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Data feedback in an integrated design-to-manufacture system

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Data Feedback
in an
Integrated Design to Manufacture System

by

Moi Keow Lee

A Doctoral Thesis
submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy

of the Loughborough University of Technology

Department of Manufacturing Engineering
November 1990

c by Moi Keow Lee, 1990

Declaration

No part of the work described in this thesis has been submitted in support of an application for any other degree or qualification of this or any other University , or the C.N.A.A. or other institute of learning.

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Abstract

This work is set within the context of a research project on an information support system for design and manufacture. This involves collaboration of other research workers and the commitment in other specific applications within a software environment. The work is targeted at the design to manufacture of prismatic parts in a prototyping environment.

The research work moves from the identification and requirement of dimensional and process analysis, through the specification of data structures within a product data model, through to the definition of a decision network and measurement graph for dimensional analysis, to the provision of verification checks and fault clusters for process analysis. The two analyses are centred on a common fault library.

The two facilities to provide support to the prototyping environment have been developed and tested through an industrial case study. The essential role of these facilities is to reduce the lead-time involved in 'prove-out'. The facility embodies a generic approach of capturing manufacturing knowledge and data feedback functionality that closes the loop from manufacture to design.

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Chapter 1 :

Introduction

Contemporary manufacture is set within the context of two stimuli, that is, computer integrated manufacturing (CIM) and within this environment rapid prototyping. The current trend is geared towards highly integrated business systems. At one time, this integrated structure would be put under the umbrella of computer integrated manufacture. Now, one sees the emergence of the ultimate concept, certainly in European terms of the computer integrated enterprise (CIE). This computer integrated enterprise has shifted attention to the enterprise as the business. Thus, to achieve the computer integrated enterprise, computer integrated manufacture has a role within each plant and each plant in turn has to be integrated at a higher information level to the enterprise. In the move towards the computer integrated enterprise, an appetite is developed for seeking integration of information and data for the sophisticated support of design and manufacture.

Market pressure causes modern businesses to go for a faster and more reliable prototyping environment. This involves higher emphasis on quality and a distinct recognition of the need for discipline and control of the product life cycle. The prototyping environment, though not specifically related to computer integrated manufacture, has the performance requirement to rapidly generate dependable prototypes and provides better management of the product life cycle. Three event phases are present in the product life cycle. These being the prototype phase, the mature product phase in production and the short-term quality phase of the mature product. This research is aimed primarily at the prototype environment, although some of its components are applicable to the short-term quality cycle.

The integration of information and data is emerging as a key issue. It is therefore not surprising to see effort being directed to using the 'product modelling' concept aimed at representing product information. Product modelling enables product data to flow from design to manufacture with minimal friction and no loss of data at any stage. This integration is the

starting point for the successful emergence of a new product. Focus on integration has led to many contemporary research projects and in particular the Information Support System for Design and Manufacture at Loughborough University and Leeds University, described in Chapter 4 and illustrated in Appendix II, to which this thesis makes a contribution. Much of the research is directed at providing a robust forward data link from design down to manufacture. The problem to be addressed in this thesis is in closing the 'loop' back from manufacture to design which has to deal with both design for function and design for manufacture. The former involves the passing of data through dimensions and tolerances [339], machine plan and code generation [347] to inspection plan and code generation [88]. Each of these forms a complementary doctoral contribution in its right. The closing of the 'loop' through data analysis and feedback is the subject of this thesis and has been given the heading 'manufacturing data analysis (MDA).

A number of contemporary concepts are available and have been reviewed and utilised throughout the thesis. These range from simultaneous engineering: the consideration of design in the light of design, manufacture and inspection; to 'towards zero defect' manufacture through emphasis on dimensional and process control; to total quality control (TQC) to maximise quality within a wider organisation framework and; the human-centred engineering concept which provides for human involvement in the feedback system.

The thesis commences in Chapter 2 with an extensive survey on the current trends, emphasis and developments in production quality control. This survey thus provides the current state-of-the-art. Novel software and hardware concepts and developments for measurement assurance are also reviewed.

The use of decision support aids is imperative to this research. A number of decision support aids are available and are reviewed in Chapter 3. The choice has centred on the use of modified statistical process control (SPC) and influence diagrams for representation of the inter- and intra-relationships between quality decisions.

The emergence of the 'product modelling' concept and its use within the Information Support System is the focus of Chapter 4. The emphasis in this chapter is on the integration of information and data flow within an integrated design and manufacture environment.

The data feedback issues in contemporary manufacture are discussed in Chapter 5 with an objective of providing a backcloth and the purpose for the research work. Chapter 6 describes the data feedback system in the context of the Information Support System. Investigation into the links with other related software have also been explored.

The two analyses aimed at near 'zero defect' manufacture in the prototype environment, namely dimensional and process analyses, are described in Chapter 7. This chapter moves from presenting a view on workpiece representation to describing the configuration of each of the analysis modules.

The detailed data structure to support dimensional and process analyses within the project's product data model is described in Chapter 8. The data structure is presented through a computer implementation vantage point and also from a user's view. This chapter also illustrates the feedback process through the viewpoint of product modelling.

The organisation and management of data as well as the data feedback system itself are described in Chapters 9 and 10 respectively. Chapter 9 focuses on the building and use of each component of the feedback system within the environment defined in the previous chapters. Chapter 10 presents a coherent view of these components and provides a discussion on the integration of other applications in the environment. The software structures of the feedback system are presented in Appendices 2A and 2E.

Chapter 11 provides an overview of the knowledge elicitation and acquisition process. Chapters 12 to 14 present a user driven viewpoint of the data feedback system. The value of the research work is validated through an industrial case study at Renishaw Metrology. The case study environment is presented in Chapter 12. Chapter 13 presents the implementation

of the data feedback system within the Renishaw prototyping environment. A critical assessment of the data feedback system through this case study is presented in Chapter 14. The results and software validation are presented in Appendix III.

Much of the work is strongly influenced by a club of collaborators and supported by the ACME section of the SERC. The work reported in this thesis has also been carried out in close collaboration with a number of parallel research programmes, mentioned earlier and cross referenced in the text, and in particular with Renishaw Metrology. The main interest of the latter lies in providing a feedback system for enhancing productivity at 'prove out' for a particular workpiece at the prototyping phase.

Chapter 2 :

Literature Survey

2.1 Introduction

The scope of this literature survey is to give a background assessment on the flow of data for measurement assurance in the contemporary factory. The identification of the problems, the approaches adopted by other researchers in this area and the factors that influence quality are covered.

The topics, shown in Figure 2.1, include the concept of measurement assurance and the role played by statistical process control in assuring measurement. The current emphasis on process control is highlighted. A cross-section of currently available quality feedback techniques for measurement assurance are also reviewed. These range from the gauging techniques, through the types of control, the advances in non-contact measurement assurance and finally to the soft-gauge approach of measurement assurance. The main findings of other research and investigation into the issues pertaining to data feedback are mainly reviewed in this chapter.

2.2 Assuring Quality in the Contemporary Factory

2.2.1 What is Quality ?

Quality is defined as 'fitness for use' which implies that if a product has achieved its quality, it has meet the needs of the marketplace. This has prompted Genichi Taguchi to define quality as the 'cost to society' [312]. Quality is or should be one of the most influential driving forces in manufacturing industry today. With the advent of BS 5750, quality is now gaining recognition amongst management. Quality, as the Japanese proved, is not so much a matter for concern as a matter for survival [25]. The main theme of manufacturing a product is to produce quality rather than to measure quality. This does not mean improving methods of detecting faults but organising production so that faults

do not arise in the first place. Thus, although quality has developed a jargon of its own, at its simplest it boils down to completely satisfying the customer now and continuously improving the ability to satisfy the customer in the future [240].

Sumner [305] and Elshennawy [110] argue that there are two distinct but interrelated aspects to quality: quality of design, the degree of achievement of purpose of the design itself, and quality of conformance, the faithfulness with which the product agrees with the design. Much emphasis has been placed on the latter. Gettings [125a] further emphasizes that quality has an internal and external focus. Internally it is focussed on improving machine, material and labour efficiencies and doing it correctly first time. Externally the focus is on consistently meeting expectations of customers. The goal is to make the manufacturer a low cost producer of high quality products. Lopes [192] dispels the myth that the better the quality, the higher the costs by balancing prevention costs against failure costs in a total cost of quality equation. Dowding [102a] argues that any economical solution to production and quality efficiency must involve a change in managements approach to improving quality within the business. There is no magic solution. Top-down commitment to quality can be combined with a bottom-up approach to automating the quality functions.

In the past existed a division of responsibilities between production and the quality assurance function. The modern understanding classifies Quality Assurance (QA) as an integral part of production and is considered as the end result of a carefully thought out and controlled production process. As a result, Quality Assurance (QA) demands coordination between design engineer and quality assurance man responsible for drawing up inspection specification says Holler [143a]. The real key to integrated quality assurance rests with the management and analysis of quality information as well as the timely feedback of meaningful information. The ideal approach to this fulfilment is to combine the automation of inspection/gauging functions with automated data reduction and analysis. This is a task best performed through the application of computers for generating and

processing the information by using techniques such as automation, SPC and data management. The result of which is to close the process control loop, thus eminently compatible with the principles of CIM. QA also contributes to the many benefits that can be achieved through CIM implementations: increased productivity, greater flexibility, faster response time, reduced work-in-process inventory (WIP) and the economy of scale through the application of group technology in short term environment. In fact, vendors of CIM-related equipment and systems are increasingly beginning to include QA in their programs and it is evident that existing CIM technology also holds the key to meeting these challenges.

2.2.2 Factory of the Future

Lopes [191] observes that manufacturing and quality automation is growing at an ever increasing pace towards 'lightless' and 'paperless' factories in the near future. These factories will extend beyond the shop and the next phase of industrial development will undoubtedly require that quality be integrated into all aspect of the product life cycle, starting with design. 'Factory of the Future', 'Second Industrial Revolution', 'Computer Revolution' and 'Smart Factory' are some expressions which have sprung out from these requirements with unclear views. The 'Factory of the Future' suggested by Lopes [191], will contain four key building blocks such as people, Manufacturing Resource Planning (MRPII), just-in time (JIT) and computer integrated manufacturing (CIM). These can be utilised both individually and independently with due consideration given to reduced throughput times, total quality control (TQC), electronic data sharing, products designed for their manufacturability, continuous flow of material and data and implementing automation where applicable. Hutchin [147] adds that this factory structure will be flatter, populated by more autonomous units, quality conscious, more responsive and faster at innovation. It will not be long before these expressions can become reality.

To realise the 'paperless' factory, there are still some quality issues that need resolution in the contemporary factory. Gillespie [126a] confirmed that problems often arise from deficiencies in the quality system rather than the manufacturing process. Examples

of quality systems issues which must be considered are: dimensioning practice, audits, control of reworked material, process characterization, calibration, failure prevention, process simplification, and SPC. Each of these issues are classified under total quality control (TQC) or total quality management (TQM). The total quality control view is strengthened by Purves [243] who argues that corporate commitment to total quality is rapidly being recognized as the foundation for future success. Leading companies across all sectors have realised that this is the most effective response to increasing competition and economic change. Some quality consultants argue that TQM is BS 5750 Part 1,2 or 3. BS 5750 implies that quality must be built into the product during manufacture and not left to be 'inspected out' at the end of the line [65]. However, this standard has a number of omissions as exposed by BS 5750 Part 0. These are economics of quality, motivation for quality, quality in marketing, product safety and product liability. The Guildford College of Technology [23] argues that TQM is more of an objective or target rather than a set of requirements (as with BS 5750) although both BS 5750 and TQM necessitate a structured approach to implementation.

2.2.3 Total Quality Control/ Total Quality Management

While various definitions of TQC/TQM are used, the concept can be summarized as: design to assure quality from the start of the process, analyse potential failures before design release, know the real process capabilities, simplify processes, assure conformance at first point of production, control of the quality system, audit the quality system and keep quality improvement a continuous effort.

Oakland [227,228] defines three major components of TQC besides management commitment as: a documented quality management system, SPC and teamwork. The system he suggests is set out by ISO 9000 series (equivalent to BS5750, 1987] in which all the activities associated with quality can be implemented. SPC is the strategy reducing variability and ensuring conformance. The emphasis on SPC should be on continuous quality improvement rather than just on technique. Teamwork is essential due to the

complexity of some of the problems encountered. Badiru [43] adds to this definition by suggesting a systems approach to TQM. His Triple C concept for TQM is based on communication, cooperation and coordination. These functions he argues are necessary to facilitate TQM. The importance of design is reflected by Houston [145] who suggests that a TQM system provides a two-pronged offensive. First it affords a way to directly attack the areas of greatest current cost to the organisation through data collection and analysis tools. The second offensive focuses on better design, development and planning. These areas offer the greatest future savings to the organisation.

