 100% inspection is 100% efficient, that maintenance will restore an item to good as new condition. These all assumptions made by the engineer hinders both the effective application of FMEA and the degree of detail.

*Other limitations and issues:* There are other minor issues associated with the use of FMEA and is elaborated below:

- It is difficult to include degrees of failure, the FMEA tends to be an all or nothing technique.
- It is limited to single failures whereas multiple failures may some times occur simultaneously.
- Secondary effects of a failure is rarely considered in a FMEA.
- Conducting FMEAs on complex systems and products becomes a difficult process.
- Products with many similar components may cause difficulties in rating.
- Bias views are likely when re-rating after re-design to avoid failure.

### 9.4.6 Introduction of FMEA within the CM Organisation

The findings of the case study culminated in significant management backing to introduce and implement FMEA within the CM design engineering process. Although there were numerous limitations associated with the use of the FMEA, the overall impression gathered from the case study was that proper application will provide a more effective means of analysing designs. This will enable deficiencies to be identified early on in the design process and corrected, rather than during the latter stages.

Prior to the case study being performed, the engineers involved were only briefed on the general principles of FMEA. Therefore, further training together with senior management commitment was essential for successful operation of the technique. A FMEA manual was developed by the researcher for use in

training engineers in the use of the technique. This training manual was created using literary information from different sources.

In order to formalise the use of the FMEA within the CM organisation, a quality system procedure (QSP) fully devoted to the technique was devised. This explained the criteria for performing FMEA, the preferable composition of the team, execution of FMEAs and worksheet issues, revisions and follow-up actions. Appendix U details the quality system procedure.

Taking into consideration some of the limitations and difficulties identified during the course of the case study, brief guidelines were defined for where and when to conduct a FMEA. These are:

- Poor service history of existing designs.
- Unproved service history of existing or new designs.
- Novel use of existing or new equipment or technology.
- Failure would cause expensive maintenance.
- Item has a life limitation which adversely affects cost of ownership or availability.

Compiling FMEAs during the case study was extremely laborious and time consuming. Automation of the process can significantly ease this burden and help to integrate FMEA with the overall design process. Automation can be achieved in two ways or stages:

1. Automating the knowledge acquisition and clerical component of FMEA.
2. Automating the analysis component of FMEA.

In stage 1, it is vital that all FMEA related data be stored in a well structured database where it can be efficiently accessed and manipulated. The database also should facilitate expanding the FMEA programme into a multi-user environment. Automation of the analysis component requires additional

knowledge representation and reasoning capabilities that can be developed over the database. This thesis excludes stage 2 of the FMEA automation as it is beyond the established framework of the research.

In the context of this case study, the question of how best to organise a database for FMEA to resolve the problems were addressed. There were two options open to the researcher. Either a database for FMEA could be designed or a commercial software package could be purchased. A decision was taken to purchase a computerised database to ease the processing and subsequent administration of the FMEA worksheets. The advantages of such a software packages are discussed below.

### 9.4.7 Advantages of Using a Database for FMEA as Evaluated by the Case Study

*Meaningful division of data:* One major advantage of having a database for storing FMEA data is that the many types of data required to do the FMEA analysis, as well as the enormous amount of data generated by it are stored in a well organised fashion. The data is not stored in a single file at one place. Instead, it is distributed in several files which can even reside on separate systems. However, it is possible to link data in files containing related data. These files store the relational database tables which have been designed after conceptually modelling the data types involved in a FMEA.

*Faster access:* Huge amounts of data can be generated in a FMEA. On a complex system such as a machine tool product, a complete FMEA can be several hundred pages in length. Operations like editing parts of that data or viewing a specific type of data are frequently required during the analysis. Using a conceptually correct database design ensures that all relevant data reside together in a table and so only the required table needs to be opened for specific operations.

*Consistency:* A FMEA is a lengthy and tedious engineering analysis which requires inputs from engineers with expertise in design, manufacturing,

assembly, service and quality assurance. As highlighted in the case study, a team of individuals with specialised knowledge in these fields is assembled to work on the FMEA. Sometimes the FMEA is circulated with requests for comments. Either way, the FMEA is developed by many individuals which often leads to the use of inconsistent terminology. This, in turn may lead to extraneous, redundant and inconsistent data. Furthermore, it may possible lead to incomplete analyses. The use of a database promotes the use of consistent terminology. For example, the failure effects are stored in a 'effects' table with a code attached to each failure effect description. Many failure modes can have the same failure effect description and use of a table removes the need for storing the same effect description for each mode separately.

*Validity Checks:* As mentioned previously, multiple individuals working on the same FMEA project can give rise to inconsistency and incompleteness problems in the analysis. Some examples of incompleteness are (1) some new failure modes added to a sub-assembly may not be propagated up to the system level, (2) some vital data related to a sub-assembly may be missing or (3) some failure modes may not have been analysed completely. Validity checks are required at different stages to ensure that these types of incompleteness do not exist in the finished FMEA analysis. When the engineers move from one item failure to another, it can be checked whether the previous failure has been completely analysed. When engineers start working on a new level, it can be checked to ensure that all the failure effects from the lower level have been propagated up. These checks can be organised so as not to prevent the engineers from moving ahead but to provide a warning to remind the person of any incompleteness. These test can also be done and a list of incompleteness in the data can be presented, before a FMEA is approved.

*Easy maintenance:* Since the FMEA data is divided into meaningful groups and stored in separate files, maintenance of the data is easier.

More configurable capabilities for reports: A FMEA is essentially a reliability task. However, the data generated also provides valuable information to other

engineering groups in a company. As highlighted earlier, A FMEA can act as a common communications tool between design, reliability, development and manufacturing engineers. These engineers would prefer to view the FMEA data in a way that makes their work easier and less time consuming and the results better. Once the data is available in the form of tables in a database, each group or person can select precisely what they want to have included in a report and the way they want it presented.

*Fast, Easy and Specific Browsing of Similar Projects:* One way to improve the quality of a FMEA is to use FMEA data from similar projects for assistance in deciding upon the failure modes and their corresponding effects. This is often not feasible even if similar projects exist due to the volume of the FMEA worksheets which are often available on a flat spreadsheet. Conducting a FMEA is already a tedious process. If more than one similar project exists, browsing through their worksheets for help can greatly increase the workload on a FMEA analyst.

Maintaining the FMEA data in a database makes browsing through the data from similar projects not only possible, but less time consuming and more specific. Depending on the type of data which is needed for reference at a particular stage in the FMEA, the related FMEAs from other similar projects can be opened. A basic advantage of such a procedure is that all the projects in the system cab opened in parts. This replaces the cumbersome activity of flipping through the numerous worksheets used in a manual FMEA analysis. the activities of browsing and searching for the relevant data are integrated within the FMEA system itself.

*Data can be Used as Input for Other Reliability Techniques:* The use of a database facilitates the use of FMEA data for other reliability or design analysis techniques. This reduces duplication of effort.

### 9.4.8 Key Observations

The FMEA technique is purely a design analysis technique which when applied correctly can enhance the reliability of the final product design.

For effective application of FMEA, the technique must not be used in isolation from the design process. However, FMEA should not be adapted as a mandatory design activity which needs to be carried out for every new product design, subassembly and parts. This will lead to the failure of FMEA. In order to realise all the potential benefits of FMEA it should be conducted on a where relevant or where needed basis.

There are numerous difficulties associated with the use of FMEA. In particular, the technique can be a time consuming and tedious design engineering analysis activity. However, proper use and application should outweigh these limitations.

Automation of the FMEA process has significant advantages. It will allow the team to concentrate more on the analysis than on the associated clerical tasks such as collecting and organising input data, entering redundant data and formatting reports. It will also improve consistency and completeness of the analysis by encouraging the use of standard terminology, a common database and standard formats. It will also expedite the analysis by filtering the data and providing the analyst with faster and more timely access to it.

## 9.5 Summary

This chapter has examined the use of reliability-based techniques within the machine tool industry and the degree of application. In the light of the analysis and findings the following conclusions can be made:

1. The use of formal techniques in the machine tool industry is significantly low. However, there was considerable evidence which indicated that FMEA and Value Engineering are practised on a regular basis. Benefits such as engineering cost reduction, reduction of

warranty claims and reducing the need for unnecessary design features and parts results from the use of such techniques.

2. Manufacturers rely on the more conventional techniques of reliability assessment and analysis. Of the most profound significance is the reliance given to burn-in type testing and failure reporting and corrective action (FRACA).

3. Their are significant limitations and difficulties associated with the use of FMEA. However, if correct application can enhance the reliability of the final product design.

The next chapter focuses on use of field performance data in design improvements and the extent of application.

## 10. Analysis, Acquisition and Management of Reliability Data

### 10.1 Introduction

This chapter begins by briefly exploring the methods adopted by machine tool manufacturers to the analysis, acquisition and management of in-service data on equipment lifetimes. The main objective is to evaluate the extent to which such data are used for the purposes of (1) assessing field reliability and making comparisons with engineering predictions, (2) providing information for product modification and improvement, (3) assessing the effects of design changes, (4) estimating and explaining warranty costs and (5) to aid in the design of warranty and spare parts replacement programmes. Attention is then focused more specifically on the failure patterns of machine tool products. A reliability analysis exercise is conducted on a sample of machine tool products with the overall objective of evaluating the underlying failure distribution of machine tool products.

The basis for this inquiry was to test a series of hypotheses put forward in chapter 5 in relation to the use, analysis and management of reliability data in the machine tool industry. In chapter 5 it was postulated that the majority of the manufacturers pay insufficient attention to the collection and analysis of field performance data. In particular such data are not being fed back to design in a timely and systematic fashion. One reason may be that comprehensive data are often seen as expensive to obtain; another may be a lack of familiarity with methods for response-selective observational schemes for combining information from different sources. The purpose of this investigation was to test this presumption. This activity was necessary in the overall schema of the investigation in order to establish if a generic methodology needs to be developed.

### 10.2 Data Sources for Reliability Analysis

To calculate the reliability, maintainability or availability of a machine tool product requires information on repair time, run-time hours, part consumption,

nature and root causes of failure. Further, to investigate the root causes of field failures and suggest corrective actions, the integrity and accuracy of such data is critical. It is important that these calculations and failure investigations are based on the equipment failure and repair modes that have a direct impact on the system capability to meet specific functional requirements. The objective of this exercise was to understand and analyse the type of in-service data recorded and kept for archival and reliability analysis purposes by manufacturers.

There are clearly many factors that will determine what data should be collected. For the purposes of this inquiry, we assume that the study in question is directed at:

- Estimating the mean time between failure (MTBF) and other related reliability performance measures.
- Systematically analysing field failures and formulating corrective actions.

Many sources of in-service data exist which the manufacturer can consult on. Due to the difficulties involved in acquiring field data after the elapse of warranty, no effort was made on the side of the manufacturer to obtain data on repairs carried out by customers after the warranty period. Beyond the warranty period, there is a high probability that customers will either carry out repairs themselves or employ low cost machine tool maintenance and service organisations to carry out such activities.

Manufacturers have little factual information about the reliability of their products after the warranty period is completed. This is of some significance since the average length of warranty only amounts to 1 - 2 years. It appears that there is very little communication between manufacturers and users on this subject. Manufacturers are informed occasionally about major failures of a machine tool but, in general, they do not possess factual evidence concerning the reliability of their products such as average downtime.

All manufacturers kept archival records on service calls during and after the warranty period of some description. However, as Figure 10.1 illustrates, manufacturers make little use of these records for the purposes of reliability analysis. One explanation can be that most of the companies do not measure and evaluate field reliability performance or do not have a conforming system in place for failure reporting and corrective action (FRACAS). In the case of spare parts shipment, such data was regularly consulted and acted upon. It would appear that manufacturers use this data source for targeting improvements on high cost and high consumption parts on a pareto basis.

### 10.2.1 Types of Data Held

Table 10.1 shows the type of data recorded on a typical "service call" report. As illustrated in Table 10.1, in the majority of cases manufacturers record the serial number of the machine. The description of the failure is recorded in terms the failure mode, unit affected by failure, the component which failed if applicable and the cause of failure. The nature of repair, as well as repair time and travel hours is also recorded. Where possible and applicable, information on the part number and description of the part is also recorded. Although, "time of failure" and "time back in service" was not recorded, both the "date of failure" and "date back in service" was recorded for archival purposes. It was not possible to record the operating hours of a machine tool, due to the difficulties and costs involved in acquiring the value of this variable on a continuing basis.

Only 5 (30%) out of the total sample of 17 respondents indicated that they employed a coding system of some description to describe the failure. The coding system was such devised that the nature of failure (e.g. mechanical, control or electrical), nature of repair (e.g. repaired, modified or replaced), failure mode (e.g. fractured, backlash or noise), unit affected by failure (e.g. spindle assembly, axis assembly, tool magazine etc.) and component which failed (e.g. proximity switch, ballscrew etc.) can all be recorded in a coded fashion. Seventy per cent of the respondents descriptively recorded these

Table 10.1: Types of Reliability Data Recorded on a Typical Service Call Document

| Time Variables | Root Cause Variables | Component Variables |
|---|---|---|
| Date of Failure | Nature of Repair (e.g. Replaced, Repair) | Unit Affected by Failure |
| Date Back in Service | | Component Which Failed |
| Repair Time | Nature of Failure (i.e. failure mode, types of failure) | Part Number |
| Travel Hours | Causes of Failure | |

information. This is surprising since the use of a coding system facilitates easier processing and analysis of failure data, both manually and through the use of a computer.

### 10.2.2 Technical Analysis of Failed parts

Technical analysis of failed parts either carried out by the manufacturer of the machine tool product or the vendor forms an important element in the continuous improvement process of product reliability. In many cases analysis of field failure data is not sufficient to ascertain the root cause of failure. Therefore, technical analysis of a sample of failed parts needs to be conducted to ascertain the root cause of the problem and set corrective actions.

Several criteria are used by manufacturers for claiming and subsequently collecting failed parts from the field. Clearly, the majority of the manufacturers claim parts which only fail under warranty. Below is a list of three major criterion used by the majority of manufacturers for claiming parts which fail under warranty:

1. High cost items.
2. High failure rate items.
3. Items under vendor warranty.

Manufacturers highlighted a number of issues and logistical difficulties which impede the timely collection and technical analysis of failed parts. Tracking of failed parts, lack of customer co-operation in the return of failed parts and lack of vendor co-operation in owning the problem are the three major difficulties associated with the management of failed parts under warranty. In particular, difficulties are associated with tracking the physical location of failed parts in the field and within the manufacturers organisation. Chapter 7 illustrated the development of a 'quarantine' area within the Cincinnati Milacron organisation, specifically dedicated for the systematic collection and technical analysis of failed parts in the field.

### 10.3 Product Reliability Measurement and Evaluation

A key aspect in the process of monitoring, feedback and improvement of product reliability is that of measuring reliability and evaluating improvements on an objective basis. However, defining and measuring the reliability of machine tool products is often viewed as a complex, difficult and elusive aspect of reliability management. The purpose of this study was to understand and evaluate the type of reliability attributes used by manufacturers to measure and monitor field reliability performance.

Measuring product reliability can be seen as an objective means of evaluating field performance and identifying design improvements. There was clear evidence that the majority of manufacturers base their reliability measurements within the warranty period. Taking into account the difficulties associated with collecting field data beyond the warranty period, it was not possible for manufacturers to measure reliability within the useful economic life of a machine tool product. Similarly, manufacturers tend to base their reliability measurements on the total population of machines under warranty.

There were considerable variations in the characteristics used to measure product reliability. The majority of the manufacturers used conventional figures like 'failure rate' as a measure of reliability. This was measured as a proportion of the total machines under warranty. However, this performance figure was less likely to provide an accurate and objective measure of product reliability. A moderate number of respondents use the parameter 'mean time between failure' (MTBF) which reflected a more objective and effective measure of field reliability performance. Due to the difficulties and costs associated with monitoring machine elapsed hours, manufacturers tend to base their MTBF calculations on the assumption that all machines under warranty are operating on a continuous basis. Normally, a 8 hour, 5 days a week production shift pattern is assumed.

Usually, manufacturers measure reliability at system and unit level. The lack of integrity and accuracy of data caused significant difficulties in measuring

reliability at a component level. However, a small number of respondents indicated that where feasible and where needed, reliability is measured at a component level.