Total Quality Control is not just about tools and techniques, Purves [243] argues, but the core element driving the process is people. His argument is supported by Feigenbaum [117], Chamberlain [76] and Lopes [192] who agreed that TQM is as much to do with people as it is to do with operating management and automation. Chamberlain further suggests that the complex tasks of quality management can be approached through simple management techniques such as Deming Circle methods. The return on investment in the relentless pursuit of total quality can be maximised by allocating a significant part of that investment to the needs of people. As Deming says in one of his 14 points, it is essential to 'drive out fear in the organisation' [89]. The 'need for people' has also encourages many researchers of quality system design to be oriented towards human-centred measurement assurance which will be discussed in section 2.3.1

The implementation of TQC in the East has contributed some significant lessons which can be learned by the West. This view is supported by Juran [90, 158] who states that quality is now a management issue for most of the companies in the West. In the case of major Japanese companies it has been that way for some time. Most of the Western companies now embracing TQM are the ones that have been severely damaged by competition.

The ultimate aim of TQM, Hutchins [148] suggests, is to create an organisation whereby everyone from top to bottom is involved on a daily basis with making their company a world class leader in its field. He also agreed that there is no evidence that the road to world class quality is through BS 5750 / ISO 9000 but argued that industry must stop following the false trails and encourage the best in proven TQM practices. Quality management practice in the UK falls far behind that of Japan where Kaizen (continual improvement involving everyone) is an established concept [23]. Hutchins argues that government initiatives in the UK play an important role in this aspect. They focussed too heavily on the standards although no evidence is available that any company anywhere in the world has achieved world class quality simply through the application of these concepts. Actually the achievements of these standards should be seen as the minimum requirement.

2.2.4 Process Control

Computer integrated quality control systems utilising known statistical procedures are set to play an important role in manufacturing operations. Rembold [250] suggests that this approach will reduce technological and marketing risk as well as the manufacturing risk at which older quality control procedures are aimed.

Kendel [169] discusses the manual involvement of inspectors in traditional factories. The distinction between the responsibilities of the inspectors and the production operators is highlighted as the root cause of the many misconceptions of quality control mainly through lack of training and understanding of the fundamental concepts of statistics. Kendel outlines that passing responsibility for quality to production operatives is fundamental to meeting the demands for improved quality. This requires management commitment to setting and defining concrete quality standards, ensuring that production equipment is reliable and capable, that proper measuring equipment is adopted and that the authority for making corrective actions is passed.

The foundations for using both statistical quality control and statistical process control (SQC/SPC) in manufacturing industry were laid nearly 60 years ago. Many companies have not always made the best use of these techniques and as a result are finding it increasingly difficult to compete. Nowadays quality is perceived by the customer in terms of performance and reliability thus forcing companies to pay greater attention to quality and production efficiency.

The emphasis on manufacturing quality has moved beyond statistical measurement of product to include critical issues such as process control, in-process data collection, analysis and corrective feedback. This change is being driven by the fundamental desire to reduce costs and achieve zero defects. McKee [209] suggests that the automated factory must achieve quality by building it into the system. Quality will be attained by monitoring the system, the processes and the machines to assure the quality of the output. The concept of building parts or products and then inspecting them is unacceptable when one considers the available technology.

2.2.5 Quality Feedback Issues

The development of sensors has made it practical to introduce automated inspection. This has spur a variety of users and toolmakers to implement automated inspection. This move is evident in many of today's factories development. The next few years will see automated inspection entering into the many aspects of manufacturing and make factories smarter. This is supported by Ewaldz [114] who suggests that although exciting developments have been made in automated inspection and process control, unfortunately very little progress has been made in integrating the quality function into the overall production. To a large extent, quality is still delegated to specialists who work in isolation and chronicle performance with lots of inspection.

One does not have to wait for the delivery of the totally automated factory before modernising the approach to quality control. The future of the factory depends on selective

automation that is the introduction of new approaches when and where the technology permits. Technologies required for automated inspection and product control are here. The future of the factory depends upon taking advantage in a systematic way of every possible improvement to keep the competitive edge.

Another major development is the co-ordinate measuring machine (CMM) which is rapidly moving from the role of final inspection policeman to that of process control. It is used less as a standalone metrology room device and more often as part of an integrated system. It is one of the quality assurance premier tools that best combines the automation of the inspection process with that of the data processing function. Most CMMs are equipped with computers and appropriate software for inspection procedure, data collection and analysis as well as having communication capability. Ideally, quality assurance should be a built-in, totally integrated function encompassing the whole of design and manufacturing process [275]. The computer is the mean to achieving this reality. The CMM also provides programming and measurement feedback via CAD/CAM system.

In addition to combining and automating the inspection and data processing functions, CMMs also provide the kind of flexibility needed to complement the growing use of flexible manufacturing systems which are best suited for the increasingly batch oriented needs of manufacturing. To provide maximum flexibility for processing a wide variety of parts, flexible inspection system (FIS) comprising CMMs, other inspection equipment and necessary parts-handling equipment are beginning to parallel and complement the growing use of flexible machining cells. A combination of artificial intelligence techniques and extensions to CAD technology will be required to automate the generation of inspection procedures. FIS typically involves more than one inspection station and the interaction of several levels of robotics, automated inspection and automated materials handling coordinated by a central host computer. It also has the capability of off-line multi-station automated dimensional-verification system.

Getting it right first time is to move from an appraisal oriented assessment of product quality towards a prevention oriented quality assurance. The current trend in industry is towards small cells. For the process to remain in control the inspection function must be able to service the manufacturing cells with prevention oriented information obtained from a device capable of inspecting a variety of parts with the same flexibility as the manufacturing process. This specifies the design of a flexible inspection system. Rawlings et al [247] report that the elements of such a cell are a flexible inspection centre, a database, statistical analysis of data, corrective feedback, and a communication and control module.

Advances in computer technology and generation of real-time feedback are two of the most powerful tools for reducing production costs and raising product quality. Sophisticated testing and measurement systems can now be linked directly to computerised systems to provide direct links between quality, design and manufacturing. The emergence of DMIS (Dimensional Measurement Interface Specification), developed originally by Illinois Institute of Technology Research and which was funded by CAM-I, allows a generic interface to be defined [42]. This Quality Interface (QI), consists of a neutral command file, a neutral data file and protocols, have been developed to link measuring machines to computer aided design systems enabling the integration of both design and manufacturing and quality and inspection information. The foundation of computer aided quality systems are thus already in place. What are required are total quality programs.

Staveley and Dale [299] point out that designers may play a key role in improving the quality by requesting quality-feedback information from customers and by monitoring the request for spares. The information would be requested in those areas where there might be design uncertainty. Houston [145] argues that in terms of how much quality costs, repair is usually the most expensive way to maintain quality, design is probably the cheapest. Sumner [305] and ElShennawy [110] argues that quality of design is also an important component of a TQM system and adopting a design approach can lead to more efficient use of company resources.

To conclude, Rembold [250] suggests that as many activities in a factory are directed towards attainment of a high quality product, that a systems approach (CIM) is required to integrate all the efforts. It is evident that all activities influence each other such that a feedback loop can only function when the inputs and outputs of each activity are taken into consideration. Information or data flow thus is the key to control and reduce current costs and create an environment for continuous improvement and further cost savings.

2.3 Concept of Measurement Assurance

Measurement Assurance is considered as the key to raising quality and the technical level of production. The effects of metrology on quality assurance stem from the development and adoption of quality control systems and methods. This, says Udovichenko and Koifman [326], involves the development of novel sub-systems and the emergence of new management objectives. This necessitates: the enhancing of the control of the parameters of the product per se in its intermediate and ultimate states and also the parameters of the manufacturing process; introduction of new program-adjustable production facilities of control, verification, functional diagnostics, recording and conversion of data as well as handling, storage and delivery of parts; using the dynamic structure of quality control at the stages of development, tooling up for production, manufacture, servicing of products etc. Metrology is important in resolving these problems and consequently metrology or measurement assurance can be considered as part of the quality control system.

The two schools of thought which are evident in this concept are: the conventional technocentric or technology-centred approach to system design which involves designers in the practice of man-machine compatibility, functional requirements being realised with respect to the technological state of the art, where man takes over those functions that are not yet technically solved. The alternative anthropocentric or human-centred approach to man-machine system design rejects the notion of man-machine comparability and focuses

instead on how they may complement each other. In this view, men and machines help each other to achieve an effect of which each is separately incapable. The view on the two schools of thought are also supported by Brodner [66].

2.3.1 Human-Centred Measurement Assurance

A human-centred system must aim to utilise existing skills and allow to develop into new skills. However skill analysis is an analysis of performance rather than behaviour, a measure of the man-machine system rather than of the human in isolation from the equipment.

To this, Dressman et al [103] suggest that the journeyman machininsts use their senses and experience to monitor and control machine tools despite widespread use of computer numerical control (CNC). They suggest that the human operator has a fundamental role in machining. The journeyman machinist possesses the experience of an artisan/craftsman and the expertise of a technician/controller. To be able to produce a product with an accuracy greater than the 'specification' accuracy of the tool is an art, and such a challenge cannot be met without an expert human operator. No two machines are identical. A journeyman machinist recognizes this and learns to know his machines, their capabilities and their peculiarities. He know his tools and the ways to maximise their usefulness and he knows his instruments and the routine and non-routine uses for them. He can access standard machining references and knows when and how far to deviate from 'standard practice'.

The Dressman viewpoint is echoed by Bourne and Wright [60] who have researched into the machinists' use of visual and auditory monitoring during machining, see Figures 2.5 to 2.7. These functions performed encompass planning, NC program, fixture setup, part setup, tool setup, phantom pass, rough cut, finish cutting and inspection. They clarify the structure of the tasks and decompose the elements of craftsmanship into sensing and control and investigate how their components can be automated. They conclude that there

are several practical and theoretical hurdles to overcome before true unattended operation. Their experience suggests that there are no currently adequate solutions to solving process control problems. The use of expert systems/AI is offered but problems remain in maintaining flexibility of the system.

Wright [343] argues that full automation of complex processes such as machining will only be feasible when some of the more qualitative, sensor-based and heuristic information is gathered. A preliminary analysis of machining revealed through somatic knowledge experiments that at least seven different sensory cues are used during the complete machining cycle and that the skilled machinist blends all these together to make diagnostic decisions. Visual information is more important during setup, but during real-time machining a combination of intense visual and aural information is used by the machinist. Domain expert visual sketches and aural signatures have been proposed as a way of gathering the qualitative and colloquially described knowledge of craftsmen. The visual sketches and aural signatures identify the symptoms of the in-process changes of a craft-operation or manufacturing process. The sketches also identify the subgoals and long term goals that craftsmen work towards, during a tasks completion.

The need for human intervention is also discussed by Hammer [29] who states that experience has shown that the monitoring of tool readiness and the dimensional accuracy of workpieces with sensors and measuring probes as well as the initiation of correctional and evasive measures are so far possible to a limited extent. The great expectations and promises made in this area have remained largely unfulfilled., humans are still being required. The achievement of complete automation though is still a development objective.

Because of unforeseen disturbances that may enter the system, the operator must be able to control all tasks that contain choice-uncertainty via an interactive interface. This view is supported by Corbett [87] who discusses the importance of man-machine interface

design for overall system efficiency and describes how interface software enables operator and machine to help each other to achieve an effect of which each is separately incapable, see Figure 2.8.

An operator cannot control a system without comprehending its functions and as such devices are developed to assist in his decision. Hitachi Seiki [283] suggest some of the functions and devices that make the man-machine interface more efficient. These include cutting monitoring, tool breakage detection, overload detection, tool life management, workpiece machining time, spare tool call, non-cutting time reduction facility, pre-machining tool check facility, feed override reduction, universal touch sensors for inspection and workpiece measurement, devices for efficient setup and machining completion .

Rouse [261] argues that manufacturing is undergoing a metamorphosis more slowly than anticipated but which is nevertheless progressing. He suggests three important trends: First, information technology is replacing physical technology as the central concern; second, as a result software is replacing hardware as the key to productivity; thirdly cognition and reasoning abilities are replacing sensorimotor skills as the raison d'etre for the human role in manufacturing systems. Rouse thus suggests a conceptual design of support systems for humans in advanced manufacturing systems. A design methodology is presented that includes five major steps or phases: characterising users tasks, assessing demands of tasks, identifying approaches to support, determining likely obstacles and anticipating user acceptance problems. Sharit et al, [280] also provides a conceptual basis for the design of a decision support system (DSS) for the human supervisory controller in a computer integrated manufacturing (CIM) system. This system acknowledges human cognitive abilities and limitations as well as the unique features of the CIM environment.

Slatter et al [286, 287] and Besant et al [50,51] contend that a technology-centred approach results in unforeseen organisational and human impacts that can significantly impair system

performance and the future capability of the company to react to market requirements. The development of the human-centred view is discussed whereby technical and human aspects are considered in parallel, see Figure 2.4. They argue that there is no concise definition of human-centred since the approach is more a philosophy than a set of rigid rules but they list a number of key features: that the technology should account for the existing skills of the user and should provide the user with the opportunity to learn; that the technology should facilitate the maximisation of operator choice and control; that the technology should be designed such that operator knowledge of the whole process is maximised. The authors have built a demonstrator CIM facility (a CNC lathe and machining centre with associated workholding and inspection equipment) as a vehicle for testing hardware and software developed according to human-centred guidelines. Murphy [222] reinforces the human-centred view through overviews of a number of projects carried out at Bitz, BICC, and Rolls Royce.

Despite the obvious benefits of adopting a human-centred approach there are obstacles to its widespread adoption such as attitude, and the possibility that it may make an already complex task more complicated by the addition of human factors considerations. However, there is a steadily growing recognition that the dominant technology-centred approach is increasingly dysfunctional and there are indications that market requirements, the premiums on flexibility and thereby shopfloor skills demand that companies pay greater attention to the human aspects of manufacturing systems.

2.3.2 Technology-Centred Measurement Assurance

Evidence of technology-centred cells is varied and discussed essentially under cell-based inspection systems. Some examples of technology-centred cells are given below for completeness of argument and purpose of illustration.

Veron [330, 331] describes the in-process quality control and corrective feedback in a flexible manufacturing cell at LACN. The dimensional control is realised through a CMM.

Integrated inspection allows an appropriate feedback on the manufacturing process. Measurement analysis ensures on-line correction of the NC programs, thermal drift and tool wear which are predicted during processing through an auto-regressive model which identifies dimensional fluctuations and then correction values are estimated through a Kalman filter. The dimensional results allow storage by the cell robot according to quality classification.

Gien et al [126] also describe real-time quality feedback in a flexible machining cell. He discussed an on-line adjustment system where data obtained from inspection are used to compute tool offsets. The computation of tool offsets from the measurement of a part allows some corrections for the machining of the next part. The authors propose an optimal model for control of the process based on fuzzy sets. But as in Verons work the system relies for a final decision on the operator.

Kanai et al [162] describe an 'intelligent machining cell' in which workpiece recognition, process planning and cutting process are integrated. The cell employs a non-contact distance sensor vision system to measure an arbitrary blank shape and to generate a process plan by comparing the measured blank shape with a geometric model of the product. By integrating the measuring system with the process planning system and the cutting process the setup is simplified as well as enabling the system to adapt to different blank shapes and thus generate good product.

Chang et al [77, 78, 219] describe an integrated design, manufacturing and inspection system for prismatic parts in what they call QTC (a quick turnaround cell). The system includes four tightly coupled modules: a feature-based design system, a cell controller, an automatic process planning (using AMPS, Automatic Machine Planning System) and part programming system and a vision monitoring and inspection system. The only human input required during the entire design/part realisation process is during the design phase.

Upon completion of the design, the system generates the process plan, part program and inspection plan automatically. The system is implemented in a university environment and it is not clear if feedback of measurement result are used for process correction.

2.4 The Role of Statistical Process Control in Measurement Assurance

Process control, with the aid of statistical process control (SPC) and process control devices, has become an important tool in the highly competitive environment of the Western world [338]. It is not new but has been resurrected as an effective tool in the reduction of operating costs, improved product quality and increased productivity. It's use by the Japanese has resulted in improved customer satisfaction and the desired level of product quality. In itself process control is not a panacea; it will not correct poor product or bad processes. The heart of process control lies in the area of charts to control the process accompanied by other process control devices, review in section 2.5.2, which provide operators and management with the information and means to adjust the process. The most important of these is for closed loop control for data to be fed back to machine or higher level design for corrective action, if any, to be made. Whyte reviews four consecutive modes within the process: part manufacture; characteristic measurement, measurement of communication and machine or tool adjustments as required for further manufacture. Reducing variation in characteristic measurements requires a diagnostic journey to be undertaken from symptom to cause and on completion of this journey a second follows from cause to remedy.

Many definitions and applications of SPC had since been defined and researched into. SPC can be defined as a process control method which gives confidence that components produced are within tolerance without having to measure every component. It is associated with the theme of controlling the process not the product and is a form of feedforward. SPC is also about achieving the highest possible quality first time in the most efficient and least costly way [39,40,106]. In contrast, Statistical Quality Control (SQC) is an after the fact detection

function to make accept-reject decisions on production materials and parts. Although SQC shares statistical techniques with SPC the difference is the time frame over which the data is collected and analysed.

Nolen [226], Napper [224], Whyte [330] and Stanton [298] refer to SPC as the application of statistical methods to identify, monitor and control variations that exist in a manufacturing process. Variations are caused by either of two principal factors 'assignable causes' and 'random cause'. SPC separates out and focuses on the assignable causes. In this classical definition, a process that exhibits only random variation is said to be in (statistical) control. Nolen further claims that a large percentage of processes in a typical factory are not routinely capable of the tolerances demanded of them. He suggests that since SPC investigations are time consuming, group technology may be employed to assist in determining where efforts may be focussed on the critical features of the largest part family.

The key element to maintaining quality is simplicity in approach claimed BenDaniel [48]. Although SPC is based on some fairly complex statistical theories, the general application principles and the statistical understanding necessary for implementation are relatively simple. BenDaniel also describes the accompanying application of 'bakayoke' (the Japanese term for devices that automatically check for abnormality in the process). Bakayoke was used to sort out defective product, and if an increased amount of product was rejected, would effectively flag when the process may be working incorrectly.

SPC may also be used for operator monitoring of work and to allow reaction to information. The use of such a system, described by Blache et al [55], allows more knowledge to be gained about the variables affecting targeting and capability. As these variables are identified and controlled continual improvement can be made on the process thus ensuring that only good parts are delivered to the assembly process.

2.4.1 Review of Novel Research

There is a vast literature base covering the area of statistical process control and statistical quality control (SPC/SQC). This review is to highlight some of the novel techniques emerging from that research base and previously neglected areas of application. The tools to apply SPC can be divided into hardware and software and a combination of the two.

Alsup [8] argues that the design of a SPC system architecture should accommodate a stepwise technology migration path and permit integration with an existing host system. Steizer [301] says that SPC then tightens the loop in real time quality. The assumption was that if quality problems could be found when they occurred and key decision makers advised immediately, the line flow would not be interrupted. The solution hit upon at S. Weston was to use some type of radio frequency data terminal to communicate with a central computer. Inspectors could then go anywhere in the plant and interact with the database in real time. The computer would respond on completion of the inspectors inspection with out-of-control or in-control and the inspector would react accordingly. At the central facility managers could make decisions whether to use the parts, scrap or rework them. All the relevant authorities would have access to the system thus providing a control loop.

Waller and Hames [335] describe the GKN Kent Alloys SPC experience and concluded that the use of SPC was a bonus as it provides existing and potential customers with a quantified and extensive documentation of their production control cycles.

Ooi and Kumar [230] outline a software controlled system for real time monitoring (RTM). The RTM system they developed for IC manufacture (they claim it has equal applicability to other large scale manufacturing operations) consists of two main software systems communicating with each other via a database, the heart of the system. This on-line database stores results of inspections and through generation of reports, is able to

provide regular checks on the process variations and thus reduce the rejection rate. The on-line program runs in the foreground and controls execution of the RTM system and an off-line system operating in the background does the house-keeping and report generation. They claim the systems advantages as reduced cycle time, enhanced production quality, reduced possibility of biased sampling, quicker decision making and reduced human involvement.

Sauer [274] describes 'operator aid' a system that provides on a simplified drawing the connection between the product features and data measurement for the respective machining operation. The operator aid is further identified with those features considered as critical using a letter based system. The operator uses the basic part number and measurement letter to track any unique feature into the SPC system. When the operator is ready to enter the data the data sheet for that particular feature will indicate the gauge or type of gauge that is required to take the measurement.

Kamal [161] researchs the computerised fitting of equations to the data to predict future data in advance of actual production to aid in process control. Kamal offers an expert system integrated with SPC. There are two well defined knowledge domains related to the solution space: the statistical domain and the physical domain that reflects the behaviour and characteristics of the product in question.

Birman [53] goes a step further by arguing that the general purpose SPC approaches and software are poorly suited to most manufacturing processes and require that operators be trained in statistical techniques. Overcoming both of these deficiencies, he argues, are process specific expert system based SPC which are able to work in production as a reliable partner for the machine operator. This provides plain English like messages that enable the operator to control the process better. Birman argues that tailoring SPC to process by

embedding knowledge about a particular process in a rule based system goes beyond the 'one size fits all' approach of other statistical software/SPC packages no matter how sophisticated their capability.

Dooley and Kapoor [102] discuss the application of a rule based SPC-time system for classifying faults in continuous processes modelled by time series and monitored by statistical tests which check the underlying distribution of the model residuals. A rule based fault classification system is used to identify fault type, and a least squares algorithm estimates fault magnitude and time of occurrence by matching sample results with theoretical expectations. For a shift in the process mean, fault time occurrence is estimated as the time at which the violating cusum last passed the target value line. Fault magnitude is assumed to contain both step and linear shift components and theses values are estimated through a least squares method.

Kelton, Hancock and Bischak [168] look at what happens when a process shift is detected. They argue that very little guidance is provided to an operative as to how to conduct an investigation to find the assignable cause of this variation, yet he is expected to ultimately make a decision about the appropriate action to take and the amount of any adjustment. Kelton et al propose readily implemented techniques for specifying the amount of adjustment to be made. The first of their recommended adjustments A_0 uses the out of control point itself and thus involves no additional sampling but unfortunately displays a bias towards over adjustment which in many cases is more costly than under-adjustment. Three other estimators A_1, A_2 and A_3 require that the process be left in operation for sometime after the out-of-control indication to obtain unbiased information on the current process mean. In this way Kelton et al claim companies can afford to obtain the information necessary to attempt one-time accurate re-centring of the process.

Hart and Hassan [136] describe the use of an attribute control chart using monitor limits. Shewhart proposed the use of statistical control charts using either variables or

attributes. One of the problems with attribute charts was that no information was able to be extracted on the process change or the true process mean and standard deviation and possibilities for improvement in the process. Hart and Hassan devised a chart based on two monitor limits used on the distribution of a single quality characteristics values: a marginal limit and a poor limit. These two monitor limits will divide the product based on the single quality characteristic inspected by attribute inspection into marginal product - product beyond the marginal limit but not beyond the poor limit, poor product - product beyond the poor limit and good product - product to the left of the marginal limit.

Jaehn [156] discusses real time statistical process control through the use of zone control charts. Real time control requires control chart procedures that are fast efficient and simple. The zone control chart is Jaehns answer to maximum simplification of the shewhart chart. Its construction is simple- just seven straight horizontal lines. On each line a box is furnished to record the target and the one- two- and three-sigma values.

The use of non-contact inspection such as vision system to assist in the control of process is becoming popular. Braggins [62] suggests that machine vision systems which can measure and make other quality checks on products using a combination of imaging sensors and computing power are well suited to integration into statistical process or quality control systems. One of the most obvious advantages of vision systems is that the information produced is digital and available in computer readable format. Another advantage is that the measurements are non-contact and independent of any operator or procedure influences. This means that a trend indicated by vision is visible at earlier stage than from an equivalent conventional measuring technique. Vision systems are fast and make 100% inspection practical provided the information obtainable from a single view point is adequate.

2.4.2 Emphasis on Process Control

There are two basic approaches to quality control: product control which checks the output for acceptance or rejection after production and before despatch and; process control which influences the quality of the process itself. Current literature has focussed on the value of process control contrasted with product control as a better means of achieving product quality. The idea behind this as stated by Tunner [325] is simply that if the manufacturing process is understood and controlled the product will emerge satisfactorily. Since process control can occur well upstream of the finished product, the higher costs associated with product testing and inspection and waste can be significantly reduced. Conceptually this idea can be reinforced through practice and applied to all manufacturing operations giving rise to total manufacturing process control. Tunner outlines the four steps to achieve the latter : understand the product, analyse the process, improve the process and control and monitor the process. The moves to a much tighter control of industrial processes inspired by Taguchi methods has led to a greater appreciation of system variables in many processes says Sanders et al [270].

Another approach is towards building the quality rather than inspecting the quality. This requires a system approach to quality control at each process rather than inspect at the finishing stage. Hartopp [137, 138] suggests that this shift in emphasis from error detection to error prevention can be achieved by monitoring quality from materials-in to goods-out; in-line inspection functions so that feedback signals detecting counter-productive situations allow rectification before the condition creates major costs and scrap.