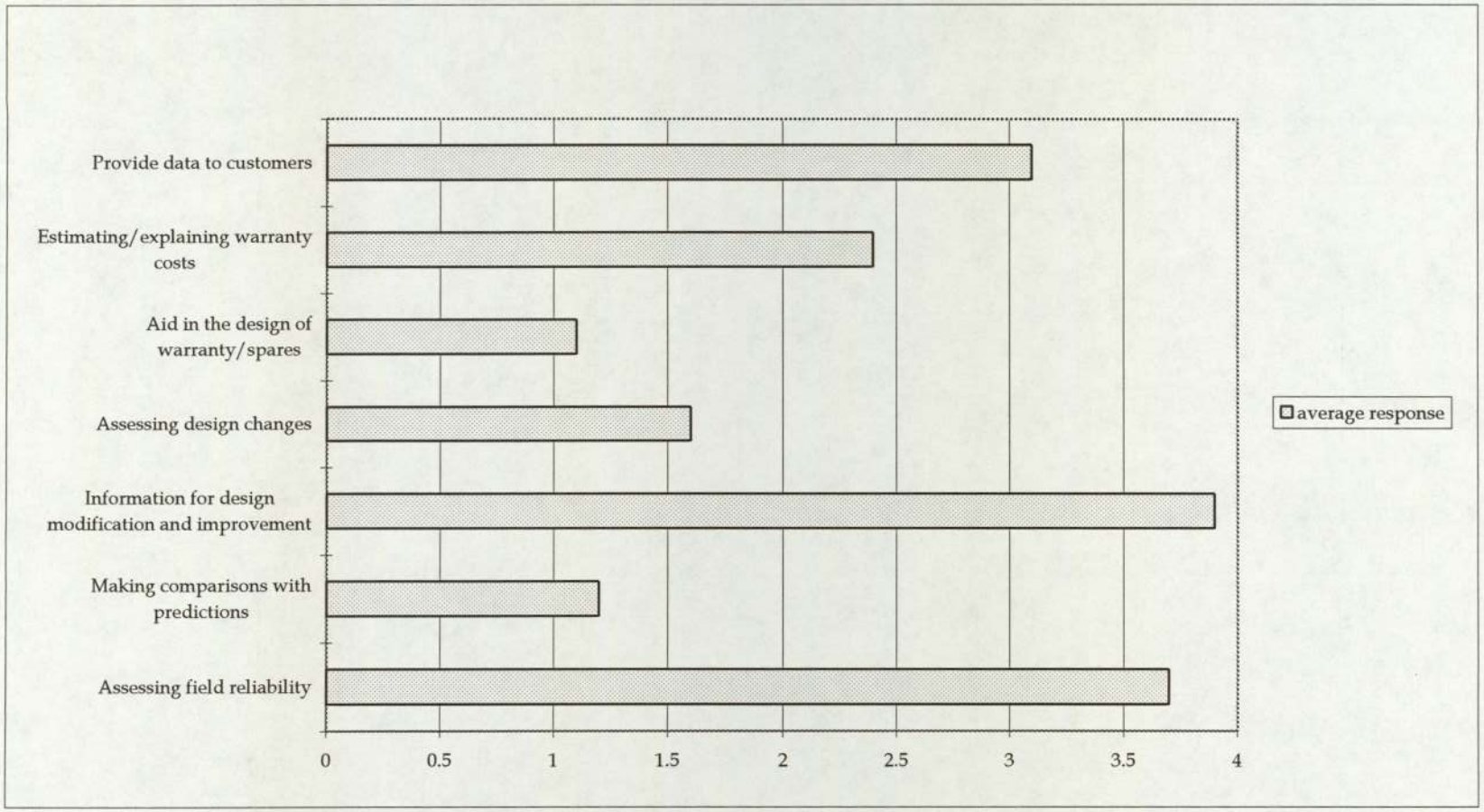
Figure 10.1 details the extent to which manufacturers use reliability measures as a means of (1) assessing field reliability, (2) making comparisons with engineering predictions, (3) providing information for design modification and improvement, (4) assessing the effects of design changes, (5) estimating and explaining warranty costs, (6) to aid in the design of warranty and spare parts replacement programmes and (7) provide data to customers.

Clearly, manufacturers frequently make use of reliability data as a tool for assessing field reliability and providing information for design modification and improvement. There was little evidence which indicated that reliability data is used for the purposes of predicting future warranty costs or in the design of spare parts planning. However, the results of this analysis suggests that there is a now a general trend where a significant number of sophisticated customers now demand information on the reliability of machine tools (see Figure 10.1).

## 10.4 Tests for the Validity of the Assumption that the Underlying Distribution of Machine Tool Life is Exponential

The above section highlighted the significance of MTBF as an objective means of measuring and monitoring the field reliability performance of machine tool products. Although, there has been a lack of interest on the part of many machine tool manufacturers in assessing quantitatively the reliability of products in the field, this is not the case for other sectors of the manufacturing industry. Indeed, many manufacturing organisations use MTBF to characterise the reliability of their products or systems. This form of practice is more prevalent in the electronic sector of the manufacturing industry and defence related industries.

Figure 10.1: Use of Reliability Data



Comprehensive quantitative analysis of reliability performance in the service of customers is less common for various reasons. Scientific sampling of items during service tends to be difficult and costly. Furthermore, warranty claims and other field record data are usually in a form inconvenient for reliability analysis.

This study deals with the reliability of machine tool products. The overall aim is to highlight the benefits of quantitatively assessing the field reliability of machine tool products. In context to this objective, a reliability analysis study of CNC machine tools was conducted to ascertain the following:

1. Evaluate the underlying life distribution of CNC machine tools within the warranty period.
2. Measure the reliability of CNC machine tools in a quantitative basis.
3. Evaluate principal causes of machine tool failures during service.

The case study deals with vertical machining centres (VMC) for application in a wide variety of production environments. The product was designed during the late 1980s and entered into service in early 1989. A CNC machine tool which has an automatic tool changing magazine and a manipulator is defined as being a machining centre. With the completeness of the machining centre's function, its composition is getting more and more complex. Therefore, the failure probability during operation also increases.

### 10.4.1 Background to Reliability Analysis

The reliability of a product is usually assessed in terms of events such as failures, repairs, part replacements and in terms of time averages such as operational availability. To limit the analysis the following failure events were considered:

1. Lifetimes or times to failure of machine tools.
2. Repeated events such as repairs and replacement of parts.

An important point concerns the time scales on which such events are considered. In particular, the distinction between calendar time and operational or usage time for a product must be recognised. Many products are used intermittently. Machine tools most definitely fall under this category. It is, therefore, often normal to define a process that represents the total "usage" time for a product up to a specific calendar time $x$. Probabilities or rates of occurrence of failures and other events usually depend both on calendar time and the usage time process. Depending on one's objective and the process in question, analysis may focus on calendar time, usage time or both. However, in many reliability studies, the difficulty of obtaining accurate information about a unit's usage time process limits the accuracy of any calculated reliability characteristics.

Machine tools are prime examples of the points made. Due to the difficulties and costs involved in acquiring actual operating hours of machine tools during service, the following assumptions were taken:

- Machine is used constantly during service life.
- An average of 16 hour production shift pattern was assumed.

Furthermore, the machines entered into service individually. The implication of this was that the population of machines in service was growing. With a young and growing population of machines, it is entirely possible that failure data will comprise of relatively short times in service, making it essential to obtain all failure information on those machines still in service and yet to fail. Therefore, in order to eliminate this problem, reliability analysis was conducted in terms of operational time $t$, rather than calendar time.

Whenever possible an analysis is to be performed by making as few assumptions as possible. In this case study, the actual machine tools were of the same design and manufactured by the same production line. However, field conditions are not entirely identical for each of the deployed products. The operation of the system as well as the environmental conditions varied

quite considerably. For example, some machines were used on a continuous 24 hour production basis, while others were used intermittently.

Analysing the field behaviour for each individual machine tools was not practical in the present case, because some of the machines did not fail at all. Furthermore, the number of failures per product for the failed systems were reasonably small.

### 10.4.2 Data Collection

Two options were available to the author concerning the collection of field failure data:

1. Longitudinal field tracking or follow-up studies where a group of units is closely monitored over a specific time period.
2. Warranty or failure record data.

Longitudinal field tracking studies were ideal for collecting failure data, since they provide maximum information. Studies of this type are sometimes conducted by companies who designate and track a group of units. However, this method of data collection tends to be expensive and therefore the sample number is usually small. Warranty and failure record data was used as the main source for this reliability analysis study. This provided a much larger source of information.

The warranty and failure record data were extracted from the service reports produced by service engineers for the machines which were under the warranty period. Initially a number of customers were contacted in an attempt to collect field failure data beyond the warranty period. However, this proved to be unsuccessful due to the inadequate and incomplete maintenance records kept by the majority of customers. In this respect the reliability analysis was conducted within the warranty period which amounted to approximately 1 year.

After consultation with various departments at Cincinnati Milacron, it was decided to collect qualitative and quantitative failure information. The failure information recorded were divided into the following variables:

- Time variables (e.g. date of failure)
- Failure description (i.e. failure mode, causes and effects)
- Sub-systems and components affected by failure (e.g. tool magazine, proximity switch).

Alpha-numeric codes were adopted to codify the information. This code represented the main assembly affected by the failure, the component which failed, the root cause of failure and corrective action taken. Figure 10.2 details an example of a code.

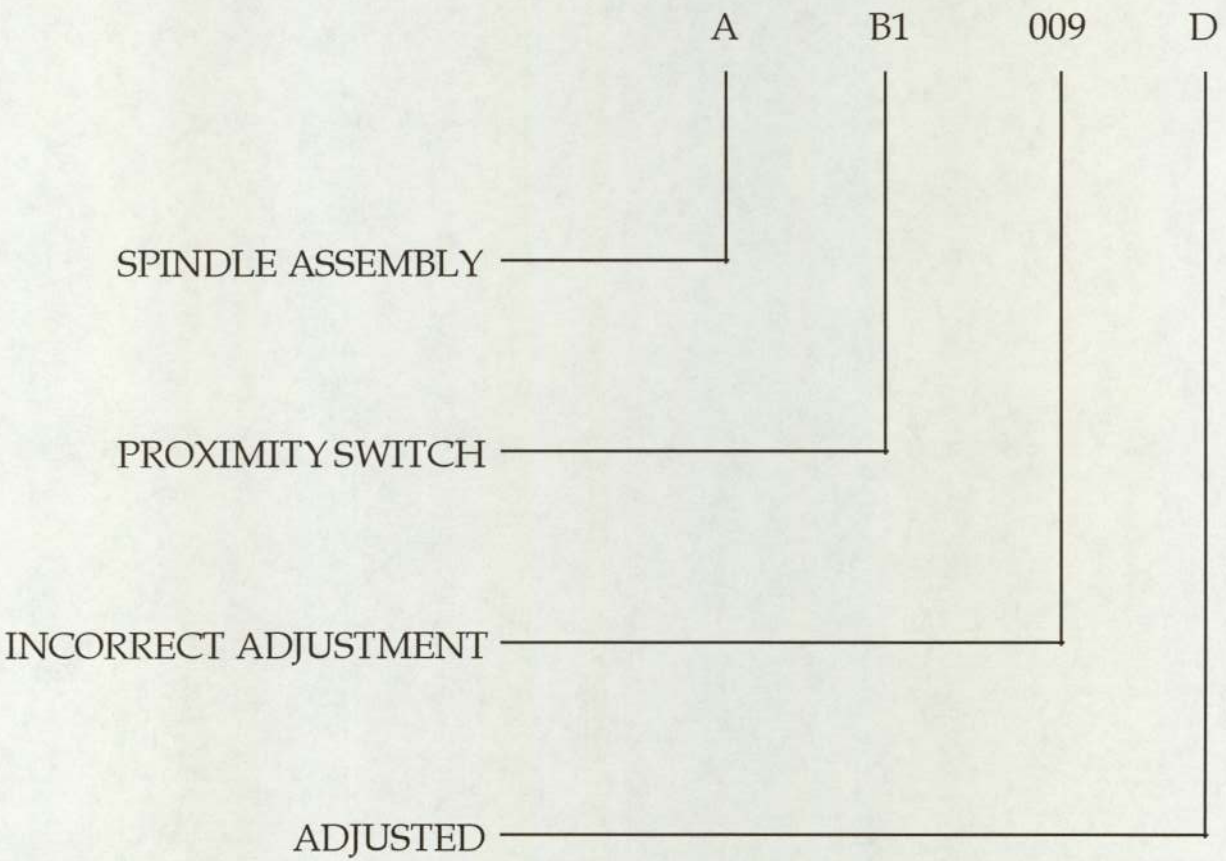
### 10.4.3 Probability Distribution of Machining Centre Failures

To evaluate the probability distribution of machining centre failures, the Weibull distribution was used. The Weibull distribution is one of the most versatile and widely used distributions in many fields of statistical measurement. It was originally derived by the Swedish scientist Walodi Weibull, who used it to describe the breaking strength of materials and life properties of ball bearings. It has the great advantage in reliability work in that by adjusting the distribution parameters it can be made to fit many life distributions.

The reason for selecting this distribution model was as a direct result of the following features which make it attractive for reliability analysis studies [Davidson, 1988]:

- Flexibility. It can deal with increasing, constant and reducing hazard.
- Mathematical simplicity.
- Amenability to graphical analysis.

Figure 10.2: An Example of a Failure Code



- A demonstrated ability to fit most lifetime data better than most of its potential competitors.

In terms of the reliability function, the Weibull distribution may be defined as follows:

$$R(t) = 1 - F(t) = \exp\left[-\left(\frac{t-\delta}{\eta}\right)^{\beta}\right] \quad \ldots\ldots\ldots 1$$

where,

$\eta$ is the scale parameter, known as the 'characteristic life.' It is the value of $t$ at which there is an approximately 2/3 probability that the component will have failed. Precisely, the probability is 0.632. The characteristic life is an indirect measure of overall reliability. The larger its value the longer the component is expected to survive.

$\beta$ is a shape parameter which is related to the behaviour of the hazard function. The shape parameter defines the form of the Hazard Rate Function, z(t), and indicates whether it is increasing, decreasing or constant.

- For $\beta = 1$, the Hazard Rate Function is constant. This is equivalent to the exponential function and therefore exhibits a constant failure rate. When shape parameter equals 1 then the mean life is equal to the characteristic life.

- For $\beta > 1$, the Hazard Rate Function is increasing. The larger the value the more rapidly it increasing. It is unusual to encounter values greater than 4. Values greater than 1.5 - 2.5 normally indicates wear-out failures.

- For $\beta < 1$, the Hazard Rate Function is decreasing. Values must be greater than zero and it is unusual to encounter values greater than 0.5. Values within the range of 0.5 -0.6 normally indicates early life

failures (infant mortality) which are primarily related to design and manufacturing defects.

$\delta$ is defined as the location parameter. Normally the appearance of a monotonic curve indicates that the origin of the *ti* values is not zero. This situation arises when there is some interval (from $t = 0$ to $t = \delta$) during which failures cannot occur.

Equation 1 represents the 'three-parameter' Weibull which has a minimum (non-zero) life. This means that the population of products operates for an initial period of time without failure. Many real-life products fit into this category. As machine tool products do not exhibit any minimum life, the 'two-parameter' Weibull model was used in this case study:

$$R(t) = 1 - F(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad \text{.....2}$$

Weibull analysis was conducted at system level failures to ascertain the underlying failure distribution of machining centres. This involved the process of obtaining the value of the shape and scale parameter from the observed failure data. There were both graphical and analytical methods available. Analytical methods involves the estimation of maximum likelihood estimates (MLEs) of the shape parameter and the characteristic life. This is determined using algebraic methods. This is easily done for 'complete' data where, for example, the mean and variance of the data provide estimates of the corresponding population values. However, it is more difficult for when there is any censoring. Normally a computer program is used to ease the calculations involved in MLEs. Due to these difficulties associated with using MLEs to estimate Weibull parameters, analysis in this particular case study was conducted using the graphical technique. This graphical technique has the attraction of producing additional subjective information about the data beyond that included in the estimates.

As the operational time amounted to 1 year (i.e. the warranty period), graphical analysis itself was considered under two headings. One referred to what is known as 'complete' data (where all the items in the population had failed) and the other to 'censored' data which includes unfailed items. Failure data was analysed as if it consisted of a life test on a number ($n$) of similar units that were tested until $k$ of them failed.

Two methods of conducting Weibull analysis under the graphical method were open to the researcher:

- The Cumulative Distribution Function (CDF) method and;
- The Cumulative Hazard Function (CHF) method.

The CDF technique involves calculating the percentage of population failed using the method of Median Ranking. Typically, for samples between the 25 and 50, statistical tables are used to determine median rank values. For samples greater than 50, the median rank values can be determined from the following "Bernard's" Expression:

$$\text{Median Rank} = \left(\frac{i-0.3}{n+4}\right) \times 100$$

where,

n = number of machines under analysis and;

i = number of failures so far.