Brankamp and Bongartz [64] suggest monitoring the process in stages rather than just at the end. They parallel the increasing importance of process control with the increasing demands on greater quality. This increasing quality requirement, they comment, cannot be met by sampling as only a small percentage of product will be inspected and furthermore they suggest that the extent of control may in itself vary. As process control controls every

product the beneficial economical effects have to be validated, for example more use of lost time caused by manufacture of defective products or sorting of scrap from good products; increased machine running time and finally savings in material and tooling costs.

The notion of error prevention has led Goh [128] to broaden the term 'process' to denote productive operations involving combinations of men, machines, materials and methods, see Figures 2.2 and 2.3. The mechanics of process control outlined entail continuous monitoring of process output; the moment a feedback signal indicates possible defective products, the process is halted for troubleshooting or adjustment. Information feedback on a real-time basis is necessary for such a system. The success of process control depends very much on the judicious intervention of the process as over-reaction would lead to numerous unnecessary stoppages and adjustments, while untimely reaction would result in frequent runs of defective product.

Napper [224] and Owen et al [232] suggest that by definition SPC is a preventative based system. They claim it is understandable that experience in SPC may well be based on product analysis such as component dimensions. This is product control but as confidence builds up greater attention will be directed to factors such as tooling, raw material control, process temperature etc.

Kamal [161] and Owen et al [232] add that the enhanced performance of SPC through either human expertise (if available and/or financially feasible) or by deploying expert systems as an integrated part of the entire process can contribute to prediction of product specification, prediction of product quality in a particular environment, the automation of procedures related to the process.

Hill [141] further adds to the discussion by introducing the economic links between cost, price and quality. He questions whether the rationale as put forward by other

researchers that it is economic to automate inspection and product control holds as a way of reducing unit cost whilst maintaining quality. Hill draws no firm conclusions but suggest the factors and influences that play a role in such decisions.

Bentley [49] puts forward the view that in an ideal world, the desire would be to maintain 100% control throughout every operation. Such a system, he argues, is feasible in the process industry and in automated assembly lines and flexible manufacturing systems. But in batch manufacture, the effort would have to be focussed on bottleneck operations due to the distributed nature of processing in such manufacturing systems. The Bentley view is still based on the premise that product control should start at the design stage as experience shows that 60% of product cost is determined by the design, 30% by the configuration of the manufacturing resources and only 10% by the effectiveness of usage of such resources.

The techniques that facilitates process control are currently gearing toward vision control although the technology stills remain distant in its achievement of total manufacturing integration. Wright, Bourne and Milligan [344] discuss the on-line quality control in a flexible machining cell with particular regard to product control through a vision system. The vision system is used to compute a three-dimensional (3D) image of a manufactured component into a 3D representation of a product. This enables measurements to be taken and correlated with possible error conditions. This enables rapid inspection of a product after manufacturing and prevents errors in subsequent parts.

Hirata, Hibara and Tanaka [143] also point out that vision systems are essential to realise the potential of advanced automation. Vision systems are envisaged as an integral part of the factory of the future.

Rembold and Levi [251] suggest that changes in material requirement logistics will demand data processing systems that are compatible with the material handling systems

and that provide standard interfaces. Optical, acoustical and multi-sensor pattern recognition systems are being developed to recognize parts as they move from one process to another. Users in the 1990s, it is claimed, will be able to follow parts as they change shape during the manufacturing process.

Ranky [245] argues the shift from inspection after completion of a manufacture process (often resulting in batch failure detected far too late to take any corrective action in the machinery and/or in the process involved) has demanded integration of some kind of quality control system at cell level as well as at the FMS system level. With CIM computer control and supervision and furthermore with expert systems, quality control and quality assurance goes hand in hand with the design and the process itself. The result is dramatic since no machine (or cell) is passing on bad parts to the next machine (or cell) thus cutting down scrap to a minimum, often to zero. The use of SQC, Ranky argues, was the traditional method for maintaining quality at a desired level. It allowed management a mathematically proven method for setting a line for allowable failure. In CIM, the aim is to design quality into the product and to maintain quality as an integrated part of every process the product or its components go through. The aim, in other words, is to provide 100% quality assurance at the desired level of quality which has been decided by the management, issued as quality guidelines and 'in-house' standards, designed into the product and maintained throughout the manufacturing process.

2.5 Quality Feedback for Measurement Assurance

Gauging/inspection is usually carried out as a dimensional check for measurement assurance within the framework of quality control system. But when accuracy demands as well as the costs of machining and workpiece are high, the gauging operation is advanced into the process sequence in order to take place as closely as possible to the machining cycle.

Fully automatic gauging, says Murphy and Arnold [221], plays a dramatic role in the success of the automated factory. Automatic gauging performs several tasks of which the

most important is to remove rejected parts out of the system. In many cases, it also provides signals to automatically compensate tools make adjustments, initiate alert signals for self diagnosis, provide a wealth of information for counting and using other statistics to evaluate system operation and effectiveness and provide for quality feedback.

2.5.1 Gauging Techniques for Measurement Assurance

The single most important concept to emerge in recent years is process control. The aim is to make products right first time and to get as close as possible to the zero defect target. Process control is achieved by two main routes which are interrelated [26]. First, measurement is applied during or as soon as possible after machining. Second, by exploiting the power of the computer for data processing, information on large numbers of measurement readings can be aggregated, analysed and expressed in a variety of ways in order to detect drifts and trends. These movements in quality can then be corrected before they exceed preset limits and the possibility of never making a reject component is at least theoretically feasible.

The two trends in recent manufacturing developments are: the move towards increased flexibility in machine tools and; the drive to reduce capital locked up in work-in-progress by employing such production techniques as Just in Time (JIT) manufacture. Both developments have had a fundamental implications for process and quality control, one being that flexibility in the manufacturing process must be reflected in flexible gauging systems. Getting it right first time has led to the realisation of the contribution that some form of automated gauging can make in its three basic forms: in-process, in-cycle and post-process. The definitions, applications, advantages and disadvantages will be discussed below.

2.5.1.1 In-Process Gauging

Hermann [139] defines in-process gauging as process intermittent measurement of tools and workpieces and suggests that this has gained importance because of growing interest in extended automatic operation of manufacturing equipment in the form of unmanned second and third shifts.

Ricketts [257], Treywin and Edwards [324] and Astrop [39] argue that in-process gauging, defined as measuring the part while it is being made, machined or processed, is the ideal situation but for practical reasons this can only be applied to grinding [33a]. For all other processes there are three options: inter-operation gauging, immediate post-process gauging or a combination of both. Most of these solutions are based on simple and elegant solutions found in the touch-trigger type of probe system.

Zeppelin [332] states that in-process gauging generally employs 'switching' sensors, the actual measurement is effected by the traverse measuring system of the machine. This leads to a considerably lower cost for in-process gauging but environmental difference between the shop floor and a clean room have also to be considered.

2.5.1.2 In-Cycle Gauging

Roe [259, 260] defines in-cycle gauging as the method by which gauging is carried out on a machine tool as part of the total machining cycle but not at the same time as cutting takes place. This definition covers the ability of the system to inspect components and update tool offsets, set a datum on a component, measure tool positions and update tool offsets as well as a variety of related activities. The main areas of application for this method are on CNC lathes and machining centres where small to medium batch work is done. The system accuracy is normally lower than post-process or in-process systems.

Roe suggests that in-cycle gauging has its advantages in the elimination of drift effects, the elimination of tool presetting, and the ability to monitor the effective size and cutting performance of the tools. What the system cannot do is improve the capabilities of a machine tool. In fact, the performance under the control of in-cycle gauging with feedback, over a period of time, will not be as good as the machines part-to-part repeatability. However, it will provide a significant improvement in batch size control and can also perform this automatically.

In-cycle gauging has the obvious disadvantage that it stops the machine from carrying out its primary function while the gauging process takes place. Nevertheless, Ricketts [258] argues that there is an important niche in the market for in-cycle gauging. This can be defined as where a critical dimension is machined near the start of a long cycle.

2.5.1.3 Post-Process Gauging

Post-process gauging is the fastest growing area for advanced manufacturing applications. In post-process checking, the component is either checked with probes, at the end of the cycle, while still in the machine or it is placed in a multi-dimension gauge by the operator (or a robot). In both instances automatic feedback of error data to correct tool positions can be provided. In the majority of automated post-process gauging installations the part is automatically transferred to the gauging machine via a robot or other automated handling system. The actual gauging solution is largely dictated by the volume of the work and the complexity of the component. Dedicated post-process gauging stations are most cost effective in the higher volume market. For medium volume production the optimum gauging fixture can be constructed from a modular system of work handling and gauging heads. With careful design, it is possible to construct such a fixture to handle a family of similar components with minimal adjustment. von Zeppelin [332] adds to this by stating that post-process gauging always requires a 'measuring' sensor with its own measuring system.

Ricketts [257] states that experiences with some early post process gauging systems prompted the introduction of feedback corrections based on SPC. This eliminated over-compensation based on a single rogue result. Also, SPC irons out any hunting in the inputs to the machine. The next logical step, in this from the development of SPC, is to introduce, as Marposs have in the 'E42', a combined programmable gauge and statistical analyser.

In-process, inter-operation and post-process gauging now have the benefit of microprocessor based SPC which automatically collects data, collates and analyses it, then triggers action on the conclusions it draws. Hartopp [138] describes such an implementation at Clayton Dewandre at Morley. Each installation at Morley comprises a host computer located in a monitoring centre within each department. Connected to this computer are upto seven Precom gauge units situated on the shop floor. The operators are able to transmit and receive, via a keyboard and screen monitor, all required component dimensional data. Five consecutive machined components are gauged and checked at intervals. All statistical information is stored and used in SPC and for 'Go-NoGo' gauging.

2.5.1.4 Open-Loop vs Closed-Loop Systems

There is nothing intrinsically new in any of these approaches argue Ricketts [257]. The crucial difference developed in recent years has been to automate these processes and convert the gauging from an open-loop to a closed-loop system. With an open-loop system, the gauging unit takes the measurement, then the operator based on that result, takes corrective action to keep the process within preset tolerance bands. The closed-loop system further automates this process by taking the signal from the gauging unit and feeding it or a proportional signal back to the machine control system so that corrections are made automatically. The ideal system would be a closed-loop, in-process gauging system so that parts would be continuously monitored. Data would be fed back to the machine tool or manufacturing system to close the loop and initiate corrective action.

Marposs have been producing such systems for several years notably for controlling processes such as grinding and honing [34]. One of the worlds leading suppliers of in-process gauging equipment, which provides both the degree of accuracy and repeatability necessary and which can also be integrated into the control systems needed to automate the machining process, is Movamatic, the Swiss-based manufacturer.

Ricketts [258] argues that each method has its advantages and disadvantages. The common denominator for all processes is the increasing awareness that some form of closed loop control is essential to take any time lag out of the system. With open loop gauging system, maintaining components within tolerance is dependent upon the operator initiating some corrective action to keep the machining process within pre-determined tolerance bands. The move towards closed loop systems eliminates this operator intervention. Signals are fed from the gauging system to the machine and can incorporate SPC if required.

With JIT and the move to minimise stocks and smaller batch sizes, the emphasis on post-process gauging, Rickets [258] argues, has switched to sophisticated easy to program, rapid operating, high speed inspection machines. Interfaces on these machines are provided for connection to statistical analysis systems and closed-loop feedback to upto four different production machines. As manufacturing moves towards automated cells, there is a growing requirement to pull this data together into a co-ordinated system. This has led to more recent development in local area networks specifically tailored for quality control data. Ricketts argues that quality systems no longer measure the manufacturing process, they control it.

Marshall [205] also advocates a closed loop system by linking a post-process gauge to the machine controls. The difficulty, he notes, is that the size of a machined workpiece can be affected by several causes and it takes an 'intelligent' gauge to identify the causes, assess the effects, and determine the action to be taken. Marshall notes that deviations

in measurement are usually due to failure, random variation and drift and that facilities do exist in current CNC control system for self diagnosis of failure but not necessarily drift and random variation.

2.5.2 Machine-Based Sensory Control

This section is aimed at providing a comprehensive review of that section of the literature describing the functions available at machine level to control specific parameters. This is to ensure that a machine tool performs within specified limits and produces to a required quality level.

Among the most important factors in regard to metal cutting is the condition and accuracy of the cutting tool. Tool compensation is thus an important consideration in any attempt at process control. Many machine tool builders have focussed their energy in this area and it is now almost common for sensors or probes to be present, together with in some cases sophisticated control strategies, [13, 14], to function in an almost traditional role of detecting tool wear and breakage.

The majority of tool sensing systems are effectively alarm monitors which stop the machine or trigger an alarm when the system detects tool breakage or excessive wear. No evidence is apparent which has linked these systems with adaptive control software (aside from toolchanging) to maximise tool life/wear by modifying the cutting conditions via sensor analysis. A UWIST research team [15] suggests that the potential benefits that can be gained are not accepted by the majority of users/manufacturers.

A vast literature base exists which in the main reviews the trends in sensors and their application in machining [83]. Kalpakjian and McKee [160] suggest that only a core of this base has any significance to machining operations. The following is a brief review of research and developments in this area.

2.5.2.1 Forces

The monitoring of cutting forces has been an essential part of adaptive control [179, 16], both for process control as well as for optimisation of machining. By monitoring forces it is possible to detect the onset of excessive wear and thus the failure of cutting tools. In addition to the adverse effect on forces and surface finish excessive wear contributes to increased temperature with subsequent loss of dimensional control and surface integrity. Models and simulations have been developed to estimate this wear: Ueda and Sugita [327], Thisty and Tarng [318], Shumsharuddin and Lawrence [285], Koren et al [180], Jiang et al [157], Takata et al [314] and Conrad and McClamroch [86].

2.5.2.2 Vibration and Chatter

Monitoring of forces allows the determination of vibration and chatter in machining operations. The on-line observations of chatter are indirect measures of detoriation in workpiece finish and dimensional control as well as an indicator of possible tool failure. Researchers that have addressed this area include Astantin et al [38], Sakai, Nakato, and Ohkusa [267], Lindstrom and Lindberg [187], Sata et al [273] and Rahman [244].

2.5.2.3 Temperature

Because temperature and tool wear are intimately related, emphasis has also been placed on the on-line monitoring of temperature during machining. Research has been undertaken in measuring the temperature at the hot junction of tool-workpiece by Kalpakjian and McKee [160] and Donmez et al [101].

2.5.2.4 Acoustic Emmission

This has shown to detect both flank wear, crater wear, as well as stick-slip at the tool-chip interface. Takata et al [313] describe a sound monitoring system using a speech recognition technique.

2.5.2.5 Dimensional Control

The use of sensors for dimensional control has been another area of interest [5, 159, 202]. There are three strategies. Firstly, the use of monitoring systems that measure the conditions of the machine tool or process. Secondly, the use of diagnostic systems that try to find a functional or causal relation between failures in machining and their origin. Thirdly, the use of adaptive control. The latter, at its most simple just activate a machine stop. More sophistication is gained through the use of adaptive control with constraints (ACC) and adaptive control with optimisation (ACO) systems. Many of these systems can now be found commercially in some form such as torque control monitoring (Cincinnati Milacron), adaptive feed control (Mazak), cutting force monitoring systems (SMT [4]), sizing control (Traub [277, 333]) and tool breakage monitoring (Sandvik and Valanite). The use of probes on machine tools has also transferred to a limited extent the quality decision on dimensional control to the machine [5, 159, 307, 47, 276, 308].

2.5.3 Cell-Based Total Manufacturing Control

The latest developments in automated manufacturing have generated a need for computer assisted quality assurance (CAQA). Ercole [111] says that "the higher the automation level of a process, independently from the nature of the process itself, the higher is the necessity to control in field and in real-time, the quality output of the process". This necessity has been immediately grasped by both the manufacturers and users of automated systems, consequently major co-ordinate measuring machine (CMM) manufacturers have endowed the task of realising the first integrated inspection cells.

The strategic purpose of these foreseen CMMs would not only be to prevent bad parts, but also to aid in data collection and evaluation and in linking to other factory information systems in what some researchers and consultants have termed 'total control manufacturing' [99]. Still whatever the view of the future CMMs, with advanced imaging

capabilities could virtually guarantee 100% on-line inspection of all critical parts for a wide variety of products, helping manufacturers to realise elimination of bad parts altogether.

The concept of total manufacturing control is supported by Treywin, [321, 322, 323] who suggests that inspection will become part of this control in assessing production trends and the capability of machine tools to reform their functions.

With increasing acceptance of automated production, it has become evident that inspection devices particularly CMMs are not ideally suited to shop floor use. As more emphasis is placed on strategies for integrated manufacturing, the CMM is perceived by many as the missing link in the cycle. Traditionally housed in a controlled environment, the transition of the CMMs onto the shop floor requires a rethink of their design and use. One method around the potential environmental problems, particularly temperature, has been used by Yamazaki at its factory in Worcester [345]. The whole atmosphere within the building is controlled to within 2°C, this luxury is not possible for most factories.

Despite the above, the relatively fast on-line inspection capabilities possible with CMMs helped spur the movement of the equipment from corporate and university laboratories onto factory floors. Here, they are being used with greater frequency as part of flexible manufacturing systems, just in time production and total quality control programs [33]. One of the primary incentives for using CMMs, instead of hard gauges, has been the potential for substantial time savings although CMMs are not seen as a replacement for hard gauges, which can still be used to determine feature size. CMMs are perceived as a complement to hard gauges since CMMs can measure form, such as roundness or flatness and the geometric relationships of a parts features to each other. This is performed with flexibility, speed, accuracy and repeatability that cannot be matched with conventional hard gauge measurement.

Treywin and Edwards [324] review the developments of the CMM. The CMM has followed the basic design configuration of cantilever, moving bridge, overhead gantry or horizontal arm. Coupled with these structural variations are automatic probe changing, vector drives (which move the probe along the shortest path between two points), DC servo drives (non bearing, backlash free), carbon fibre arms (to offset the risk of droop), geometric compensation (dynamic compensation control for the squareness of axes relative to each other), laser scanning (primarily for the measurement of shape), and volumetric compensation (computer software corrections). Developments in computer control include real time multi-user operating systems allowing several tasks to run concurrently, enhanced file storage, print spooling, part program creation, greater disk storage, network communications, inclusion of inspection language and distributed control. Treywin and Edwards argue that the integration of inspection in an FMS is now a reality. This has led to demanding speed of measuring sequence equal or better than the NC cutting program. One of the factors beyond physical integration highlighted is the need for a by-pass cleaning facility to clean the component and reduce the temperature prior to inspection.

Lotze [193] also reviews developments in CMMs and suggests that higher accuracy is necessary for application in a precision engineering environment. This higher accuracy is tied to a requirement for higher standards in software control. Higher measuring speed is necessary to achieve 100% inspection in automated manufacturing environments. The application areas may be widened by hardware and software developments coupled with the integration of databases and information processing of design, manufacturing and quality control based on unified geometric workpiece definitions.

Wright [342] stresses that the primary purpose of a CMM is negative feedback of production errors so as to control the manufacturing process, especially in unmanned factories. Output from the CMM is primarily numeric and can be transmitted into information relevant to production. The CMM also provides capability of storing measured results to enable detection of trends and generation of instructions for preventive action.

Wright suggests that current interest is focussed on downloading of 'drawing' data from CAD system directly into the CMM programs, and even the generation of the CMM program itself in the CAD system via a Neutral Data File concept. This, he argues, although helpful is preliminary to the real task of meaningful and automatic error feedback. The suggestion is that a CMM has the potential to turn the facility into a central loop and one with substantial (de-stabilising) delays.

Bowman [61] says that until recently there were no standards for transferring data between CAD and CMM, each system needed a post processor to convert the CAD data to that recognized by the controller on the CMM. While there are few examples of links between CAD and CMM in the UK there are several recognized installations in Europe and the USA. Ferranti, Computervision and McDonnell Douglas have software interface links available to a range of machines.

Anon [17] says that with CIM, it becomes possible to close a major cultural loop in the design-production cycle and superimpose manufacturing capability directly on design. This, sometimes referred to as 'reverse engineering', entails the designed and made product being measured on the CMM and its tailored-to-fit-the-process dimensions fed back to CAD. Renishaw's mastery of touch trigger technology has become the 'tooling' of CMM as well as other modes of in-process gauging.

A CAD/CAM graphics based CMM interface has been developed by McDonnell Douglas Information Systems [31]. This pre-CMM processor converts a language source file into the structured language of the specified CMM. McDonnell Douglas's own language is called DMIS (the dimensional measurement interface standard). The post-CMM processor carries out the opposite function.

Bowman [61] argues that incorporating CMMs into an integrated manufacturing system calls for more than just a link to computer-aided design (CAD). The problems lie in two main areas: To physically integrate through automatic loading, palletising, automatic

probe changing [27] in now what becomes a measuring station, and the second area is the environment. Communications through MAP is still immature and some companies like LK Tools favour DECnet. The environment with problems, like temperature equalisation between part and system, can be tackled through design with programmable adjustable gauges.

Bosch [58] suggests that flexible inspection systems (FIS) represent the most significant trend in manufacturing today because of the desire to measure a wide variety of parts using the same equipment. Bosch argues that the FIS concept involves considerations for highly dynamic machines automatic temperature compensation, powerful statistical analysis capability and interfaces with the manufacturing host computer systems as well as automatic part handling. To achieve this uptime is a new requirement of CMMs (machine design must be robust enough to sustain continued operation), system accuracy need not be traded off against throughput (again the CMM structure must be capable of withstanding the forces of acceleration and decelerating without distortion), CMMs must move out of climate controlled areas to bring inspection closer to the manufacturing process, CMMs used in FIS must be designed to handle palletised parts, and the task of real time statistical monitoring must be realised without operator involvement. The latter should be coupled to dynamic statistical process control to improve inspection efficiency, for example there may be just one area of concern on the part and thus a selective flexibility to check just a few features is vital to the practical application of a large FIS. Bosch, on the other hand, reminds the reader that traditional dedicated gauging may still provide the best inspection solution, for example in those situations in which a product has a stable design and is to be manufactured in very high volumes for long periods of time, thus a highly accurate, extremely fast dedicated system may be the most cost-effective solution.

Franck [121] examines the various elements that comprise the emerging flexible inspection system (FIS) required to exploit the benefits of automated manufacturing [28]. The FIS must have the same degree of flexibility and automation as the system machines

themselves in order to prevent defects prior to manufacture. The FIS serves the process monitoring and auditing function and ultimately provides real time feedback to aid in keeping a process within specification. The central element of the FIS is the CMM which enables increased throughput, minimised operator and repeatable quality. Franck defines the FIS as a system that can measure the dimensional characteristics of randomly presented parts of virtually any configuration and complexity and provide real time feedback to the manufacturing process. A major element of the FIS is a control system that can be fully integrated in a flexible manufacturing cell or system. The FIS software has to meet the dimensional inspection demands of the flexible manufacturing environment and its varied operations from process monitoring to full inspection. To achieve real time feedback, the FIS control must be able to process large volumes of data and control many peripherals (such as CMM, bar code readers, materials handler, temperature monitor) with fast real time responses. Franck suggests that the ideal system can easily be configured for a specific application by adding, replacing or deleting modules based on the hardware (CMM, robot) and the software functions (SPC, remote communications). The FIS can be as simple as a basic desk top computer or as complicated as multiple CMMs serviced by material handling devices and controlled by one computer.

One subject that excites interest is using the machine tool for in-process checking. Taylor [317] suggests, that to date, feedback has not always been timely enough to assure that each part manufactured is dimensionally correct. Also described [32] is an integrated inspection system at the Flight Refuelling Group which attempts to solve the problem of measuring a large number of dimensions with computer assistance on a Maxi-Check CMM. The CMM besides being used as an inspection machine is also used to develop process capability studies to prevent components being machined incorrectly on machining centres. Small batches are subjected to 100% inspection, the results are used to generate target diagrams in turn employed to indicate whether or not the process is under control. By a continuous sampling procedure, a precise picture identifying any adverse trends can be obtained. This has been caused by the distance between the CMM and the machine tool,

the time to schedule and inspect the part on the CMM and the lack of automatic feedback systems. Taylor describes how a machine tool can perform part measurement and how this capability can be improved significantly so that actual CMM measurements with error correction will be done on the part by the machine tool prior to leaving the machine. This involves feeding back any differences between machine tool measured values and CMM measured values for measurement error correction programs for the machine tool. The requirement to shuttle part is diminished and only sampling is needed to update for longer term drift errors. The method alluded to by Taylor is known as 'footprinting'.

McMurtry [212] defines footprinting as a method by which computer aided manufacture may be used to error correct the manufacturing process (in order that parts may be produced more accurately) and the machine tool (in order that it may be used as a CMM to inspect parts to a 'traceable' standard). The method offers considerable benefits when used in an FMS or JIT environment. The challenge tackled by McMurtry [211] of Renishaw was how to machine parts on a standard CNC machine in an FMS environment to accuracies one would normally expect from a precision jig borer. The method is as follows: During prove-out on the machine tool, a probing sequence measures the part in a clamped position. It is removed, stabilised and then measured on a CMM which has been maintained to a traceable standard. A footprint is now established of the part as measured on the machine tool and also a footprint of the part as measured on the CMM. Differences between the measurements taken on the CMM and those sizes resident in the CAD database are used by the CAM system to generate a new corrected part program. This not only corrects for repeatable errors in the process but also the errors in the machine tool geometry such as deflections under cutting loads of the part cutter and machine structure and part deflection caused by clamping. This corrected part program can correct for circular interpolated errors which cannot be handled by the standard offsets.