The CHF method involves determining the hazard rate functions against the number of survivors. This is carried out on a cumulative basis. Both the CHF and CDF methods were used for the purposes of conducting the analysis. The procedure that was followed were as follows:

1. Due to the large amount of failure data, time between failure (TBF) were grouped in class intervals of 200 hours.

2. The frequency of failure for each class intervals were noted. Complete and censored data were separated to avoid ambiguity.
3. The hazard rate *z(t)*, for each class interval were determined.
4. Using the hazard rate values, the cumulative hazard rate *H(t)* for each class interval were determined.
5. Using the formulae below, the failure distribution function for each class interval were determined:
    - $F(t) = 1 - e^{-H(t)}$
6. The F(t) values were plotted against operating hours in Weibull graph paper and the best straight line was constructed through the data points. All appropriate Weibull parameters were determined from the graphical plot

The calculated results of hazard and distribution function are shown in. The results are plotted in Figure 10.3 from which the Weibull parameters were estimated as follows:

- Shape Parameter, $\beta = 0.8$.
- Scale Parameter, $\eta = 1100$ hours.
- Mean Life, $\mu = 1300$ hours.

From these estimated parameters the following conclusions regarding the reliability of vertical machining centres and their lifetime distributions can be drawn:

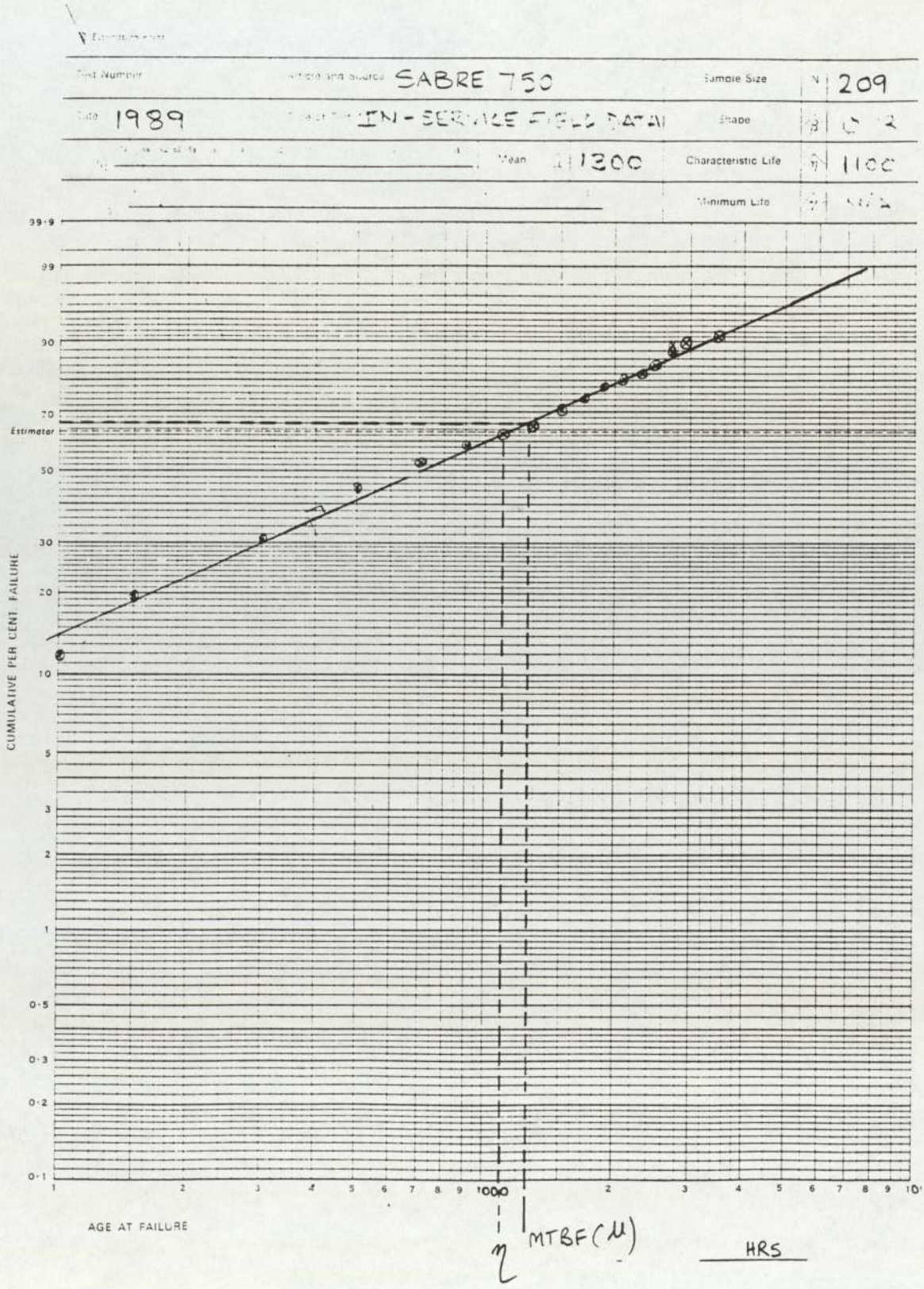
*Machining centres exhibit a constant failure rate:* The failure pattern of machining centres fits the exponential distribution. This is consistent with the fact that the data analysed corresponded to the warranty period. In general, one would not expect failures due to wear-out or infant mortality failures during this period.

This also indicates that the failure rate ($\lambda$) and MTBF ($\theta$) of machining centres can be estimated using the following two simple formulae:

Table 10.2: Weibull Table of Machine Failures

| Category | Frequency (F) | Frequency (C) | s | z(t) | H(t) | F(t) |
|---|---|---|---|---|---|---|
| 0 - 100 | 25 | 0 | 209 | 0.127 | 0.127 | 0.119 |
| 100 - 200 | 16 | 0 | 184 | 0.091 | 0.218 | 0.196 |
| 200 - 400 | 25 | 0 | 168 | 0.161 | 0.379 | 0.315 |
| 400 - 600 | 29 | 2 | 143 | 0.227 | 0.606 | 0.455 |
| 600 - 800 | 16 | 5 | 112 | 0.158 | 0.764 | 0.534 |
| 800 - 1000 | 11 | 2 | 91 | 0.130 | 0.894 | 0.591 |
| 1000 - 1200 | 6 | 1 | 78 | 0.081 | 0.975 | 0.623 |
| 1200 - 1400 | 4 | 2 | 71 | 0.059 | 1.034 | 0.644 |
| 1400 - 1600 | 12 | 2 | 65 | 0.207 | 1.240 | 0.711 |
| 1600 - 1800 | 6 | 3 | 51 | 0.129 | 1.369 | 0.746 |
| 1800 - 2000 | 6 | 0 | 42 | 0.154 | 1.523 | 0.782 |
| 2000 - 2200 | 3 | 1 | 36 | 0.088 | 1.612 | 0.800 |
| 2200 - 2400 | 2 | 2 | 32 | 0.067 | 1.678 | 0.813 |
| 2400 - 2600 | 4 | 1 | 28 | 0.157 | 1.835 | 0.840 |
| 2600 - 2800 | 6 | 1 | 23 | 0.308 | 2.143 | 0.883 |
| 2800 - 3000 | 1 | 0 | 16 | 0.065 | 2.207 | 0.890 |
| 3000 - 3200 | 0 | 0 | 15 | 0.000 | | |
| 3200 - 3400 | 0 | 2 | 15 | 0.000 | | |
| 3400 - 3600 | 3 | 1 | 13 | 0.273 | 2.480 | 0.916 |
| 3600 - 3800 | 0 | 1 | 9 | 0.000 | | |
| 3800 - 4000 | 0 | 8 | 8 | 0.000 | | |
| **Total** | **175** | **34** | | **KEY:** | F = Failure | |
| | **Sample Size** | **175 + 34 = 209** | | | C = Censoring | |

## Figure 10.3: Weibull Probability Plot of Machine Failures



$$\lambda = \frac{r}{\sum_{i=1}^{n} ti}$$

where r is the total number of failures of all machining centres, ti is the operating time of the ith machining centre during warranty and n is the number of machining centres. Similarly the MTBF can be estimated as follows:

$$MTBF = 1/\lambda$$

*Mean time between failure (MTBF):* The mean time between failures (MTBF) of machining centres is equivalent to its characteristic life and can be stated as being 1100 hours approximately. The equivalent failure rate per 10, 000 hours is approximately 9.09. This MTBF value for CNC machine tools is significantly large compared to conventional machine tool products. The MTBF of conventional machine tool products was estimated to be 500 hours [Stewart, 1975].

*Principal causes of failure:* The hazard rate characteristic indicates that the failures are most likely due to general design and manufacturing deficiencies which occur during the initial warranty period of machine tool products.

Where appropriate, Weibull analysis was also conducted at unit level to ascertain 'mean life' of failed units. An example of a Weibull analysis conducted on the failure of spindle assemblies is shown in Table 10.3. Figure 10.4 illustrates the Weibull graphical plot of the spindle assembly. The 'mean life' of failed spindle assemblies only was derived as being approximately 4200 hours. A shape parameter value of greater than 2.0 indicated wearout failures.

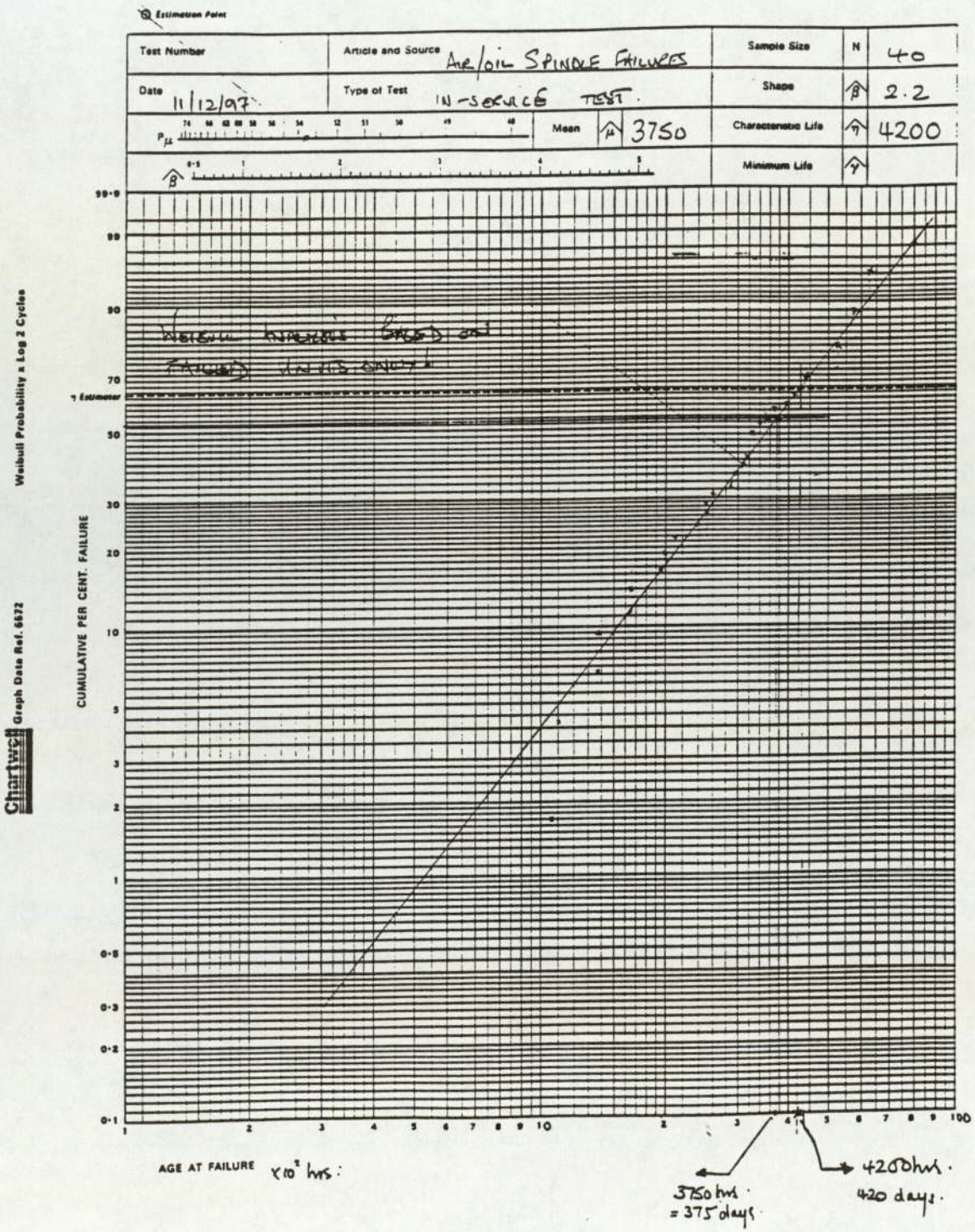
### 10.4.4 Summary of Principal Causes of Machine Tool Failures

The survey into principal causes of machine tool breakdowns covered a larger sample of machine tool products within the warranty period. All breakdowns were analysed in terms of machine tool zones in which a failure occurred, the machine components responsible for failure and the reason for failure. As this

Table 10.3: Weibull Table of Spindle Failures

| Number of Failure $i$ | Percentage of Population Failed (Median Ranking) | Age at Failure (Hours) |
|---|---|---|
| 1 | 1.74 | 1070 |
| 2 | 4.21 | 1100 |
| 3 | 6.68 | 1380 |
| 4 | 9.16 | 1380 |
| 5 | 11.63 | 1650 |
| 6 | 14.11 | 1650 |
| 7 | 16.58 | 1940 |
| 8 | 19.05 | 1990 |
| 9 | 21.53 | 2110 |
| 10 | 24 | 2410 |
| 11 | 26.48 | 2490 |
| 12 | 28.96 | 2490 |
| 13 | 31.45 | 2590 |
| 14 | 33.91 | 2840 |
| 15 | 36.38 | 2870 |
| 16 | 38.86 | 3020 |
| 17 | 41.34 | 3050 |
| 18 | 43.81 | 3080 |
| 19 | 46.29 | 3090 |
| 20 | 48.76 | 3260 |
| 21 | 51.24 | 3350 |
| 22 | 53.72 | 3530 |
| 23 | 56.19 | 3690 |
| 24 | 58.67 | 3990 |
| 25 | 61.14 | 4060 |
| 26 | 63.62 | 4120 |
| 27 | 66.09 | 4330 |
| 28 | 38.56 | 4390 |
| 29 | 71.04 | 4800 |
| 30 | 73.51 | 4870 |
| 31 | 75.99 | 4940 |
| 32 | 78.46 | 5200 |
| 33 | 80.95 | 5200 |
| 34 | 83.42 | 5290 |
| 35 | 85.89 | 5600 |
| 36 | 88.37 | 5720 |
| 37 | 90.84 | 5830 |
| 38 | 93.32 | 5950 |
| 39 | 95.79 | 6170 |
| 40 | 98.27 | 8030 |

Figure 10.4: Weibull Probability Plot of Spindle Failures (Unit Level)



survey was conducted from the perspective of the machine tool manufacturer, downtime was only recorded in terms of (1) diagnosis time and (II) repair or restore time. Logistic delay and manufacturers response time were excluded from the analysis. All software faults were excluded from the analysis.

*Distribution of Breakdowns in Machine Tool Zones:* An analysis of results of the survey provided the distribution of failures between machine tool zones. This particular analysis suggests that the majority of the downtime is caused by failures of the main spindle assembly and tool magazines. In terms of failures, a significant proportion of failures are due to CNC hardware, servo drive systems, spindle assembly and the tool magazine. Tables 10.4 and 10.5 lists the eight main machine zones in which the highest downtime and the highest frequency of breakdowns occurred.

*Machine Components Responsible for Failures:* Analysis of all the results provided a list of components responsible for the majority of the downtime and the greatest frequency of failures. Servo motors and drives, micro switches (limit and proximity), bearings, relays, protective telescopic covers and coolant pumps are examples of high failure rate components which lead to poor machine tool reliability during the warranty period. Table 10.6 details main machine tool components responsible for failure, with reference to machine tool zones.

*Principal Causes of Failures:* Fundamentally, a significant number of failures were due to poor reliability of commercial supplied parts. This is particularly true for electronic and electrical components, such as PCBs. Foreign matter contamination in the form of swarf and coolant is another major cause of mechanical component failures. Poor routing of electrical harnesses contributed a significant amount to the failure of machine tools.