The differences between the readings on the machine tool and the CMM are used to error correct all subsequent measurements by the machine tool when using the inspection

program. McMurtry highlights three important steps in the footprinting method: to maintain a CMM to a traceable standard, to periodically extract a machine-inspected part from the manufacturing process and inspect it on the traceable CMM, and thirdly it is essential that all machines are on a direct link to a CAM system.

One approach to the cell-based system which does not include the use of CMM but that of the typical gauging system such as active snap gauges, electronic digital callipers, micrometers, bore gauges, digital electronic gauges, thread snap gauges and active thread bore gauges is described by Pratt [239]. He outlines how users of CNC production cells create an integrated measuring system that matches the output of their high technology machining installations.

The broad emphasis in the literature is on dimensional control and machining processes which lend themselves to closed loop control under feedback from in-process gauging of integrated CMM based inspection systems [30]. The message is that the technology and methodology for automating inspection and for product control is here. The opportunities offered by the power of present day computer technology, vision systems and machine error correction capability provide the means of integrated unmanned inspection. What is less clear is the evidence of the problems facing those charged with implementing much of the technology on the shop floor as much of the literature is written by the manufacturers of CMMs or their representatives.

2.5.4 Intelligent Diagnosis for Quality Feedback

The rapid development of expert systems results in the production of numerous prototype systems. However, the transition from a prototype to a fully operational working system is not easy and as such, very few systems are presently used in industry. One of the principal difficulties associated with the development of expert systems is the elicitation of the knowledge itself, which is in the form of specific codifiable rules. Another area of difficulty arises when a number of experts are involved in the evaluation of the system.

This tends to become correspondingly more difficult to evaluate as more than one solution to the problem may be supplied. On the other hand, the self-learning capacity and the relative ease in which knowledge may be added or modified distinguishes expert systems from other traditional methods. The emergence of expert systems provide new insight to specialists in manufacturing as a means of solving problems in their domains states Dagli & Stacey [92]. As a result, a number of researchers and large corporations have begun to develop expert system application domains in which the fundamental task is design and/or manufacturing process planning and control. Several of these intelligent analysis tools which are thought to have a degree of relevance to this research are reviewed.

Expert systems technology is well suited to many problems in the manufacturing realm. The tasks of interpretation, diagnosis and monitoring are particularly suited. Each of these tasks deal with the ability to obtain data from sensors, make judgements or reason based on rules and take corrective action, tasks in which these systems excel [37, 3].

Sanders, Sanders and Cherrington [270] suggest that the continuing demand for improved product quality control and the involvement of operators in assessing quality of their own work have led to various types of software packages as aids to the process operator for the meeting of production schedules. Expert systems are now considered as useful tools for this purpose and are frequently integrated with the automatic control of the plant. Problems still lie besides potential for widespread application in real time systems, in the area of model verification and validation as well as proper knowledge elicitation.

There are a large number of reasons why expert systems are a very effective part of modern condition monitoring systems, says Hill and Baines [142]. These include: repeatable diagnosis given the same data; the knowledge from more than one expert can be incorporated; the expert system can be available at a number of sites simultaneously and throughout any period; and because the knowledge base is not part of the inference program,

changes can be made to the knowledge far more easily than with conventional programming techniques. Hence as more knowledge becomes available , the expert system can be easily updated.

Kelly [167] notes that many of the problems solved through the use of expert systems can be solved by alternative means. The choice of expert systems, he argues, is frequently an economic decision caused by the lack and inavailability of experts, availability of traditional methods of algorithmic software and appropriate database technology. Kelly cautions on the use of expert systems and questions the ability of validating expert systems for heuristic knowledge and their capability in dealing with multi-faceted problems.

One application of the technology identified by Posco and Brown [237] is the analysis of complex manufacturing test and process data. They claim that whilst an overwhelming volume of information is systematically collected, it lies under-utilised because queries do not lead directly to useful answers. Thorough analysis requires considerable time and interpretative skills as findings from one area usually need to be combined with other results before conclusions can be drawn.

Steinberg [300] claims that expert systems are often confused with artificial intelligence (AI) applications. The AI application involves some specific features which include symbolic representation, inference and heuristic search. Expert systems are significantly different because the emphasis is on building a knowledge base rather than developing specific methodologies for solving problems. This distinction between emphasis on knowledge that underlies human expertise and formalised methods for solving problems is significant. Expert systems are particularly useful in complex areas such as fault diagnosis which often involve the interactions of several humans or other difficult or management tasks. These problems do not lend themselves to specific algorithmic solutions or mathematical formulation.

Major [200] reviews the limitations of, and influences on artificial intelligence. He suggests that the pioneers of AI were greatly influenced by the then prevailing technology of serial computers which execute operations one at a time and that this is now reflected in current systems, although he notes a move towards parallelism and distributed computation to understand how problem-solving can be distributed across a network of interacting highly sophisticated concurrently active processors. Another limitation noted is the large search spaces imposed by the sequential approach. Major notes that parallel medical research has greatly influenced AI in areas of parallelism and vision strategies enacted by layered arrays of processors.

Ippolito et al [152] discuss how the application of AI and product control can exist in an organised structure. They describe a multi-decision maker integrated expert control system combining procedures derived from control theory with relational tools and knowledge structures typical of AI. This is outlined in a structure claimed to harmonise quality control with market demand. The system is capable of quality measure selection, that is, the definition of the evaluation criteria of the quality level of a product as requested by the market; engineering techniques choice, that is, the definition of selection criteria of the production characteristics based on the difference between the required and offered quality levels; and a quality creation model, that is, a description of the connections between planned work programs and quality level which can be obtained for the resulting product.

In contrast to expert systems that use heuristic methods in problem solving, Saridis and Valavanus [271] provide a mathematical formulation of the organisational level of an intelligent machine. Their hierarchically intelligent control system applies a mathematical approach based on a probabilities model. Their control system is intended for use without human interference and is divided into the three levels: the organisational level is the highest level and interprets the input commands and related feedback from the lower level. It defines the tasks to be performed and decides the order of execution. The co-ordination level is essentially for dispatch of organisational information to the third level which is

the execution level. The control level or execution level performs the execution of various tasks through hardware using feedback control methods. Their system finds applicability in uncertain environments without the supervision of a human operator and for those machines driven by control with special characteristics such as robots.

Dawson [95] describes a method for integrating knowledge based techniques with quantitative modelling techniques in the construction of an expert diagnostic system. The knowledge based techniques are used to detect and diagnose a problem and then search for a corrective recommendation. The quantitative modelling techniques are used to control the search for the recommendation, to refine the recommendation, and to verify that the recommendation will indeed solve the problem. Dawson draws from a computer performance domain but claims that the approach is applicable to any diagnostic domains where there are quantitative models available.

McKeever and Blundell [210] describe a fault diagnosis system utilising fault trees as a precursor to the automatic development of an expert system. They use LISP to write a number of algorithms which simplify a fault tree in preparation for a graphical interface which will subsequently generate the rule base. The minimal cut sets produced are shown as expert system rules in abbreviated form. The example given is based on an automotive fuel system. Ward et al [336] focus on defect recognition in textile materials . They describe a set of primitive features to give optimal visual recognition based on the statistics of defects in the manufacturing process. A knowledge base is described which gives the system the ability to recognize the cause of the defects.

Karel and Kenner [163] describe KLUE a diagnostic expert system tool for manufacturing. Klue was developed in response to a number of observed problems in using expert systems, these included: program control and connectives of the rule base and the requirement of expert maintenance of the rule base. KLUE is a diagnostic expert system tool that addresses these problems by representing the knowledge in the form of decision

graphs. In Klue both the program control and the diagnostic strategy are explicitly represented. Domain information is added or modified by direct operation on the decision network.

Posco and Brown [68, 237] have also proposed a theory of "expert diagnostic browsing" in manufacturing databases. The essence being that the browsing activity employs strategies that guide the application of diagnostic knowledge to portions of the database. The system posed by Posco and Brown consists of five levels: user, strategy, selection, diagnosis and data. The strategy level establishes such mechanisms as hypothesis selection, evidential pruning, diagnostic persistence, reporting and performance evaluation. The diagnostic level is composed of hierarchies of diagnostic specialists that attempt to produce specific conclusions about problems that may exist.

Bacon and Posco [42a] describe Karljr which is claimed to be a global diagnosis system. The motivation behind Karljr was to achieve a reduction in the amount of time spent by an expert in examining test data in a multi-stage VLSI-like manufacturing process. The goal of this effort was to automate the diagnosis of common problems in the manufacturing process as well as in the material produced by this process. The system has been in successful daily use at Digital (USA) since 1987. Posco has long been involved with the development of knowledge-based systems which analyse manufacturing data stored in large databases [67, 68].

Karljr is based on the concept of global diagnosis characterised by the need to examine a large amount of data taken from a key test stage usually late in the process to see if there are any interesting observations worth pursuing. Other characteristics of global diagnosis are: that diagnosis of entity problems must be conducted in order to perform diagnosis on the process; and that knowledge of the domain is incomplete. The system comprises a

database, used to store measurements and threshold values for comparison with measured values, and a knowledge base which scans for failures or near-failures and determines the interest of result and characterises wafers by relating observations to regions.

Other diagnostic systems include those by Zheng et al [348], Puetz and Eichhorn [242], Alvey and Greaves [11], Snoeys and Dekeyser [291], McKeever and Blundell [210] and Ward et al [336]. A survey of expert systems in mechanical and manufacturing engineering is given in Pham and Pham [236]. The Zheng et al work is for diagnosing faults in automobile engines. A hierarchical and modular approach is adopted to describe the structure, operation and possible faults of an engine, which consequently allows a complex diagnosis task to be decomposed into simpler components for which solutions are known. The LISP based system uses deep and shallow reasoning in a combination of forward and backward chaining. Forward chaining is employed to obtain the hypotheses about location and cause of fault and backward chaining is then employed to verify the hypotheses, a total procedure repeated till the fault is determined in sufficient detail. Puetz and Eichhorn focus on diagnosis of faults in CNC machine tools.

Sood [293] discusses the introduction of expert systems into real-time non-destructive testing systems and claims it is a breakthrough in realising minimum time in fully automated inspection. The use of expert systems enables data to be qualitatively, quantitatively and scientifically analysed and stored for references. A significant use of such a system is that as more experience is taught to the system, the resultant accuracy and reliability is improved. Sood predicts that self-contained expert systems will communicate over a network of industrialised expert systems leading to a realisable factory automated manufacturing system through cross migration of knowledge.

Puetz, Eichhorn and Faehnrich [241] discuss the application of an expert system for fault diagnosis on CNC machines. The system was developed at the Fraunhofer Institute in Stuttgart in collaboration with Traub AG. The system, based on 500 rules, is considered

marketable for a lathe with double turret. The system is integrated with the computer control system of the machine and permits the user to interact with a dialogue screen which leads him through the process of fault deduction and finally to repairing instructions.

Soos and Szalontay [294] describe a Remote Diagnostic Expert System (RDES) designed to assist maintenance personnel in detecting the fault components of a machine tool with CNC cost efficiency.

Bannister and Moore [44] describe a general rotational machinery expert system for condition monitoring for machines which fall in the broad class of 'rotation'. The system is intended to respond to abnormality in the behaviour of the machine through intelligent interpretation and correlation of the readings from machine monitoring equipment for vibration, sound and temperature. Bannister and Moore put forward a three level structure for such an expert system based on quantification - are the current running conditions likely to result in damage, diagnosis - what fault is being suffered, and action - what can be done to improve the situation. The system thus aims to perform the function of fault detection, identification and alleviation. The system is claimed to be generic and modular allowing modules to be used concurrently as well as permitting focussed attention on a module for specialist or non-specialist users.

Majstorovic and Milacic [201] describe EXMAS, an expert system developed for conceptual diagnosis and condition monitoring of automated work stations. The system is capable of being interfaced to other software and also able to communicate between work stations. The system operates on the basis of competitive analyses of real behaviour and simulated diagnostic parameters.

Dressman et al [103] review frameworks for expert system control of metal cutting. They argue that widespread use of CNC has partially displaced the human machininst and suggest that this gap can be closed by the use of expert systems for trouble shooting CNC programs and for in-process control. They argue that two attempts have been made to fill

the 'gap' previously occupied by the intelligence of machinists: (i) actual NC programs are written conservatively, speeds and feeds are set low enough such that machine integrity is not threatened and tool chatter never occurs, also tools are replaced well before the end of their useful life; (ii) adaptive control (AC) systems have been developed in the research laboratory although their acceptance by industry has been poor.

Kumara et al [181] describe a number of systems used in fault diagnosis. In particular, they describe DELTA a system developed by General Electric for locomotive trouble shooting. On selection of a particular fault area, the system asks a series of detailed questions then associates a cause with the fault and generates specific repair instructions. Also described is FOREST which emulates experienced engineers whose specialty is to diagnose faults indetectable by test equipment.