Table 10.4: Downtime as a Function of Machine Tool Zone in Which Failures were Recorded

| Machine Zone | Downtime % | Average Repair Time (hrs) | Nature of Failure Downtime % Mechanical | Electrical | Servo/Control |
|---|---|---|---|---|---|
| Pneumatic System | 3.33 | 0.50 | 3.17 | 0.17 | N/A |
| XYZ Slideways - Base/Saddle/Table/Column | 10.27 | 1.50 | 5.65 | 1.54 | 3.08 |
| Main Spindle Assembly | 30.14 | 4.40 | 25.62 | negligible | 4.52 |
| Tool Magazine/Changer | 21.23 | 3.10 | 19.11 | | 1.91 |
| Machine Guarding - External and Internal | 14.38 | 2.10 | N/A | N/A | N/A |
| CNC Hardware | 6.16 | 0.90 | N/A | N/A | N/A |
| Electrics | 6.16 | 0.90 | N/A | N/A | N/A |
| Servo Drive and Control System | 8.22 | 1.20 | N/A | N/A | N/A |

Table 10.5 Number of Failures Occurring in Various Machine Zones

| Machine Zone | Failures % | Nature of Failure Failures % Mechanical | Electrical Electronics | Servo/Control |
|---|---|---|---|---|
| Pneumatic System | 5.03 | 3.87 | 1.66 | N/A |
| XYZ Slideways - Base/Saddle/Table/Column | 7.65 | 7.65 | also servo motors | also servo motors |
| Main Spindle Assembly | 34.70 | 29.84 | 4.86 | also servo motors |
| Tool Magazine/Changer | 21.79 | 19.83 | 1.96 | N/A |
| Machine Guarding - External and Internal | 2.30 | N/A | N/A | N/A |
| CNC Hardware | 10.20 | N/A | 10.20 | N/A |
| Electrics | 7.66 | | 7.66 | |
| Servo Drive and Control System | 10.67 | | | 10.67 |

Table 10.6: Typical Components Responsible for Failures

| | Typical Components Responsible for Failures | | | |
|---|---|---|---|---|
| Pneumatic & Coolant System | Valves (air operated & solenoids) | Air/Oil Filters & Regulators | Pneumatic Cylinders | Coolant Pumps |
| XYZ Slideways - Base/Saddle/Table/Column | Thrust Bearings | Telescopic Covers | | |
| Main Spindle Assembly | Polychain Belts | Spindles | Spindle Bearings | Rotary Couplings |
| Tool Magazine/Changer | Geneva Mechanisms | | | |
| Machine Guarding - External and Internal | Safety Interlocks | Safety Switches | | |
| CNC Hardware | PCBs | Main Processors | VDUs/CRTs | |
| Electrics | Cables/Harnesses | Relays | I/O Modules | Power Supplies |
| Servo Drive and Control System | Servo Motors/Encoders | Servo Drives | | |

### 10.4.5 Reliability Database for Continuously Monitoring Machine Tool Reliability

A PC-based reliability database (named 'MTBF Predictor') was developed for measuring and monitoring machine tool reliability on a periodic basis and for automating the reliability analysis task. A model of the reliability database is illustrated in Figure 10.5. The database was designed using relational database technology concepts and predicts machine tool reliability based on the constant failure rate method. It consists of an active element and two forms of output.

The active element stores field and machine information like failure mode, units affected by failure, component responsible for failure, serial number, machine tool type and repair time. Reports from the database are of two types:

1. Periodic reports of performance with respect to maintainability and reliability. This identifies possible areas of reliability improvements up to component level.
2. Periodic reports providing MTBF values of machine tool products at system, unit and component levels. These reports also compare actual performance against a MTBF goal and monitors trends in reliability performance.

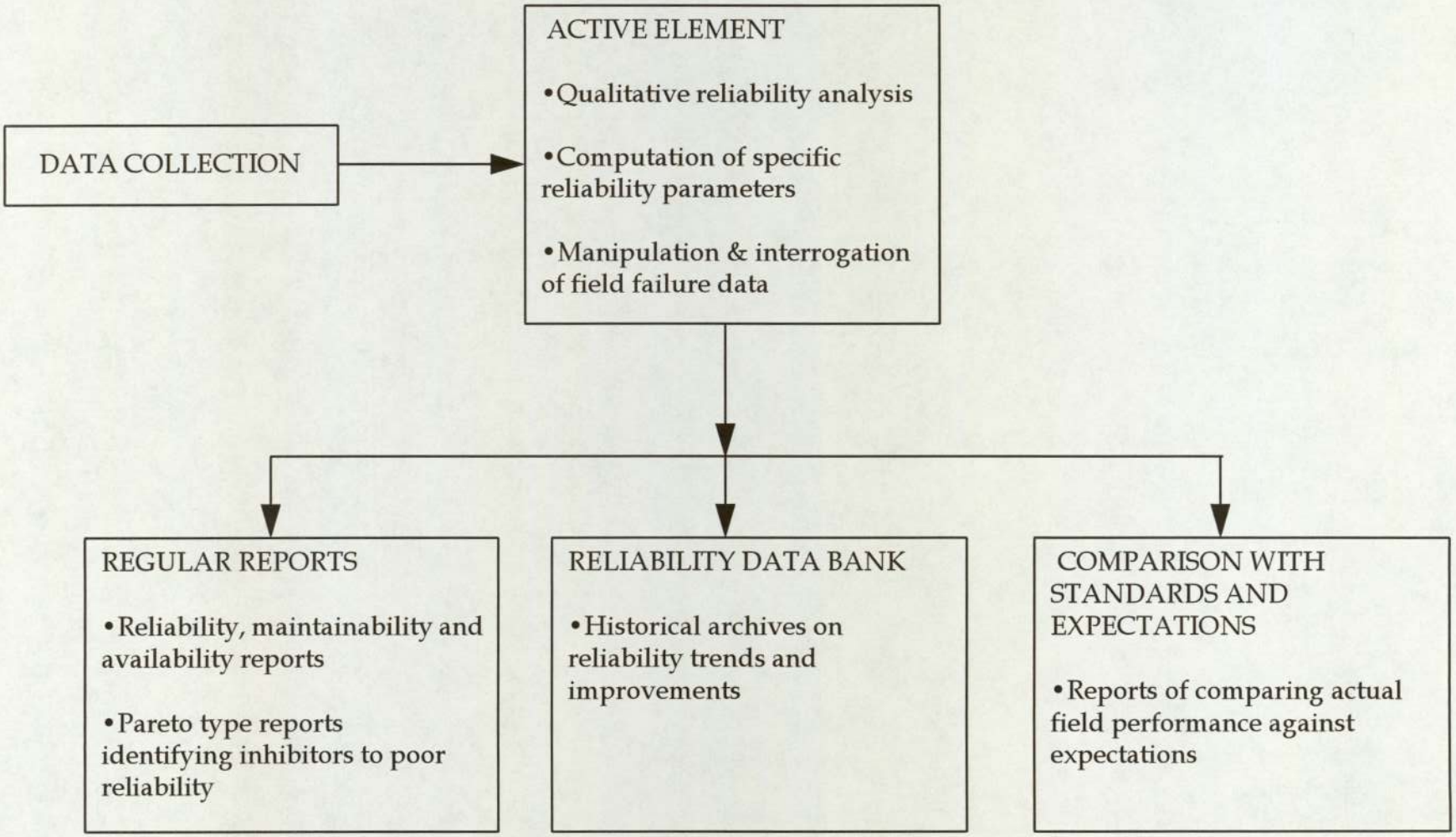
Further information on the design and development of the 'MTBF predictor' database is provided in Appendix T.

## 10.5 Concluding Summary

A subjective approach is adopted to the investigation of field failures by the majority of machine tool manufacturers. The analysis of the survey data suggests that machine tool manufacturers do not measure or monitor the field reliability performance of their machine tool products.

Little use is made of field failure data in assessing field reliability and making comparisons with engineering predictions, assessing the effects of design changes, estimating and explaining warranty costs or to aid in the design of

Figure 10.5: A Conceptual Model of the MTBF Database



warranty and spare parts replacement programmes. However, there was significant evidence that many machine tool companies make use of field data in the area of product modification and design improvement.

The survey of machine tool breakdowns proved a useful exercise for (1) ascertaining the overall failure distribution of machine tool products within the warranty period and (2) evaluating the fundamental causes of machine tool breakdowns. The survey also provided useful evidence of the benefits of conducting this reliability analysis exercise from an industrial perspective. Companies who pursue this essential engineering activity on a periodic basis are more likely address field failure issues on a systematic and objective basis, rather than relying on a subjective field information. The following conclusions were drawn from the analysis of the survey results:

1. The average downtime recorded during the breakdown survey was approximately 2% of the available production time (75 hr/week, with an average repair time of 1.8 hours.
2. CNC hardware, spindle assembly, servo drives and tool magazines contributed approximately 75% of total number of failures recorded. As was expected failures of a mechanical nature involved more downtime than electrical or control related failures. These are, perhaps, the most obvious areas where improvements in machine tool reliability are required and can be implemented by better design and the use of advanced technology with high reliability.
3. Examples of components which were observed to have the highest frequencies of failures were spindle and slideway bearings, geneva mechanism, limit and proximity switches, servo motors, servo control drives and printed circuit boards (PCBs).
4. The most common reason for failure was poor reliability of commercial parts. This is not surprising, since a significant proportion of the constituent parts of a machine tool product is

commercial. Supplier development is therefore a critical area of reliability improvements of machine tool products.

In view of the above survey, a PC-based database was designed for the automation of the above engineering activity. The database was designed using 'relational database technology.' It proved to be a useful software tool for (1) predicting MTBF of machine tool products at system, unit and component level and (2) identifying areas where improvements in reliability is needed.

The next chapter is concerned with developing a generic methodology for improving the reliability of machine tool products.

# PART III

# DESIGN AND EVALUATION OF RELIABILITY MONITORING, FEEDBACK AND IMPROVEMENT SYSTEMS

# 11. Developing a Generic Methodology for the Improvement of Machine Tool Reliability

## 11.1 Introduction

Previous chapters have identified a number of shortcomings with the approaches adopted by the majority of manufacturers to the management of product reliability in general. These deficiencies can be broadly attributed to a limited knowledge in the current 'state of the art' methods of solving product reliability problems and not undertaking particular aspects of the reliability management process effectively. However, the fundamental problem underlying the approach taken by the majority of machine tool manufacturers is a lack of a systematic and holistic approach to the reliability improvement process. This chapter has the objective of developing a generic methodology which will provide guidance to manufacturers who are seeking to improve their reliability management process.

The key foundation of the methodology is to provide a single unifying conceptualisation that encompasses the complexity and diversity of the reliability improvement process of machine tool products. Therefore an integrative and comprehensive methodology is constructed which embraces both the design, manufacture and service aspects of machine tool reliability. The reason for constructing a comprehensive methodology is that without considering all aspects of the reliability improvement process, it is not possible for users to benefit substantially from improving upon or implementing a single technique in isolation.

The main aim has been to develop a generalised methodology, or more precisely a set of guidelines, to assist in the improvement of the reliability management process. The derivation of the methodology has been primarily achieved by (1) compiling a detailed longitudinal case study of Cincinnati Milacron (CM) and their approaches to the management of product reliability and (2) a comprehensive survey, employing five sets of questionnaires.

The methodology is firmly placed in the domain of machine tool and machine tool equipment reliability. It is not intended as a methodology for use in other sectors of the manufacturing industry, although many of the considerations and principles are general to the problems experienced by other sectors. The methodology is itself flexible, enabling users to focus on all or some of its sections depending on their own particular needs.

### 11.2 The Development and Use of the Methodology

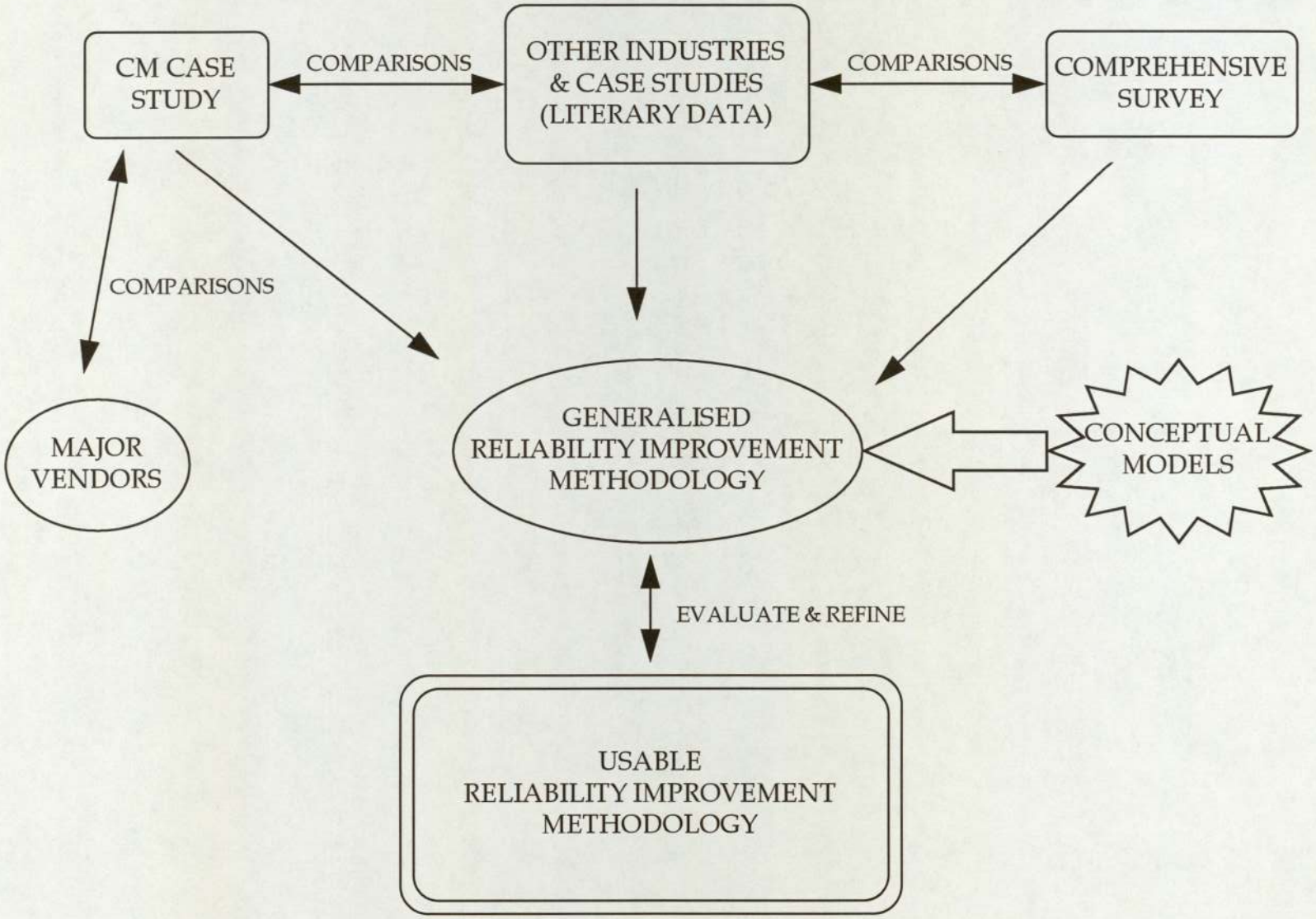
The methodology is primarily based on CM's reliability management and improvement process. As a result of the research programme this has been generalised, refined and reproduced in a form which can be used by the majority of machine tool manufacturers in the machine tool industry. Figure 11.1 illustrates the development of the methodology.

The generation and where possible the evaluation of the methodology was carried out in parallel with a detailed study of CM. The results of this longitudinal study can be found in chapter 7. Comparisons were made with similar companies through the use of a survey and through contacts with the Advanced Manufacturing Technology Research Institute (AMTRI) and the Machine Tool Technologies Association (MTTA). As well as conducting 'action type' research, the researcher undertook semi-structured interviews on an informal basis and used a variety of primary and secondary documentary sources. In particular references were made to major vendors of CM.

The methodology can be best described as a set of 'guiding rules' that allows companies to adopt the state of the art methods of reliability management and improvement. It is based around a general philosophy rather than being a rigid model.

The methodology has resulted from investigations carried out primarily within the machine tool industry. It is therefore evidently clear that the methodology is readily available for use in firms who are engaged in the manufacture of machine tool and machine tool equipment products. Although, use of the

Figure 11.1: The Development of the Methodology



guidelines and principles is not limited to any particular size of company, it is more beneficial among the larger machine tool manufacturing organisations. In practice, the concept could be considered in all situations where market demand is for high product reliability at low cost.