Efstatiou [108] reviews the features of industrial control ranging over the activities of control, fault diagnosis, scheduling and planning that make it different from the areas traditionally associated with knowledge-based systems. The main points are that the domains and their environments may be bounded with a controllable amount of complexity, for example the expert system may be targeted on particular components in a particular environment. Time is introduced by Efstatiou because the state of the plant or machine may be changed during or by the process of consultation. The skills of the experts are accessible, providing industrial relation problems are avoided, and an expert system must be accommodated for each users knowledge about the structure and behaviours of their domain as well as the rules of thumb that can lead to short cuts in the diagnostic process. Automatic and objective data acquisition from human and sensors improves the speed and accuracy of performance leading to an adequate return on the investment involved in control by expert systems.

Subrahmanian et al [304] argue that diagnostic systems within the rule-based expert system paradigm have been limited to shallow evidential reasoning without the benefit of

using underlying causal structures and functions directly. They report on HEDR (Helicopter Engine Diagnosis and Repair System), one of the first they claim to integrate rule-based diagnostic reasoning with causal reasoning and numerical simulation. Their contribution is an illustration of multi-level modelling for diagnosis that uses the surface knowledge for most of the tasks, causal models for hypothesis generation and elimination and numerical models for hypothesis discrimination.

2.5.5 Advances in Non-Contact Measurement Assurance

Non-contact inspection methods can be classified into optical and non-optical. The optical methods are the current focus because of the fascinating new technologies employed. These techniques include vision systems, laser beam scanning systems and photogrammetry. There are several limitations with current systems mainly related to computer technology. These limitations include image states, limited number of stored images, part overlapping and picture quality.

The typical vision system involves a television camera interfaced to a computer which digitises the picture and analyses the image by comparing it with a limited number of models stored in memory. Laser beam scanning is activated by the measurement of time rather than light. A laser projects a continuous beam of light against a rotating mirror which deflects the beam and causes it sweep past the part whose width is to be indicated. The system is programmed to measure the time lapse corresponding to the interruption of the laser beam as it is blocked by the part.

Photogrammetry involves the extraction of 3D information about an object from two photographs of the object taken at different angles. A device called a monocomparator determines coordinate and dimensional data from the two photographs. An obvious drawback is the time consuming element of the development of photographs. Instead, some systems use two cameras arranged in a stereoscopic configuration interfaced to a computer that performs on-line analysis. Non optical systems use electrical field (reluctance,

capacitance or eddy current) techniques and can be readily interfaced to computer systems to integrate the production process. These systems, says Groover [131], enable inspection to be carried out on a 100% rather than on a sampling basis and provide feedback and compensating adjustments for defects and out of tolerance conditions. Non-contact methods usually involve less time than contact methods, avoid the need to re-position the part for inspection, and avoid damage to the part as a result of contact.

Hirata, Hibara and Tanaka [143] described three types of automatic visual inspections: the first is the application of a laser to flaw inspection on the surface of a machined surface, the second is automatic adjustment of convergence and purity for colour picture tubes using photo sensors and the third is the application of microscopic image processing techniques to dimensional measurement of a photo resist pattern on wafers.

Anon. [25] describes Vidispec, a non-contact test instrument from Ealing Electro-Optics to test a range of different components ranging from disc brakes to welded structures. Vidispec measures vibration or stress induced displacement using the wave length of light as its yardstick.

Espirit No 1136 [93] embarks on a distributed automated system for inspection aid quality control (DASIQ). The system is directed to inspection work using vision and AI technique to monitor the manufacturing process.

Pederson [234] develops a prototype experimental system for flank wear measurement. The use of this technique allows a more complete measurement of the tool geometry of many different kinds of tool to be performed without requiring physical adjustment.

Elliott & Griffiths [109] describes the use of an artificial intelligence vision system, a hybrid system that uses AI techniques in combination with traditional feature extraction techniques to locate and orientate parts with complex internal features and to provide an indication of quality.

Dunlap [104] report that CBS Records Inc reduced the reject rate of its Cassette Cartridge without magnetic tape product by 33% after installing Allen Bradley's EXPERT Programmable Vision System (PVS) at its Carrollton Ga facility. The machine vision was integrated into each of the three co-assembly lines to provide 100% in-line inspection at production line speed.

The role of contact and non-contact measurement is a current source of debate. Bowman [61] suggests that laser systems are undoubtedly fast but are inaccurate when measuring edges or apertures. Contact measurement is slow and some manufacturers, like Prima, have gone for dual solutions using both laser and touch probing. The advantages of vision systems lie in their ability to keep up with the production process which results in they being able to provide information to institute corrective action before the process goes out of control.

2.5.6 Towards Soft Gauge Measurement Assurance

Programmable CMM have replaced micrometers and gauges but these cannot interpret the tolerances specified leaving it to the quality inspector to decide whether the part will work as designed. With the reliance on CAD and flexible automation to meet tight production schedules, what is required Valisys argues, is automation of the whole cycle of quality inspection not just the measurement portion. Miller [217] states that quality inspection remains an island of craft labour in a sea of high-tech equipment.

The Valisys software uses a CAD model and tolerance standards specified by the part designer to create a 'soft gauge', an electronic model of the worse fitting part for a particular feature. It compares this with an electronic model of the actual part measured on a CMM. By electronically fitting the gauge to the part, Valisys determines if the part is within tolerance and which, if any, dimensions deviate.

Soft gauging has found its first production use in speeding up mundane day-to-day inspections. Inspection programs are usually written for specific machines and cannot be verified without extensive testing on actual parts. By contrast Valisys generates inspection paths automatically from the part model and the tolerance call-outs. A side benefit of soft gauging is that it simplifies fixturing and placement. Valisys begins with preliminary measurements that establish the true position and orientation of the part on the test bed. Since the part need only be placed within about a quarter inch of its required position, inspectors can use generic mounts and clamps in place of custom fixtures and they spend less time setting up the parts to be inspected.

This orientation ability also makes in-process inspection practical. Many machine tools have inspection probes but these are subject to the same fixturing and bed inaccuracies as the cutting tools. Valisys is able to orient itself on the actual part rather than on the fixture or the mounting bed so it has an independent frame of reference for such inspections. This results in inspections now being able to be made while the workpiece is on the machine tool.

Cakir and Bowyer [72] describe the matching of measured components to solid models. They describe a group of algorithms which allow a collection of points on the surface of a manufactured component (such as may be gathered using a CMM) to be matched automatically with a solid model of the component. Once matched, the two may then be compared to find any differences resulting from manufacturing errors and those manufacturing errors can then be reported. The algorithms have been developed especially to handle the large numbers of surface points that may be gathered from a component using a laser non-contact measuring machine but are also suitable for use with conventional CMMs. The solid modeller employed was DORA, a set-theoretic solid modeller. The system is currently implemented to deal with facetted components and solid models only. They are currently engaged in extending it to work with curved components.

Chapter 3 :

Decision Support Aids for Data Feedback

3.1 Introduction

This chapter presents the rationale behind decision support and reviews some of the decision support aids available. The use of IDEF is highlighted as the project integrating methodology. The project structure represented in IDEF is given in Appendix IV. The chapter moves to a review of more specific quality related techniques to provide the background for the selection of Influence Diagrams and Modified Statistical Process Control implemented within the computer-based human-centred data feedback application. Unlike the former category of IDEF and SSADM amongst others which provide a cohesive approach to system building, the category of quality representations and automated decision aids enables fault relationships to be represented, explored and hence resolved.

3.2 System Analysis and Design

A method to assist system analysts and designers, to develop information system specification, is essential as it is necessary to digest, act and process on a large volume of information [82]. Any tools and methods used should reflect a common understanding and correctness of results [122], identify each and every item of information and how information is shared by different applications and functional areas [199]. In the absence of a method, what exists is an uncontrollable, incomplete, free-for-all system [189]. Ad hoc approaches to development have a long history of not producing the goods and it is not the appropriate way to developing system. Free-for-all allows those involved in the project to point a finger at others.

Over the years, a number of techniques have been found to improve specific areas of system development. The integration of techniques in a prescribed way constitutes a

development method. Standardising on a method permits developments to be done in the same way each time, and thus provide a basis for estimation, management, control and subsequent maintenance.

The 1987 NCC Members Survey reported that the use of a methodical approach for system development improve the quality of product by 33%, productivity of staff by 22%, timeliness of delivery by 17% and system life cycle costs by 28%. A number of formal approaches are available for developing an information system specification in a manufacturing environment. These include SSADM approach (Structured System Analysis Design Methodology), GRAI (Groupe de Recherche en Authomatisation Integrere), the Checkland Method, SADT (Structured Analysis Design Technique) and IDEF. Of these, SSADM and IDEF are prominent in the development of computer-based information system and will be discussed below.

3.2.1 The IDEF Methodology

The ICAM Definition (IDEF) methodology [199], developed by US Air Forces ICAM programme, is a combination of structured analysis and human judgement to form a discipline that may be applied to any manufacturing system. IDEF method consists of three divisions know as IDEF0, (IDEF1 and IDEF1X) and IDEF2. IDEF0, developed from SADT by DT Ross of Softech Inc, is used to produce functional models to represent the structural relationships of the system's various functions and entities graphically, see Figure 3.1. IDEF1 is used to produce information models to provide a structure for the integration of information within the total system. IDEF1X is a data modelling methodology, developed by DACOM (D.Appleton company), specifically addresses the logical structure of shared data. The structure is defined in terms of entities, attributes of entities and relationship of entities. IDEF2 is a dynamic modelling methodology that describes graphically the time-variant behaviour of the functions and information of a manufacturing system. These models complement one and other according to the needs and modelling purposes.

The Information Support System for Design and Manufacture, discussed in Chapter 4 and 6, of which this research work is a part uses the IDEF0 methodology. The strength of the IDEF0 lies in it's activity modelling capabilities and not in data modelling, discussed in Chapter 8. The IDEF0 was selected by the project for it's structured form which is systematic and has a short learning curve.

The IDEF0 [195, 203a], which stands for ICAM Definitions 0, is a methodology for describing system. It is a descriptive model that is used to describe an existing system, analyse system, design system and to specify statements of requirements. Most of all, IDEF0 can be maintained and has the added advantages of being logical, rigourous and unambiguous; easy to learn and read; and the capability of being applied from top down as far as possible. The method of analysis is top down, modular, hierarchic and structured. The model building process serves two purposes; to facilitate understanding and to provide a means of communicating that understanding.

The actual model is in the form of a hierarchical series of activity diagrams. The main building blocks of these diagrams, shown in figure 3.1, are rectangular boxes representing activities and arrows that connect to a box representing information needed and produced by the activity. In summary, the inputs and outputs show WHAT is done by the activity, the control shows WHY it is done and the mechanism shows HOW it is done. The activity is essentially a process element and can be named with an active phrase, for example produce product. Input data are data needed to perform the activity with the created data being the output data. The control describes the conditions that govern the transformation and the mechanism can be a person or a device that undertakes the activity. Each box on a diagram can be further expanded onto separate diagrams. Rules are provided by SADT for the number of boxes that can appear on a diagram, minimum of three and maximum of six.

Figure 3.2 shows the IDEF position of this research work in the context of the Information Support System. A detailed sequence of the breaking down of the Information Support System, the main activity box, into a number of more detailed boxes with each representing a major function or application. The overall project, see Appendix IV, is represented by the main activity box 'Implement and Use an Information Support System' and the research work described in this thesis is represented by the activity box, 'Pre-Production Proving'. The IDEF0 diagrams show the integration of data and the information dependency of each application. It illustrates the data needed by this research work, the output produced and used by other activity and the feedback of data to relevant activities. The detailed analysis of this research work can further be resolved by the application of decision analysis.

This IDEF0 technique is also used by Franks and Gorman [122] and Tannock et al [315]. The former utilized this methodology as part of a strategical approach to the analysis and design of a CIM system and the latter adopt this approach to facilitate the design of an integrated quality system. Marsh [204] combined the Data Flow Diagram and the IDEF0 modelling to form the Quality Improvement Methods Analysis (QIMA) for process modelling with the aim of improving the quality.

3.2.2 The SSADM Approach

Structured Systems Analysis Design Methodology (SSADM) is based on projects from National Computing Centre (NCC) [189, 190, 225] and the Central Computer and Telecommunications Agency (CCTA), and has been a standard UK government approach to the analysis and design of computer-based information systems since 1983. It is made up of an integrated set of structural, procedural and documentation standards. The structural standards break the development into six stages with each stage consisting of a number of steps. The product of SSADM is a set of detailed program specifications, a set of detailed data definitions and plans for the programming, testing and implementation phases. A number of well known techniques such as Logical Data Structures (LDS), Data Flow

Diagrams (DFD) see Figure 3.3, Entity Life Histories (ELH), process outlines, first cut data design, program specification and physical design control are integrated in SSADM to form the procedural standards of the method. The disadvantage of SSADM is that it is deficient in real-time system analysis and design and expensive to use on small system [199].