The methodology proposed provides the basis for recognising positive aspects of a manufacturers reliability management system. This is achieved by comprehensively embracing the methodology as a benchmarking tool. Therefore, the intention is not for the user to move from one component of the methodology to the next in a sequential way. Rather, it is designed to be flexible enough for the user to focus on a particular element of the methodology most relevant to their own particular needs.

### 11.3 Requirements Definition for a Generic Methodology

In addition to the key foundations of the methodology detailed above, there are a number of general requirements that are evident from the analysis presented in previous chapters. These general requirements can be combined together into a 'systems specification' identifying issues that the methodology must address. The key issues of this specification are given below:

1. The need to give consideration to reliability issues early on in the product introduction process.

2. Coupled with the field failure reporting and corrective action procedure, the methodology is also to consider the concept of planning and conducting field-tracking studies as a critical element of this procedure.

3. The methodology to consider product failure issues (during service) as an integral part of the design improvement process.

4. A measuring system is to form an integral part of the methodology. This will enable the reliability performance of machine tool products to be monitored and assessed against 'goal' orientated metrics.

5. The concept of a reliability database for measuring reliability should be embedded within the methodology.

6. Formal tools and techniques (e.g. design FMEA) for analysing the effects of engineering decisions are to form the pinnacle of the proposed methodology. These methods will form the basis for analysing the downstream effects of engineering decisions during (I) the product introduction process, (II) small scale incremental engineering improvement or (III) adaptation of new technology.

### 11.4 Overview of the Proposed Methodology

The proposed methodology is formed by the combination of three key elements each with different confines. This is supported implicitly by the assumption of best practice change management. This assumption has been made as a consequence of the commonality of this to all initiatives that seek to significantly improve organisational effectiveness. Essentially, the three elements are (1) Structured Product Development (2) Performance Metrics and (3) Supporting Methods. The three elements of the methodology are elaborated below:

*Structured Product Development* - Product reliability is strongly influenced by engineering decisions. In context to this, guidelines based on 'best practice' models are specified for the purposes of evaluating progress, consistency and technical adequacy. This element of the methodology covers the conceptual, design and development and machine build phase of the product introduction process.

The instrument provides the fundamental basis for considering objectives such as reliability estimates and achievements, identification of principal items inhibiting reliability and reviewing reliability effort. Furthermore, it allows manufacturers to adopt a systematic approach to the process of problem identification, analysis, solution development and solution implementation of the design.

*Performance Metrics* - This key element is concerned with evaluating specific reliability metrics for monitoring field reliability performance. It basically covers the 'operation and usage' phase of the machine tool life cycle. Essentially it is concerned with data collection, analysis and feedback, to facilitate reliability improvement.

*Supporting Methods* - The majority of reliability-based methods reviewed and studied in this thesis can be directly associated with one or more steps of the product introduction process. Useful methods for use in supporting engineering decisions are specified.

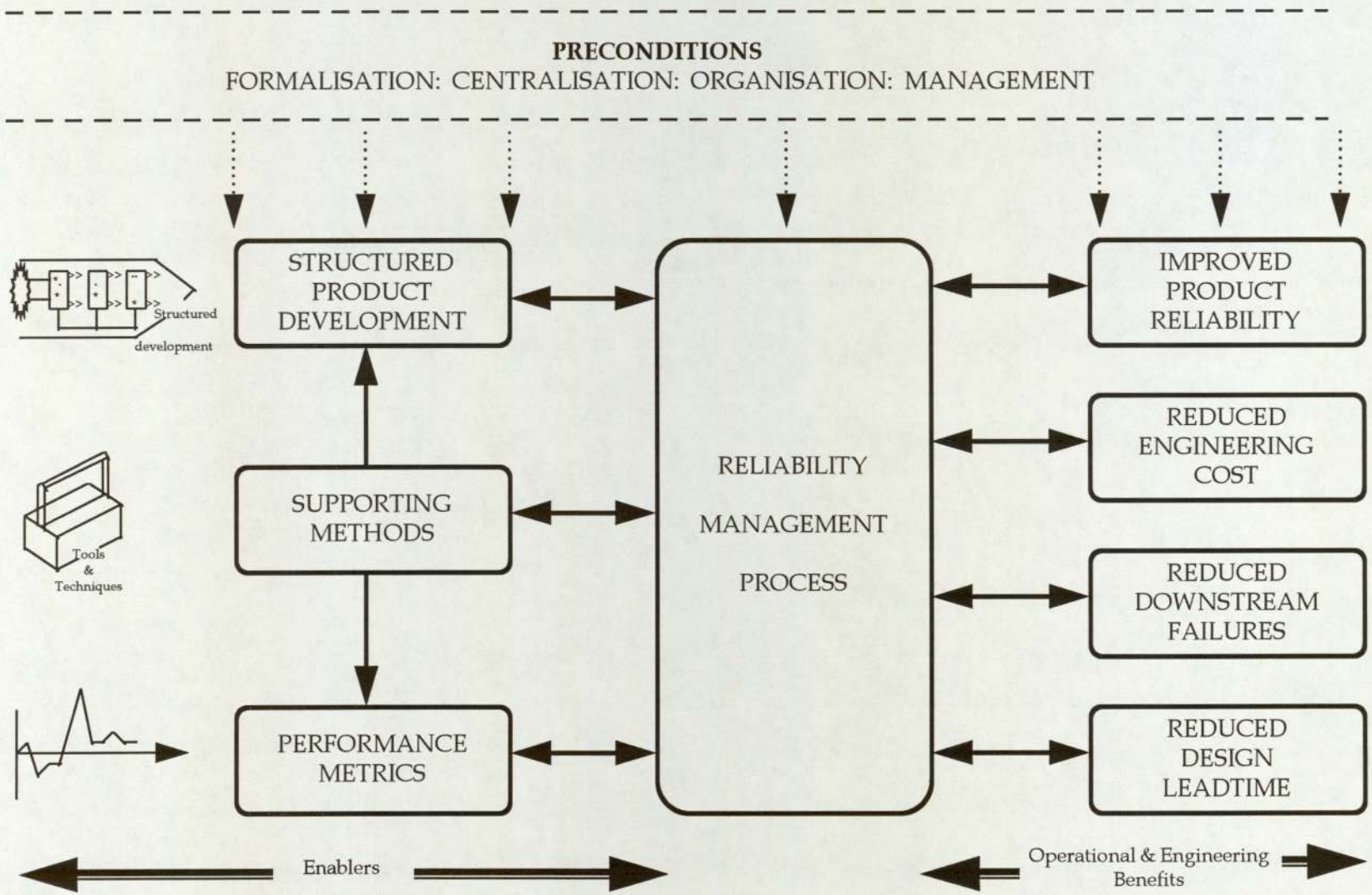
Figure 11.2 shows the broad outline of the methodology in schematic format and illustrates the links between the three key elements. Figure 11.2 also details the significant benefits that can be achieved through embracing the methodology within the design and development process of a machine tool organisation. These are:

1. Improved Product Reliability.
2. Reduction of Downstream Failures.
3. Reduction of Costs.
4. Reduction of Leadtime.

As shown in Figure 11.2, a number of 'preconditions' must be met prior to the use of the overall methodology. These conditions primarily deal with organisational structure and status of product reliability operations and are defined and discussed in Section 11.5 of this chapter.

The three elements constituting the methodology signifies the diversity of interdependent tasks incorporating reliability management. The general model can be effectively used to drive the consideration of the important reliability issues throughout the stages of product development and after sales service.

Figure 11.2: Main Elements of the Reliability Improvement Methodology



### 11.5 Preconditions

This element of the methodology is concerned with defining an effective organisation structure for conducting reliability-based operations. In this thesis 'organisation' mainly refers to the optimum configuration and arrangement of reliability operations, reliability project management and its related human resources. The following key organisational parameters needs to be investigated and satisfied prior to the application of this generic methodology:

1. Management Recognition of the Reliability Function.
2. Organisation Structure for Reliability.
3. Degree of Centralisation of Reliability-related Operations.
4. Formalisation of the Design to Manufacturing Links.
5. Formalisation of the Design to Service Links.

#### 11.5.1 Management Recognition of the Reliability Function

An effective reliability function can exist only in an organisation where the achievement of high reliability is recognised as part of the corporate strategy. This recognition must be cascaded down at an operational and functional level of the engineering management structure. Assurance must be provided that the function does not receive only a lip service, but is ranked equally among other product variables such as cost. More importantly, the reliability effort should always be treated as an integral part of the product development process and not as a parallel activity unresponsive to the rest of the product introduction process. Management recognition of the reliability function at an operational and functional level of the overall organisation structure is critical to this integration.

This research has concluded that a separate or specialist reliability service and support function does not exist in a matrix management structure within machine tool companies. It is more likely that reliability related tasks such as maintainability or failure analysis will be carried out by relevant design and

development engineers. Therefore, the responsibility for reliability achievement must be given to the project manager, who is the only person who can ensure that the right balance is struck in allocating resources and time between the various competing aspects of product development.

### 11.5.2 Organisation Structure for Reliability

The research has established that it is difficult to be categorical about the optimum organisation structure to ensure effective management of product reliability. This is because reliability is affected by several different activities like design, development, production quality and service. In theory, there are two types of reliability organisation which has evolved through time:

1. Quality-assurance Based Organisation.
2. Engineering Based Organisation.

The advantages and limitations of these two types of reliability organisation has been described through a longitudinal case study in Chapter 7. Based on this longitudinal case study, the quality-assurance based organisation was evaluated as being a more optimum structure to ensure effective management of product reliability in machine tool manufacturing organisations.

Therefore, for reliability-driven operations the desired organisation structure needs to be quality-assurance based. This organisational form is based upon the definition of *quality as the totality of features which bear on a product's ability to satisfy the requirement.* In this form of reliability organisation, the quality system procedures, audits, production quality control and all reliability-related tasks related to design, production and service needs to be integrated and centralised into one 'quality assurance' (QA) function.

This form of organisation structure will allow more centralisation of reliability-related tasks. The degree of centralisation will affect the status of the reliability function and therefore provide more recognition and attention to reliability-related issues during design, manufacture and operational use. Furthermore, it

will allow easier integration and better co-ordination of some tasks that are common to design and production. The following examples of broad based reliability tasks which normally fall under the responsibility of the design engineering function will integrate with the production quality control function:

- Reliability procedures in design. For example design analysis, approval and review, failure analysis and design reviews will be co-ordinated by the integrated quality and reliability function.
- Reliability tests during development and manufacture.
- Reliability data collection, analysis and action system, including data from production, test and warranty.

In this type of organisation, the reliability engineering team interfaces mainly with the engineering and service departments, while quality control is mainly concerned with production. However, there is close co-ordination of reliability engineering and quality control. Similarly there will be shared functions such as a common failure data collection and analysis system covering development, production and in-use.

It must be emphasised that the structure must be designed so that the degree of centralisation does not hinder (1) nominal design engineering activities, (2) functional links which exist in the Marketing-Design-Manufacturing triangle and (3) communications both laterally and hierarchically.

### 11.5.3 Formalisation of the Design-Manufacturing-Service Link

By applying concurrent engineering concepts, it is recommended that a product-focused project team is established as a cross-functional working unit during the new product introduction process. This team must be established at a functional level of the organisational hierarchy to ensure that reliability issues are considered and assessed upstream in the design cycle. This will aid in the process of reducing the likelihood of downstream failures which are costly to

rectify. Cross-functional teams at an operational level tend to only discuss and assess cost and time aspects of the product introduction process.

The team must consist of members from a variety of engineering disciplines such as design, design support, manufacturing, development, purchasing, quality and service functions. However, design engineers will form the pinnacle of the project team. The team leader will be responsible for planning, co-ordinating, managing and monitoring project activities at a functional level. This person, through the approval of the team, must negotiate the requirements of reliability activities to the project manager and provide detailed findings which may have come about from design reviews and analysis.

The members jointly participate in the translation of customer requirements into product and process design requirements. The creation of a cross-functional team will therefore ensure that the product introduction process is driven by the team as opposed to design engineers in isolation. Although they will possess special areas of expertise, the members of the team must have a product-focus approach rather than a functional focus. Each team member of the is the point of contact for his function. The structure of the team makes direct communication between different functional disciplines and enables team members to engage in co-operative problem solving.

The cross-functional team can only be successful if conditions exist within the project team that promote co-operation, communication and effectiveness. A combination of factors therefore need to be considered when establishing the team structure. The first is to ensure that the right combination of technical expertise is formed within the team. The right power structure also needs to be established so that a heavy bias towards one single issue is not imposed on the team, but appropriate weighting is given to all aspects of the design process. In addition, the individuals objectives and goals need to be recognised and their compatibility with the objectives of the team and task determined.

A participative style of problem solving is essential if the end goal is to reduce or eliminate the likelihood of downstream failures. The creation of a cross-

functional team will serve this purpose. The project team composition and degree of involvement will be influenced by the state of the organisation. In particular, the issue of labour resource availability will have to be considered. The degree of involvement by engineering disciplines other than design also needs to be identified, which in turn will influence their degree of commitment and time scales. Possible structures range from one where all members participate on a full time basis, to one where a core of the design engineers participate on a full time basis whilst other engineering disciplines participate on a part time basis. A decision therefore has to be made which balances the relative importance of the project with its success against labour resource allocation.

### 11.5.4 Concluding Summary of Preconditions

Prior to the application of the methodology, the following key conditions need to be measured, evaluated and satisfied:

Management recognition of reliability achievement and improvement is necessary at an operational level for effective management of reliability-related tasks.

A more centralised based organisation structure for the operation of the reliability function is necessary in order allow easier integration and better co-ordination of reliability-related tasks that are common to design, manufacture and service. In this respect a quality-assurance based organisation must be established. Further details of this type of organisation structure can be found in Chapter 7.

The creation of a cross-functional team during the product introduction process is necessary to allow greater formalisation of the design, manufacture and service link. Furthermore, it will allow field performance, manufacturing, supplier development and assembly issues to be considered and assessed much earlier in the design cycle. This reduces the likelihood of downstream failures.

## 11.6 Details of the Reliability Improvement Methodology

The guidelines set out in this methodology provides a series of reliability requirements that can be applied across the design and development process that are manageable, flexible and cover all phases of the product life cycle. These requirements should be integrated with the relevant design and manufacturing activities.

In many projects there are no sharp demarcations between the definition, design and development, production and operation support phases. However, distinctions are drawn in this methodology for clarity. The principle stages of the product introduction process is divided into the following four life cycle phases which is appropriate for any hardware development programme for machinery and equipment:

1. Concept
2. Design and Development
3. Machine Build and Beta Testing
4. Operation and Support

Relative to the above four phases, Figure 11.3 provides the generalised methodology for establishing a structured reliability management process. It provides the overall framework for the application of reliability and related tasks.

The link between the four phases and the three key elements of the methodology is detailed in Figure 11.4. The concept, design and development and machine build phases falls under the 'structured product development' element of the overall methodology. The machine build and operation and support phase comes under the 'performance metrics' element of the overall methodology. The component 'supporting methods' forms an integral part of all the above four life cycle phases.

Figure 11.3: Details of the Generalised Reliability Improvement Methodology

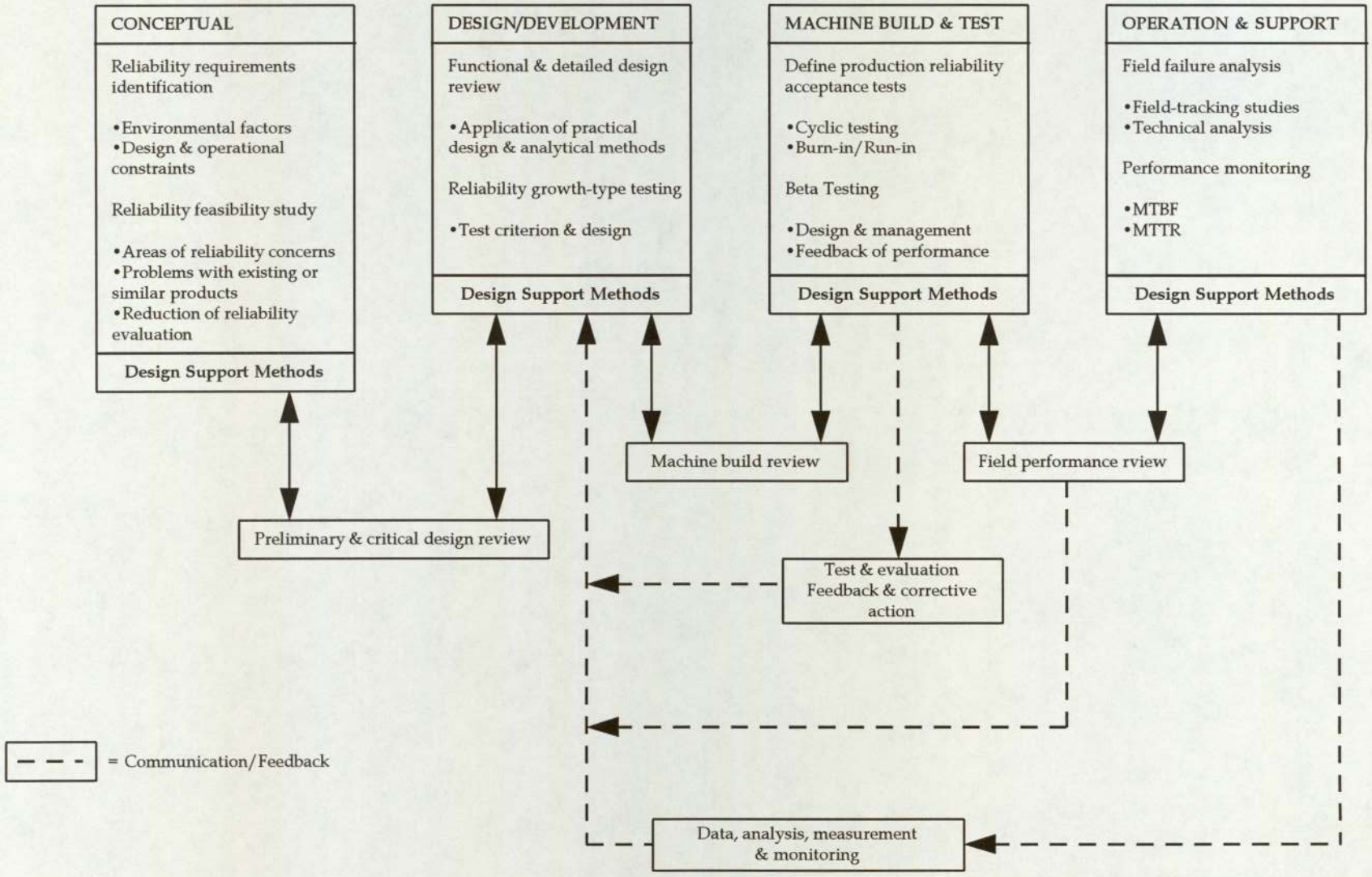


Figure 11.4: The Link Between Life Cycle Phases and Main Elements of the Methodology

| | STRUCTURED DEVELOPMENT | SUPPORT METHODS | PERFORMANCE METRICS |
|---|---|---|---|
| CONCEPTUAL | X | X | |
| DESIGN AND DEVELOPMENT | X | X | |
| MACHINE BUILD AND TEST | X | X | X |
| OPERATION AND SUPPORT | | X | X |

In practice, all the activities shown in Figure 11.3 are applied in an iterative nature. In other words, as the design develops so the tasks may be applied and re-applied as analysis is completed and data made available. This operation logic is accomplished in two ways.

First, the major mechanism used to continuously evaluate reliability issues is design reviews. The iterative design cycle should include formal reviews at appropriate stages to evaluate progress (see Figure 11.3). The review should be a formal and systematic study of the design carried out by a cross-functional team at a functional level. The review should consider the objectives such as reliability achievements, identification of principal items and problems inhibiting reliability and reviewing of reliability effort. Recommendations from the design review team or committee should then be passed to the project or design manager who will then consider the feasibility of taking appropriate action for reliability improvement.

Product reliability is mainly determined early in the design and development phases. The more firm the design specification, the more costly it becomes to make changes downstream in the product introduction process. This cost aspect of product design also reduces the scope for major engineering changes. In this context, a closed loop problem solving environment should be established as early as possible (see Figure 11.3). This approach should extend to include the entire product development life cycle, rather than limited to the traditional test, analyse and fix process. This closed loop process consists of problem identification, analysis, solution development and solution implementation.

Second, since reliability is an aspect of engineering uncertainty, manufacturers and users will expect failures during the useful life of a machine tool product. The feedback of field performance data therefore forms an integral part of the reliability management and improvement process (see Figure 11.3). Using a statistical and objective approach, field failure data can be used to report

problems, track and monitor field reliability performance and facilitate any decision making for design improvements or initiate engineering changes.

The three key elements of the methodology relative to Figure 11.3 and the four phases of the product development process is discussed below.

### 11.6.1 Structured Product Development

As part of the methodology, a series of design and reliability analysis needs to be completed on the developing design in order to identify design constraints. Further analysis then needs to be pursued on the design, the aim of which is to optimise the design in achieving maximum reliability and minimum life cycle cost. The characteristics of a structured product development process with respect to achieving this aim are elaborated below. The selection of the whole, or any part of this process which a machine tool company may be required to undertake will depend on the specific project requirements. There are six main reliability related activities which needs to be performed on a systematic and iterative basis:

1. *Reliability Requirement Identification:* This is conducted during the conceptual design phase. The purpose of this design exercise is to identify environmental and machine performance factors which may affect field reliability.

2. *Reliability Feasibility Study:* This is primarily conducted during the conceptual design phase, but also needs to be considered and assessed during the design and development phase. The purpose of this study is to identify and document potential reliability concerns on existing similar designs and as a result of environmental factors

3. *Structured Design Reviews:* These reviews are to be conducted on an iterative nature. Normally, design reviews should be performed during the design and development phase and initial operation of the machine tool product. This purpose of this process is to monitor reliability efforts, concerns and goals.

4. *Reliability Growth Testing:* This type of testing should be carried out during the latter stages of product development, prior to production release.

5. *Production Reliability Acceptance Tests:* Reliability and functional acceptance tests needs to be determined and implemented at a system and unit level.

6. *Beta Testing:* Prior to market introduction beta testing needs to be carried out from a functional and reliability performance perspective.

Further details of these reliability activities are elaborated below.

*Reliability Requirements Identification:* Many good designs tend to fail during operation and use due to the increased performance levels at the expense of reliability. Failure rate is extremely sensitive to stress levels in both mechanical, electronic and electrical products. Factors that affect the reliability performance during use should be examined through a reliability feasibility study. This study should examine the following factors:

- Complexity.
- Novel and technological features.
- Duty cycle and expected life.
- Environmental conditions.
- Constraints imposed by design and operational performance parameters.

Further to the above, the reliability requirement process must clearly define specific environmental conditions that the machine tool product will be expected to encounter. This includes the levels and rates of change. These pertinent environmental factors which may affect reliability performance should be well documented. Design solutions which minimises the effects of these environmental factors should be monitored through structured design

reviews. Table 11.1 details some examples of environmental factors which are more relevant to a machine tool operating environment.

In addition to the environmental conditions that could affect functional performance of a machine tool, considerations must be given to the effects that the process will have on the reliability of the machine tool product. Table 11.1 details some examples of machine or process operating conditions which can adversely affect field reliability.

*Reliability Feasibility Study During the Concept Phase*: This study should address and identify reliability and related design concerns at an early phase of the conceptual design process. Field data from similar machines operated under the same environment is likely to provide a list of current concerns which need to be considered and assessed early in the design cycle. Examples of reliability concerns which may need to be considered and assessed throughout the design and development phase of a machine tool product are:

1. High failure rate of spindle assemblies.
2. Poor performance of telescopic sliding covers.
3. High failure rate of tool changing mechanisms.
4. Temperature variation and migration in axis ballscrews.

These reliability concerns should be quantitatively defined in terms of cost of failure and actual failure rate. Furthermore, a list of failure modes and root causes of failure should be established to aid in the implementation of a design solution during the detailed design phase. These concerns should be documented and monitored to ensure that they are not overlooked. Typically this monitoring task should be accomplished through the structured design review process.

As well as identifying reliability concerns, the feasibility study should also identify and examine possible means of reducing the need for reliability evaluation during the design and development phase. Fundamental design

Table 11.1: Examples of Environmental and Operational Factors Affecting Reliability

| Environmental Factors | Process & Operational Factors |
|---|---|
| Temperature | Coolant/Splash, Mist, Residue |
| Mechanical Shock | Water/Splash, Spray, Residue |
| Immersion or Splash | Oil (Lube & Hydraulic) |
| Electrical Noise | Heat & Cold |
| Electromagnetic Fields | Mechanical Shock |
| Ultraviolet Radiation | Electrical Noise |
| Humidity | Cutting Chips |
| Corrosive Materials | Dust, Dirt, Sand |
| Pressure or Vacuum | Mishandled Process Parts |
| Contamination and their Sources | Humidity |
| Vibration | Vibration |
| | Noise Levels |

techniques and principles that can be used as a means of achieving this objective are as follows:

1. Re-use of design knowledge and experience.
2. Reduction of unnecessary design features and engineering costs.
3. Reduction of number of parts and process steps.
4. Standardisation of parts and processes with existing similar designs.
5. Feasibility of applying modular design concepts at sub-system and component level of the product design.
6. Familiarity of with both existing and anticipated future designs.
7. Comparative analysis of technological opportunities and their effects on product reliability.
8. Incorporation of sub-systems of existing design where feasible.

Chapter 7 details how the above design principles reduces the need for reliability evaluation in different ways.

*Structured Design Reviews During the Design and Development Process:* A structured approach is described to analyse the design of machine tool products. The methodology defines 'design reviews' as the main mechanism for assessing reliability issues and monitoring reliability efforts and goals.

The need for a structured and formalised approach to design reviews is recognised as a critical aspect of the reliability achievement process during the design stage. However, very often the review comprises a summary of the perusal of specification, cost and technical drawings to find problem areas. Such an approach is useful to highlight some potential design and manufacturability difficulties. However, the reliability and maintainability aspect of the design will not be evaluated and tends to be overlooked. Also, many problems commonly encountered during production release and early field operation are unlikely to be identified early in the design cycle by using this approach. An in-depth, structured analysis of the product design at all

levels of product design and at various times of the design process, is the best approach to avoid these difficulties.

There are many reliability-related activities and techniques which are useful in a design review exercise. This methodology will define practical and effective methods which have been identified through the longitudinal case study. Their use within a design review exercise is defined and appropriate chapters of the thesis is specified which describe the method in detail. The intention of this element of the overall methodology is to provide both a general framework for a design review which may be adapted to suit a company's particular circumstances.

The structure of the design review may be defined as 'the quantitative and qualitative examination of a proposed design to ensure that the design is robust and has optimum performance with respect to maintainability, reliability and other product design variables like pressure, speed, acceleration rate, duty cycle.' Maintainability and reliability are separately identified but that does not imply that these variables should be treated and assessed in isolation. Specific mention is made of reliability and maintainability to give them the importance they deserve as design variables and to ensure that they are not overlooked.

In a design review, it is useful to consider the review procedure as a structure with four principal stages:

*Preliminary design review:* The purpose of this review is to validate the capability of the evolving design to meet all reliability requirements and reliability concerns. This review is also carried out to identify evolving weak points in design. The process should normally initiate and evolve throughout the detailed design phase.

At the detail design stage, the preliminary design review should focus on design areas which significantly affect the reliability and maintainability or perhaps functional requirements which involve some significant high-risk

design. These areas of concern will have been identified through the reliability feasibility study. The objective is to examine the characteristics of the design with respect to these reliability concerns and to identify further weak points in the design. These weak points could be related to machining, accessibility, manufacturability, maintainability, design complexity, standardisation, variability in functional performance, reliability of commercial parts, all of which could affect reliability achievement and subsequent operational reliability.

In identifying weak points in design, the reliability may be assessed based on a detailed analysis of the proposed design. Practical methods which may be used to carry out this analysis within the design review process are listed below:

- Failure analysis.
- Use of field performance data.
- Process variation analysis.
- Design sensitivity analysis.
- Maintainability and accessibility analysis.
- Load-strength analysis.

Further details of these methods can be found in Chapter 7 of this thesis.

*Critical design review:* The purpose of this review is to verify that the documented design and related analyses are complete and accurate. This process should initiate during the latter stages of the design and development process. It is also conducted to verify the extent to which reliability concerns and weak points have been considered and assessed. Design solutions and actions which have been taken relative to the identified design weak points and reliability concerns also needs to verified and documented.

*Machine build review:* This review should address issues resulting from reliability growth testing, initial machine build, and run-off testing.

*Initial field performance review:* The purpose of this review is to address and action reliability and related problems which have been identified through beta testing and initial warranty. This review should be used to conduct failure investigation of problem areas for continuous improvement.

Thus, the theme of the design review is to identify carefully specific areas of a design for in-depth study rather than carry out a broad, shallow overview. Data from the reliability feasibility study should be used to aid in this process. The design review structure identified above is not put forward as a rigid procedure. A company can adapt it or use certain part as appropriate to its own needs and circumstances.

*Reliability Growth or Machine Cycle Testing:* During the latter stages of the design and development, it is recommended that reliability growth testing is conducted on one or two machine tools. This should be done prior to production release and beta testing. The purpose of this type of testing is to identify any weak points in the design which may have been overlooked during the design phase. Where practicable and cost-effective, this type of testing should be performed at unit level.

Before any form of reliability growth or cycle testing is initiated, a testing procedure should be established. This procedure should define the duration of the test, the operating conditions under which the testing should be conducted and the termination criteria. As a guideline, the duration of the test should reflect approximately 20% of the average annual operating hours of a machine tool. The operating conditions will be dependent on whether the growth test is conducted on an alpha or beta testing environment. However, where practicable the growth test should be conducted under a beta testing environment. This will reflect 'real' operating conditions of a machine tool. There are several termination criteria which can be used for the growth testing of a machine tool. Obviously, the criteria used will be dependent on the needs

and circumstances of the company. Below is list of several termination criteria which can be used to conduct the growth test:

1. A fixed number of cycles or hours with the last number ('*n*') of cycles failure free.
2. A fixed number of failure free test hours or cycles.
3. A fixed number of failure free test hours/cycles with an upper limit on the cumulative number of test hours.
4. A predetermined maximum number of failures within a predetermined cumulative number of hours/cycles.
5. Sample testing a further number of machines when major failures reach a predetermined level.

The above termination criteria are only given as guidelines. A company deciding to perform growth tests can select and define their own termination criteria. Failures and functional performance problems which are identified throughout the duration of the test should be reviewed, assessed and corrected through the design review process.

*Production Reliability Acceptance Tests:* Production reliability acceptance tests should be determined prior to production release. It is important that proper test procedures are determined as it will form an element of the overall production system. As a guideline, production reliability acceptance tests should be determined for major units and also should be conducted at a system level. Compared to the growth testing, the duration of these tests will be significantly lower. Normally, a fixed number of cycles or hours should be specified as the termination criteria for the test.

*Beta Test Design and Management:* The use of beta testing is specified in this methodology due to its effectiveness as a tool for evaluating the function and reliability of a machine tool product. The in-depth understanding of the beta testing process at Cincinnati Milacron and the background literary information

obtained from secondary sources provide the material for derivation of guidelines for effective beta programme management.

Despite the small sample sizes commonly found in beta tests, they can be valuable in establishing and evaluating the basic functional performance of a product. Machine tool companies will substantially benefit from the application beta testing due to the following:

- Users of machine tools are heterogeneous.
- Alpha testing is unable to guarantee a 'fault-free' product.
- High design content and complexity of a machine tool product.

The two key questions which this methodology addresses are (1) what value can a beta test provide in minimising or reducing engineering uncertainty during the design and development process and (2) how should a beta test programme be designed and managed to maximise this value? In this respect guidelines for an effective design and management of beta test programme is provided in terms of the following three dimensions:

1. *Initiation and termination of beta tests:* Beta tests should normally initiate only after the design is agreed upon and detailed alpha testing is complete. Beta testing a product with too many known design and manufacturing problems can cause problems. For example, it can create negative marketing publicity if the product is tested too early or require too many service calls. An effective beta programme should recognise the full set of benefits possible.

   Management should explicitly set out the purposes of a beta programme at the outset. In general, if the objective is to enhance the design and reliability of a product, then the purpose of a beta test will be to assess the functional performance of the product. In this respect beta test should not be deployed as a marketing or sales tool. These purposes should be communicated to all involved in the programme and be the basis for decisions on the number and type of sites, data collection and information flows. Beta testing should be

included in the design and development project plan. Appropriate time should be allocated for the completion of the beta testing prior to market release and full production.

2. *Number of sites and selection procedure:* The number of sites selected will be heavily dependent on the type of machine tool and resources available. As a general guideline, 4 - 10 sites should be used. Beta test sites should be selected using the following set of explicit criteria:

    - Sites should collectively represent a broad portfolio of applications.
    - A site should show likelihood of delivering an influential assessment of the product's performance and participate in the beta feedback and improvement process. The 'ideal' beta customers are those who place a high value on receiving the new product, have good relationship with the manufacturer, will use the product in a critical application and technical sophistication. These characteristics mean that the test site will be both willing and be able to find and report problems quickly.
    - A site should normally have previous experience of beta.
    - Where practicable, international as well as domestic customers should be selected.

3. *Utilisation of beta site data and feedback:* The performance of the beta product should be monitored on a regular basis and reviewed during design reviews. Similarly, an effective feedback system needs to be established where problems are directly relayed to appropriate functional areas for corrective action. The management of information flows of the feedback system should be the responsibility of the QA function. Periodic contact should be established with the beta test sites to review interim status. This regular contact helps indicate whether the test should be terminated or expanded. These interim contacts are also useful for acquiring design

enhancement requests from beta customers which then be implemented in the next design milestone.

### 11.6.2 Performance Metrics

This part of the methodology is concerned with the design and development of an effective data collection, analysis and feedback system. The overall objective of this system will be to measure, monitor and improve the reliability of machine tools on a continuous basis. An effective feedback system should provide qualitative and quantitative information for:

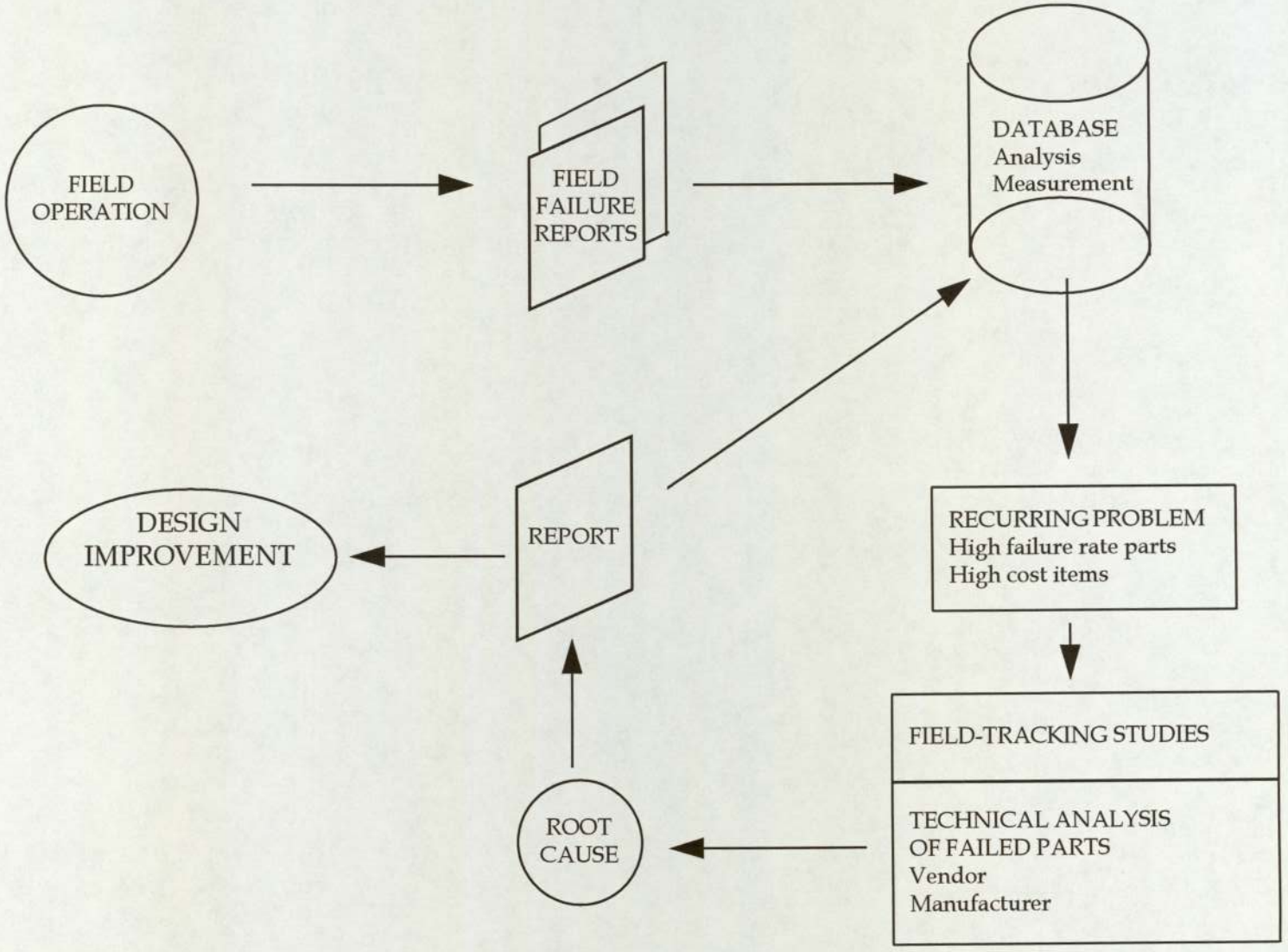
1. Product modification and design improvement.
2. Assessing the effects of engineering changes.
3. Improving future design of product variants.
4. Measuring field reliability at system, sub-system and where relevant, component level.
5. Estimating and explaining warranty costs.

This element of the generic methodology reviews the major aspects of a data collection and feedback system and provides general guidelines for ensuring successful development and implementation. The major components of a data collection and feedback system are:

1. Establishing a reliability database.
2. Establishing a feedback system between field operations, engineering and component suppliers.
3. Planning and conducting field-tracking studies on high-failure rate units and components.

Figure 11.5 details broad relationships and information flow between these three components of the data collection, analysis and feedback system. As shown in Figure 11.5, field-tracking studies is the pinnacle of the feedback system.

Figure 11.5: Tracking and Feedback System



*Establishing a reliability database:* The core of a reliability improvement system is the operation of a reliability database which measures and monitors field reliability performance at system, unit and component level during the warranty period. Using field failure information from service and spare parts replacement reports as the input, the objectives of the reliability database will be to produce regular reports on:

- Performance with respect to reliability and maintainability at system and unit level. Typical measures of reliability and maintainability that should be used are MTBF (or failure rate) and MTTR.
- High failure rate components. These components will then be subjected to a field-tracking study to ascertain the root cause of failures.

*Establishing a feedback system between field operations, engineering and component suppliers:* It is essential that component suppliers form an integral part of the feedback system. This is primarily because the majority of parts and units of a machine tool product are commercial. To avoid the difficulties associated with the return and subsequent technical analysis of parts and units, a dedicated field quality operation should be created with the responsibilities of tracking and co-ordinating the return of failed parts and corresponding 'root cause analysis' reports with component suppliers.

*Planning and conducting field-tracking studies on high-failure rate units and components:* Formal field-tracking studies (FTS) will be the basis for all failure investigations of high failure rate items. The in-depth longitudinal evaluation of difficulties associated with failure investigations provided the basis for deriving guidelines for planning and conducting a FTS. The principal steps involved in planning and implementation of a successful FTS are:

1. *Planning a Field-Tracking Study:* The principal steps involved in planning a successful FTS are:

*Defining study objectives:* Perhaps the single most important requirement for successful FTS is a clear statement of purposes that has been agreed to by the concerned business functions. A study will frequently have an impact on many different organisations through its implementation, interpretation and the use of its results.

Early in the planning of a study, small changes can easily be made to accommodate the needs of potential users. However, care must be taken not to try to answer all questions with a single study. Setting precise objectives that simplify implementation can avoid many pitfalls. For example, taking all data that are easily accessible may initially seem reasonable, since it will ensure that nothing is missed which may be important. However, large quantities of field data will invariably lead to a degraded level of data quality.

Frequently, objectives change as data are collected. This implies the need to provide for such changes initially and to monitor the flow of data to determine when such changes are appropriate. For example, a study that has the objective of comparing the performance of different product variants may quickly show that one product has significant higher reliability than the others.

Objectives within a failure investigation environment can be classified as: (1) detecting and establishing root causes of problems for subsequent design improvement, (2) establishing the cost-effectiveness of a design improvement, (3) quantifying known problems and (4) measuring the impact of design or manufacturing changes. A study can involve aspects of several of these. A study can involve aspects of several of these, but procedures must be matched to purposes. For example, some studies are intended primarily to find and preliminary evaluation of problems. Once a problem has been identified, a more detailed study can be used to better quantify its economic impact.

Early thinking about a proposed study may be clarified by the following list of objectives, stated in a statistical context: (1) Point estimation (e.g. failure rate), (2) Interval estimation (e.g. time period analysis), (3) Comparisons with a known standard or with results from previous studies, (4) Model testing, (5)

Other information (previous list). Failure to obtain agreements on specific objectives among all participants can easily lead to continuing disagreements regarding the implementation of the study and the interpretation of results.

*Planning data collection to meet these objectives:* Once the general objectives of a field study have been established, the work aimed at meeting those objectives begins with the planning of appropriate data collection procedures. Most of this planning is aimed at answering the questions related to (1) What data will be collected? (2) How will the data be collected? (3) In what study population will the data be collected? and (4) How much data (sample size) will be collected? Finding the appropriate answer to each of these questions for any given FTS is the key to its effective implementation.

There are clearly many factors that will determine what data should be collected for any given field study. For the purposes of this discussion, we assume that the study in question is directed at estimating the frequency of failures in a specified product population. This objective imposes the following minimum data requirements on the data to be collected: (1) The data must include the size of the study population, (2) The data must record or count every failure "event" occurring in the study population during a specified time period and must exclude or specifically identify events that are reported but occur outside the study population or specified time period.

In many studies it is important to determine precisely when in the life of the equipment each failure occurs. In those cases deciding when the lifetime of a product starts is of crucial importance. This is particularly true when early life failure rates are to be estimated. For example, does lifetime begin when units arrive, are inspected, are installed or first operated? Failure on arrival may show up as defective initially or later in time, depending on the type of failure, its effect on the system, the extent of failure detection and the procedure for collecting data.

Electronic hardware frequently exhibits a decreasing failure rate during its early life. Here, failures tend to occur closer together during the early weeks o f operation. Therefore, depending upon the lifetime definition, much of a study's most useful data can be lost or wrongly classified.

Detailed data on the 'nature' of failures occurring during any study generally fall in one of three categories. The first category includes a description of the failure, the particular sub-system in which the failure was observed and the results of any detailed failure mode analyses performed on the failed components. The second category of detailed failure information includes data on the particular circumstances or environmental/process conditions. The third category includes information on time variables (e.g. date of failure, repair time). Chapter 10 provides a comprehensive list of some of the detailed items and level of failure data regarding the failure event that needs to be recorded.

In most field tracking studies, the collection of field failure data involves the use of service reports and warranty data. Access of existing data sources such as these are an increasingly prominent mode of data collection in field tracking studies. However, if needed, sample field surveys can be conducted to obtain the relevant field failure data. However, this alternative source of data normally tends to costly.

In choosing a study population it is important to explicitly define the limits of the inferences to be made from the study. Are the results to be applied to all units, all units made in a given period, or under given conditions. In any field tracking study there is a trade-off between more detailed conclusions regarding a smaller population and less detailed conclusions about a large one. For example, a study may be aimed at determining whether a change in design has improved reliability in systems subject to certain load characteristics, or whether an overall reliability increase independent of load has occurred. A careful statement of objectives will greatly assist in resolving such questions.

Selecting the appropriate number of units to be included in an FTS is very important. On the one hand, a sample size that is too large may add

unnecessary expense to the study. On the other hand, a sample size that is too small may mean that any statistical test using study data may lack sufficient power to draw meaningful conclusions.

*Planning for successful data collection and 'root cause' analysis:* This step of the FTS concerns both the data analysis itself and the data storage and retrieval procedures that make the analysis possible. In broad terms, there are four applications of field-tracking data. These are: (1) Conducting 'root cause' analysis, (2) Estimating replacement or repair rates, including the calculation of MTBF, failure rates and cost, where appropriate and practical, (3) Searching the data for irregularity or trends and (4) Making comparisons of reliability performance among different types of products, product variants, units and components. Each of these procedures requires careful planning and a close linkage between the setting of objectives, the design of the data collection process and the data analysis itself.

During both the planning and implementation of a study, the mechanism by which the study objectives, the actual data collection and the data analysis are linked is the 'data model.' It is through the data model that the non-deterministic (stochastic) nature of the data is described. Through the model the statistical inferences on the questions of interest are made. A wide variety of statistical techniques are available for field data analysis. Probably the simplest but most important rule to use in choosing a FTS model is 'keep it simple.' The more complicated the model is, the more reliability parameters it will use that must be estimated during the data analysis. There are two additional rules that are closely related to the simplicity rule

- Since the data analysis, as the models core, involves making statistical inferences about parameters in the model from the available data, it is essential that the model and the collection process be matched to ensure that the right data are available in sufficient quantities to make inferences about all the parameters of interest.

- The assumption implicit in the use of any model must be verifiable or the results of the FTS will remain open to uncertainty. In some cases, engineering judgement can be used to verify certain model assumptions.

With the exception of very small scale studies, involving perhaps fewer than 50 failures or fewer than 10 products, computerised data storage is a necessity for permitting complete, sample or timely analysis of FTS.

2. *FTS Implementation:* The principal steps in the actual implementation of a FTS are:

   - *Developing procedures and training personnel:* Based on mutually agreed-upon objectives, specific procedures and forms data collection need to be developed. Determining the extent of automatic data retrieval, checking the validity of the inputs, deciding exactly what data are necessary. The training of field personnel who will actually perform the data collection is a very important step.
   - *Assuring compliance with study procedures:* It is difficult to overemphasise the importance of monitoring compliance with field tracking study procedures. The basic output of any FTS is a measure of the reliability of the equipment under study and where relevant identifying the root causes to effect corrective design or manufacturing actions. In order for that measure to be useful and unbiased (by differences in the completeness and accuracy of reporting for different products, failure types, etc.), all or substantially all of the failure events experienced by the equipment must be reported. It is the function of compliance procedures to ensure that this is the case.
   - *Conducting a procedural trial:* A trial is an excellent and effective way to shake out unexpected problems.

Table 11.2: Matrix of Supporting Methods

| | Concept | Design & Development | Machine Build & Test | Operation & Support |
|---|---|---|---|---|
| Failure Mode & Effects Analysis - FMEA | ■ | ■ | ■ | ■ |
| Quality Function Deployment - QFD | ■ | ■ | | |
| Design for Simplicity - DFS | | ■ | | |
| Design for Assembly - DFA | | ■ | | |
| Value Engineering & Analysis - VE&S | ■ | ■ | ■ | ■ |
| Weibull and Other Measuring Techniques | | | | ■ |

### 11.6.3 Supporting Methods

Tools and techniques are defined in this generic methodology as a systematic and objective means of:

1. Conducting formal reliability and design analysis.
2. Identifying possible design and manufacturing weaknesses upfront in the design cycle.
3. Aiding in the engineering decision making process.

Table 11.2 provides a matrix list of established techniques that can be applied at various stages of the life cycle of a machine tool product. There are numerous tools and techniques which are available. However, this methodology has selected those techniques which are flexible in application, require limited resources and are fundamental to sound management and design practice. More details of these techniques can be found in previous chapters of this thesis.

## 11.7 Summary

This chapter has presented a generic methodology for developing and improving the reliability management process within machine tool manufacturing organisations. The methodology aims to address the weaknesses, previously identified, of current approaches adopted by machine tool manufactures to the management of product reliability. The methodology is founded on the results of the longitudinal study and the survey on reliability management practices in the machine tool industry.

## 12. Implications of the Research Study

### 12.1 Introduction

The research reported in this thesis was prompted by several factors. First, reliability was seen as a significant characteristic of a manufactured product. This was particularly so for machine tools. Second, there was little contemporary empirical literature available on any aspect of reliability management. This provided the unique opportunity to contribute to the development of this body of knowledge. The main factor which influenced the choice of industry was the industrial collaboration with Cincinnati Milacron (UK) Ltd. In this context, the machine tool industry was selected for the study. Through the use of 'action research' and a comprehensive nation-wide survey the various aspects of design and manufacture which formed part of the reliability management process were analysed and evaluated. A key aspect of this study was to evaluate the degree to which reliability-based techniques were applied by machine tool manufacturers. Similarly, the use of field failure data in the area of reliability and design improvement was investigated.

This final chapter examines the implications of this study for machine tool manufacturers. It also considers the use of this information base for key decision makers concerned with improving their reliability management process. The possibilities for further research that could be undertaken as a result of this research are also detailed.

### 12.2 The Management of Machine Tool Reliability

The results and conclusions of the survey and longitudinal case studies suggests that machine tool manufacturers are increasingly aware of and recognise the importance of reliability to customer confidence in machine tool products. Nevertheless, this importance was not reflected in their approaches taken to the management of product reliability. The majority of machine tool manufacturers do not have established reliability and maintainability programmes. Reliability was normally assessed through nominal engineering

activities. For example, during the design phase reliability concerns are normally appraised through the designer's own experience and engineering judgement. Operational functions such as quality assurance, warranty management, service activities and product testing formed the feedback for improving reliability and design. Where manufacturers indicated that they operated a formal programme of reliability appraisal, the findings suggested that such programmes were obscured. There was significant evidence which indicated that activities such as reliability analysis and measurement, periodic warranty review, design reviews and reliability evaluation of parts are not covered by the reliability programme. These activities are key to the implementation of any reliability and maintainability programme.

In the following sections key observations and conclusions are elaborated:

### 12.2.1 The Utility of Beta Testing as Tool for Reliability Improvement

The findings of the research supported the concept of customer influences in enhancing the design of the machine tool. Significantly, the beta testing concept was used by the majority of manufacturers as a means of improving the reliability of their machine tool products prior to market introduction. This refuted previous research findings which stressed that there was little customer involvement in testing and evaluating the final design of the machine tool. Due to the nature of machine tool applications, a small number of customers are normally selected. Sites are selected on a heterogeneous basis.

Through the use of action research the effectiveness of beta testing was furthered. The capability of beta testing as a tool for reliability improvement is primarily dependent on the design and management of beta test sites. Key factors which needs to be taken into consideration in beta programme design are: (1) purpose of beta, (2) involvement of key functional areas, (3) number of sites, (4) selection criterion used and (4) feedback of beta performance. In conclusion, the beta test concept was evaluated to be a useful means of removing any minor design or manufacturing bugs during the final stages of the product introduction process.

### 12.2.2 Approaches to the Appraisal of Reliability During Design and Manufacture

The analysis of the data points to significant deficiencies to the appraisal of reliability during the design and manufacture process. These deficiencies are partly related to basic factors such as failure to apply reliability-related activities and tasks like failure analysis, design sensitivity analysis, design reviews, periodic review of field performance data and maintainability analysis. In contrast to this, manufacturers relied upon the use of strategy- based methods such as modular design, re-use of design knowledge, supplier parts reliability and standardisation to reduce the amount of reliability appraisal needed during the design stage. Manufacturers perceived a strong link between reliability improvement and these design methods.

More complex issues are also involved such as the failure to integrate and involve service and manufacturing personnel in core design activities. In context to this, it was evaluated that concurrent engineering (CE) was not practised to its full entirety. The partial implementation of CE was primarily driven by the need to reduce engineering cost and design leadtime, rather than improve product reliability. In this respect, manufacturers perceived no link between the application of CE and reliability improvement. Further to this, statistical data indicated that CE only provides the mechanism for free-flow of information between design and manufacture.

A further factor which was seen as a weak point in the reliability appraisal process was the perceived link between supplier evaluation and business performance. Manufacturers normally emphasise price and on-time delivery to the exception of supplier parts reliability variables (e.g. quality of design, technical capability, field performance). Furthermore, there was strong statistical evidence which pointed to the fact that manufacturers specifically perceive a stronger link between price and on-time delivery and general business performance. In terms of supplier involvement and integration within the product introduction process, there was little evidence which pointed to full

involvement during design. It was observed that supplier involvement was greatest during the initial and latter stages of the product introduction process. However, as findings of the longitudinal case study indicates, the level of involvement is heavily dependent on the value the supplier's component adds to the machine tool.

Alongside sample inspection of components, functional testing and reliability growth type tests (e.g. continuous cycle tests) were the main methods of controlling and monitoring production induced variability.

Underlying the relative weakness of product reliability effort is the basic problem of the relative status of reliability with other engineering objectives in the companies studied. The style of management tends to stress the importance of meeting critical design and manufacturing objectives, rather than integrating reliability concerns within these objectives. As a result considerable emphasis is given to design objectives at the exclusion of reliability appraisal.

### 12.2.3 Use of Field Failure Data

In order to improve the reliability of their machine tool products it is most likely that manufacturers will have to develop and make use of their field failure reporting and corrective action system (FRACAS). This agrees with the various models which stress the importance of failure data in the area of reliability improvement. With the exception of design improvement, there was considerable evidence which indicated little use being made of this data type in assessing field reliability from a quantitative perspective, assessing the effects of design changes, estimating and explaining warranty costs or to aid in the design of warranty.

In context to the above, the research further evaluated that machine tool manufacturers do not use reliability measures (e.g. MTBF) to effect reliability improvement. Instead, manufacturers are highly dependent on warranty cost and parts usage data in making decisions to improve reliability. Such data do not normally provide a true and accurate reflection of reliability performance in

the field. However, longitudinal case studies conducted by the researcher has shown the usefulness of field data in (1) objectively identifying areas for reliability improvement and (2) monitoring field reliability. In particular, it was shown that machine tools exhibit an exponential failure distribution pattern during the warranty phase. This finding suggests that machine tool manufacturers can simply use the 'constant failure rate method' for estimating reliability parameters such as MTBF.

### 12.2.4 Application and Effectiveness of Reliability-based Methods

The conclusion which emerged from the results of this study was that the application of reliability-based techniques (e.g. Taguchi, QFD, FTA) was significantly low. Although there are numerous techniques available for assessing reliability, this research suggests that engineers and managers alike do not use such techniques in the actual engineering analysis and decision making process. In terms of individual techniques, Design FMEA and more specifically, Value Engineering (VE) were practised regularly. Reduction of cost and reduction of warranty claims were cited by the respondents as the main operational and engineering benefits from the use of FMEA and VE.

It was also evaluated that those methods which were more difficult to apply in terms of rigid procedures and mathematical complexity were less well accepted in the machine tool industry.

### 12.2.5 Concluding Summary

The research indicates that machine tool manufacturers should make some fundamental changes in their approaches to the management of product reliability. Specifically, the status and structure of the reliability related issues and concerns should be given more attention throughout the life cycle phases. To achieve this more attention must be given to integrating formal reliability engineering activities (as discussed above) within the design process. This can only be achieved through the introduction and implementation of a reliability and maintainability programme which encompasses reliability activities such

as formal design and warranty reviews and reliability analysis and measurement. Furthermore, such programmes must be given substance and recognition by management. More emphasis should be given to reliability variables during the supplier selection process, alongside price and on-time delivery. Manufacturers should make more objective use of field failure data in the areas of reliability improvement. In particular, a more rigid reliability monitoring, feedback and improvement system should be developed in meeting this objective. Where relevant reliability-based techniques should be applied to aid in the engineering decision making process.

The Reliability Improvement Methodology developed by the researcher provides guidelines to improving the reliability management process.

### 12.3 Proof of Main Hypothesis (Ho)

There was considerable evidence gathered throughout this thesis which indicated that the main hypothesis (Ho), outlined in Chapter 5, has been proved. In chapter 5, it was postulated that there were two main approaches to the management of product reliability, namely; 'best practice' and the 'alternative' approach. The best practice approach was seen as an universal prescription, or emulation of 'text book' approach to reliability management. The alternative approach reflected the industrial situation which may hinder reliability management being practised through the 'best practice' route. In particular, the following hypothesis was put forward:

> 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.'

Table 5.1 has been reproduced in this chapter as Table 12.1. This table highlights the main similarities and differences between the two approaches.

Table 12.1: 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<br>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<br>Lacking in consistency and continuity |
| Supplier Involvement in New Product Design | Upstream in the 'NPI' process<br>Supplier evaluation driven by reliability-cost, rather than cost alone | Upstream in the 'NPI' process, but only in terms of part/component functionality<br>Lacking in continuity and commitment |
| Production Feedback to Engineering Design | Systematic feedback<br>Both technical and statistical related | Primarily observation based<br>Lacking in continuity and integrity |
| Post-Production (service) Feedback to Engineering Design | Systematic feedback<br>Both technical and statistical related | Primarily observation based<br>No systematic feedback<br>Lacking in continuity and integrity |
| Formal Methods | Application of formal methods where necessary | Little or no application of formal methods<br>Resistant to implementation |
| Reliability Performance Measurements | Quantified and derived on a statistical basis<br>Closed loop between measurement, review and action | General, indeterminate and observation based<br>Open loop between measurement, review and action |

Seven dimensions were defined in chapter 5 to describe the main differences (see Table 12.1).

There were clear qualitative and quantitative evidence that manufacturers adopted the 'alternative' approach to the management of product reliability. Indeed, the above key conclusions support this assumption. Due to the various limitations (e.g. small sample of survey data), this has not been proved in absolute terms. However, it is indicative that the majority of UK manufacturers are adopting the alternative approach. This can be shown by using the seven dimensions listed Table 12.1:

*Engineering Design and Reliability Considerations:* The results of this study indicated that manufacturers adopted the alternative approach to the appraisal of reliability during product design. First, it was evaluated that reliability was mainly appraised through the designer's own experience and judgement and through nominal design engineering activities (e.g. testing). As reported above, there is no established programmes or procedures for reliability appraisal. Second, there was little use being made of analytical-based methods like maintainability analysis. Rather, manufacturers were more dependent on technical-based methods like modular design as a means of (1) reducing reliability uncertainty and (2) reducing the need for reliability appraisal.

*Design-Manufacture Interface for Reliability Achievement:* Although the majority of respondents indicated that concurrent engineering (CE) was more than 50% operational, there was little evidence which indicated that CE was practised in its' full entirety. The results of the ANOVA experiment evaluated that CE only provides the platform for the free-flow of design and production information. However, as indicative from the ANOVA experiment, this does not necessarily lead to any substantial improvements in product reliability. This was the perception given by the majority of manufacturers.

*Supplier Involvement and Evaluation:* The results of the multiple regression analysis indicated that among several factors used to evaluate vendors, manufacturers normally emphasise price and on-time delivery and are less

likely to emphasise product reliability variables. Furthermore, manufacturers also perceive a strong link between price and on-time delivery and general business performance. These quantitative evidence indicated that manufacturers adopted the alternative approach to evaluating and selecting vendors. As reported earlier in this chapter, there is a lack of supplier involvement and integration during the design and development process of a machine tool product.

*Production Feedback to Design:* On average manufacturers operate a feedback system for production and assembly related problems. However, qualitative data gathered from the longitudinal case study indicated a lack of systematic approach being adopted to the feedback of production problems to design. More importantly, case study evidence suggests that the feedback system lacks in continuity and objectivity.

*Post-production Feedback to Design:* There was significant evidence which indicated that manufacturers regard beta testing and field failure data as a mechanism for enhancing the reliability of their machine tool products. Furthermore, the beta tests are designed and managed to enable periodic and consistent feedback to be maintained between the customer and manufacturer. In this respect, there was some evidence which indicated that manufacturers adopted the 'best practice' route to the feedback of post-production reliability performance data.

*Formal Methods:* Despite the existence of a large body of literature of reliability-based methods (e.g. FMEA, QFD, FTA) to be used in reliability appraisal, there was considerable evidence which suggested that managers may often disregard such techniques in the engineering decision making and analysis process.

*Reliability Performance Measurements:* Parameters used as a mechanism for measuring and monitoring reliability performance were general, indeterminate and observation based. There was little evidence which indicated reliability parameters such as MTBF being used to measure field reliability performance. In other words, quantitative assessment of field failure data are not being

carried out satisfactorily. Similarly, such information are not being fed-back to design in a timely and systematic basis. Manufacturers normally relied upon warranty replacements (e.g. high cost and high usage items) to improve product reliability as opposed to using more objective reliability measures.

In conclusion, six out of the seven dimensions defined in Table 12.1 have been proved. Therefore, there is clear evidence which indicates that manufacturers are adopting the 'alternative' approach to the management of product reliability.

## 12.4 Recommendations: The Reliability Improvement Methodology

The Reliability Improvement Methodology was primarily developed to address the significant limitations to the approaches adopted by manufacturers to the management of product reliability. In this context, the methodology provides a set of guidelines and methods for improving the reliability management process. Two main research methods enabled the analysis of the reliability management process to be conducted: (1) survey design and (2) action research employing longitudinal case studies. The results of this analysis were instrumental in facilitating the synthesis of a generic reliability improvement methodology. This particular methodology provides guidance to manufacturers who are seeking to improve their reliability management process. The methodology has four main elements (detailed below), each relating to a particular life cycle phase of a machine tool product. One particular strength of the methodology is that it covers the complete reliability management process. However, the methodology is flexible enough to allow manufacturers to apply those elements that are of immediate relevance to them. Key elements of the methodology include:

*Structured Product Development* - The element of the methodology provides fundamental basis for considering objectives such as reliability estimates and achievements, identification of principal items inhibiting reliability and reviewing reliability effort. Furthermore, it allows manufacturers to adopt a

systematic approach to the process of problem identification, analysis, solution development and solution implementation of the design.

*Performance Metrics* - This key element of the methodology essentially is concerned with data collection, analysis and feedback, to facilitate reliability improvement and measurement. It basically covers the 'operation and usage' phase of the machine tool life cycle.

*Supporting Methods* - This part of the methodology provides a list of useful methods for use in supporting engineering decisions and analysis.

The application aspects of the methodology were shown to be feasible from an industrial perspective. Some parts of the methodology have been tested and their feasibility of application have been demonstrated. To this extent, the methodology can be seen to be a useful tool for machine tool firms looking to improve their reliability management process. However, the effectiveness of the methodology has not been tested. Therefore, the beneficial aspects of the proposed methodology rests on a combination of its inherent systematic and holistic nature (compared to current approaches adopted by manufacturers), its feasibility of application and use a benchmarking tool of best practice.

### 12.5 Further Research

As a result of this research, three areas of further research have been identified. Their investigation could well form the basis for some substantial research projects:

1. Evaluation of the effectiveness of the Reliability Improvement Methodology.
2. Reliability practices of the Machine Tool Industry in the UK and other countries.
3. Comparative studies between industrial sectors.
4. The effects of vendor rating on machine tool reliability

5. Refinement of the comprehensive questionnaires as a Global Research Tool for carrying out studies into reliability practices in manufacturing industry.

*Effectiveness of the Methodology:* This research project has not demonstrated the effectiveness of the reliability improvement methodology in terms of application in the machine tool industry. However, the feasibility of application has been tested. By identifying a number of shortcomings with the approaches adopted by manufacturers to the management of product reliability, a methodology was developed. As the methodology is based on best practice models and industrial practices, it is possible to hypothesise that the proposed methodology will be effective. This assumption needs to be tested. This will involve conducting a series of longitudinal case studies on the application of the generic methodology in an industrial context. Furthermore, it will require the co-operation of machine tool manufacturers to introduce this methodology within their organisation in order that the hypothesis can be tested. Clearly, use of the methodology in an industrial situation and an 'action research' framework will also lead to refinements and improvements of the overall methodology.

*Multi-industry study:* Comparisons between the United Kingdom and more than one overseas competitor would allow detailed consideration and identification variables which may make the process of reliability management and diffusion of 'best practices' unique to a country. There has been little multi-industry research conducted on the practices of reliability management. Therefore, such studies would yield significant and initial indicators of the main differences between countries. The initial intention of this research was to conduct such a study using the German machine tool industry as a comparative indicator. However, due to cost and time constraints this was not possible.

*Studies between industrial sectors:* The advantage of studying more than one industry clearly lies in the broader base of information from which generalisations can be drawn. Comparisons between different industries could

also be expected to yield insights into the influence of variables in each sector which may make the practice of reliability management unique to the industry. For example, it would allow comparative examination of variables such as the degree of reliability appraisal during the design process. More importantly, such studies would allow one industry to apply effective 'reliability management' models from other more established industries in the reliability arena.

*Questionnaires as a Global Research Tool:* The depth and detail of the questionnaires used in this research project provides further scope to standardise the questionnaires as a Global Research Tool for conducting research studies into the management of product reliability in manufacturing industry. The questionnaires can be used to either conduct case studies or surveys of different industries or countries. Studies can be carried out on a 2 year basis to compare or monitor any substantial improvements in the practice of reliability management. These periodic studies will then allow substantial recommendations to be made into possible areas of improvement. However, further refinement will be needed to the questionnaires in order to meet this objective.

*Vendor Rating:* This study only examined the vendor reliability aspects of machine tool products. The effects of the overall vendor rating and evaluation criteria can be further studied. Such studies would yield detailed results on the importance of commercial components to improving the reliability of machine tool products. Furthermore, the machine tool industry would greatly benefit from such studies as the majority of components and parts of a machine tool product are commercial.

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