3.3 Decision Analysis

Decision analysis is the process of solving a complex problem situation by mapping the problem to a form recognisable by the computer. It can also be referred to a science of decision making that combines the field of operation research and statistical decision theory [216]. Decision problems can be characterised by the nature of the decision environment, the preferences and resources of decision makers and the process by which various individuals interact to reach a decision. Automated decision aids and quality-related techniques are developed and employed to speed up the decision analysis process and to allow the non-specialists access to the powerful problem solving tools that are currently available only to a few highly-trained and experienced decision analysts.

3.3.1 Automated Decision Aids in Decision Analysis

Automated decision aids or decision models allow analysts and decision makers to organise and rank in importance the many complex factors associated with major decisions. This can show very quickly which elements of the problem deserve the most attention by virtue of their relative influence on the final outcome as well as placing emphasis on the often neglected problem. A major decision problem can be divided into a series of smaller, more manageable problems by considering each part of the model. It also has the ability to act as a vehicle for communication which allow all concerned to contribute to the decision making.

Very often, a problem requires more than one decision aids with the choice depending on the decision maker. The four areas that are taken into consideration when developing these aids are; characterisation of the different kind of decision situations; the types of decision models available; the process of constructing the model and; an identification of several easily understood modelling concepts. The research work in this thesis uses these aids only to graphically represent the problem domain and to show the dependency of the many factors contributing to the problem. The two decisions aids used are the Influence Diagram (ID) and the Decision Tree (DT) although other techniques are available.

3.3.1.1 Influence Diagrams

Influence Diagrams (ID) are developed based on probabilistic influences and are used to facilitate the modelling of complex problems involving uncertainty. The main advantage gained from this aid is that it enables the modelling of a diagnostic situation symbolically without requiring detail knowledge of the underlying relationship, see Figure 3.4. The reasons for one factor influencing another is not important as long as it is identified that they are influencing one another. Influence Diagrams can be interpreted and manipulated at three levels; relational, functional and numerical. At the relational level, the relationship between the state, decision and goal of the factors are know. At the functional level, the relationship is based on probability and finally, the numerical level is a combination of the relational and the functional levels.

This approach is used by Rege & Agogino [248] for their system architecture. The architecture for the hierarchical integration of sensors and diagnostic reasoning in automated manufacturing and process control, uses Influence Diagrams to provide a symbolic representation of the system model to represent knowledge from the expert. The dimensional analysis part of this research uses only the relational level for its problem solving. The use of ID to model the measurements of the workpiece is essentially three folds; identification of critical measurement(s); grouping of these critical measurement(s) into sets of machining states and; identify the relationship between the

measurement(s) and associate each relationship with the ultimate goal, which is the fault type. Each relationship is analogous to each branch of the influence diagram network. This structure is represented as decision network in the data structure described in Chapter 8.

3.3.1.2 Decision Trees

Decision Trees allow the modelling of a more complex problem than is possible in the case of the Influence Diagram. The main difference between a decision tree network and an influence diagram is that the latter implies a total ordering among the decision nodes where each decision node and its direct predecessors directly influence all successor decision nodes. A decision tree network is a structure where all predecessors of each node are direct predecessors.

Decision Tree's may be set and solved very efficiently using software tools such as Interactive Financial Planning System (IFPS) and the Lotus 1-2-3 spreadsheet [127]. The manufacturing process analysis part of this research work also uses decision trees to model the problem. The structure is represented as taxonomy in the data structure described in Chapter 8.

3.3.1.3 Other Decision Aids

Many researchers have devised and developed techniques to fulfil specific manufacturing requirements. In manufacturing, human diagnosticians generally seem to compose solution strategies as a traversal of decision graph. The use of a graph structure as a diagnostic aid in KLUE, a diagnostic expert system tool, is developed and used by the Minnesota Mining and Manufacturing Company [163]. The graph structure, in the form of semantic network representation, consists of question nodes, potential problem nodes, null nodes and answer links.

A model based approach, called situational control, defines a global architecture for very short term control and diagnosis of manufacturing workshops [329]. This approach consists of three types of model: conceptual models are used to described what is being used (structural model) and how it works (functional model); situation models are used to indicate what is the state of the system (quantitative and qualitative) situations and how to control it (situation evolution graphs) and; casual models are used to state what is wrong, why and how to recover. The problem identification can also be solved using one or more of the many techniques discussed below.

3.3.2 Quality-Related Techniques

The aim to solving a problem in a manufacturing environment is to improve the quality of the both the product and the process. The approach to solving a problem is to develop some hypotheses of what might cause the problem, then try one at a time, various logical solutions to identify the real cause or solution. However, a systematic approach to improving the quality is supported by techniques such as Failure Modes and Effects Analysis (FMEA), Quality Function Deployment (QFD), Capability Studies, Taguchi Methods, Poka-Yoke and Statistical Process Control (SPC). Other techniques also exist, but they are not well catalogued or mentioned very often. In order to gain maximum benefit from these techniques, they should be used in a systematic and structured way and in the correct sequence [195]. Figure 3.5 illustrates how these techniques should be used in sequence. The use of FMEA, QFD and capability studies can act as filters to determine or identify problems that requires the use of Taguchi for the solution. Taguchi methods require substantial experimental efforts and should therefore only be used for those problems which are difficult to solve in any other way. When the optimum combination of a variable affecting the problem has been identified, poka-yoke or SPC can then be used to solve the problem. The choice of these two techniques depends on the quality approach, experience, time, cost and availability of equipment.

3.3.2.1 The FMEA Approach

Failure Modes and Effects Analysis (FMEA) is a systematic element by element assessment to highlight the potential failures of product or process. The factors which are assessed in an FMEA are Potential Failure Mode, Potential Causes of Failure, Current Controls and Occurrence, Severity and Detection and Risk Priority Number (RPN), see Figure 3.6. Some of the solutions and pitfalls of using this technique have been identified [144]. The exercise is most valuable when a Ranking Scale is set to establish the benchmark at the outset to provide consistency. A common error is setting the chances of detection against the failure rather than the cause, assessment must be on the cause.

3.3.2.2 The QFD Approach

Quality Function Deployment (QFD) is an approach to product/process design which employs a collection of tools such as Cause and Effect Diagram to highlight areas that require attention, see Figure 3.7. Its functionality has parallels with FMEA in its ability to help determine where quality technology and engineering effort should be applied. Most applications combine the Cause and Effect diagram with one other technique to maximise the use. One such application is that illustrated by Fukuda [123] and Pratt & Whitney [21]. Both use "CEDAC", cause and effect diagram with addition of cards, developed by the Sumimoto Electric QC problem study group. CEDAC is based on cause and effect or fish bone diagrams [154]. The CEDAC modification includes: the use of short sentences as opposed to single word descriptions of factors; the use of quantitative expressions instead of qualitative to represent effects.

Another combination of the use of the cause and effect diagram, known as CEFFA, is implemented by Stratton [303]. CEFFA combines cause and effect diagrams with force field analysis which allows problems to be defined and more importantly solutions to be identified. CEFFA has been successfully used at AT & T's Network system Division in USA.

System can also be built upon the foundation of QFD. A computer-assisted methodology, Technical Information Engineering System (TIES), is an innovative application of Artificial Intelligence (AI) programming techniques to support and extend the QFD process. TIES helps to achieve significant improvement in product quality by collecting and storing in the computer relevant engineering information, experience and knowledge from cross functional product/process design teams. The aim is to facilitate design decisions, resolution of cross functional issues and retaining engineering knowledge [334].

3.3.2.3 The Taguchi Method

With the problem identified by the aforementioned techniques, the Taguchi method, a manageable design optimisation process, will then be used to plan experiments that would quickly show up the best combination of design and process conditions to give robust, defect free product, see Figure 3.8. In order to make experimental design more accessible to practicing engineers, Taguchi has reduced much of the complex mathematical statistics into cookbook style methods [140]. Taguchi [310, 312] theory of quality is based on two fundamental concepts: that any loss in quality is defined as a deviation from a target, not a failure to conform to an arbitrary specification; and that high quality can only be achieved economically by being designed from the start, not by inspection and screening. A 'loss function' is used to define quality loss which contrasts with the widely used go/no-go approach to quality. Two more factors that need consideration when controlling the quality of product are: how to measure the quality and how to improve it [311]. Taguchi achieve the robust designs by dividing the design process into three sections: system design where the fundamental design and engineering concepts of the products are established; parameter design where the target values for the design are set and the sensitivity of the design to variations is determined and; tolerance design where the design tolerances are established. Detailed descriptions of these experiment are discussed in Taguchi [310, 311, 312].

The use of Taguchi methods by several users is reported by Dunn [105]. The user comments that Taguchi is considered to be a powerful tool which enables old designs to be reviewed and a clean sheet approach to be adopted for processes and product specifications. The traditional methods of accepting or rejecting products according to whether they are in or out of tolerance is considered to be a poor indication of quality. Taguchi's focus on getting products as close to a nominal value as possible by eliminating the variance. The method is reported to be in wide use in several major organisations such as Lucas and Rank Xerox in the UK.

3.3.2.4 Poka-Yoke

One of the techniques available to prevent defective products from being produced or aiming towards zero quality control system is poka-yoke, see Figure 3.9. The emphasis on quality is moved from inspecting to preventing the manufacture of any defective product. Poka-yoke or 'foolproof devices' is built into all stages of production process whenever possible to minimise the amount of finished product testing. The three types of Poka-yoke identified are contact type, constant number type and performance sequence type. The two ways in which a type of poka-yoke may be activated are: shut-out type to prevent an incorrect action from taking place and; attention type to bring attention to an incorrect action but does not prevent its execution. Poka-yoke method includes source inspections, self-checks and successive checks. An example of the poka-yoke system applied at Aisan Industries Ltd/Japan is to ensure that clips are mounted on the link. Clips would sometimes be left off in an operation in which clips were to be mounted at four sites on a link. Such errors were corrected by worker vigilance. The clip press was made so that a pin would protrude at any site lacking a clip underneath. More examples of the poka-yoke system can be found in Shingo [284].

3.3.2.5 Capability Studies

Capability studies is used to ascertain whether the process is capable of producing the specified tolerances required by the product design. Very often, statistical reliability formulae are used [195], see Figure 3.11.

3.3.2.6 Statistical Process Control

Statistical Process Control (SPC), in contrast to poka-yoke, is a method which gives confidence that components are produced within tolerance, without having to measure every component, see Figure 3.10. It is associated with the theme of controlling the process not the product. It is based on the premise that 100% inspection is burdensome, expensive, time-consuming and can be adequately replaced by sampling inspection and statistics. The role of SPC in measurement assurance had been described in Chapter 2 previously.

SPC, refers to mathematical techniques, which when employed to measure the consistency of manufacturing process, determine on the basis of empirical data whether or not the process is consistently capable of producing parts that conform to the specification. The first step in the resolution of quality problems is the identification of sources of quality problems and their frequency of occurrence. The Pareto diagram [154], used for this purpose, graphically illustrates the 80/20 rule and lists the results of poor quality and the frequency of occurrence. Results must be identified before their causes can be located.

One of the cause-effect diagrams, the 'gozinto' or 'fish bone' helps to identify potential sources of the problem, may also serve as a guide to identifying separate causes that work in combination to produce a problem. Histograms and other data-gathering techniques may also be employed to illustrate a variety of process behaviours. One such system that employed the latter is developed by Electric Power Research Institute (EPRI) [166]. The mechanical and electrical condition of values, with set points established, are

gathered are displayed to correct a problem before a malfunction occurs All the methods mentioned above may be used to identify the symptoms of quality problems and trace them to their root causes. Once the root cause is know, corrective action may be taken. However, it is important to remember that taking corrective action does not ensure that a solution is reached. Rather, we must return to the process and measure the improvement after our corrective measures have been taken to ensure that our analysis was correct and the problem solved.

3.3.2.7 Other Techniques

Some of the practical applications found in a vast literature base are presented below to illustrate the use of supplementary techniques in industries. No definitive applications of Taguchi and poka-yoke are found in the literature.

A survey was conducted by Revelle and Harrington [256] to establish the use of statistical process control in the defense industries in particular. SPC methods utilised included control charting (72%), acceptance sampling (90%) and only 10% identified critical dimensions on engineering drawings that mandate SPC procedures. 25% utilised experimental design such as Taguchi methods to pinpoint sources of variation even though engineering collected SPC data to enable these experiments to be conducted. The conclusions drawn from the studies were that a majority of the industry were past the start-up phase in SPC but very few had matured in SPC methodology to the point at which the design personnel were trained in and utilised experimental design as a routine part of product development. Experimental design, multi-factored, Latin-square or Taguchi methods do not seem to be taught and utilised as frequently as could or should be.

The use of user's experience to assist in the maintenance of quality was considered by Liddle [185]. This system, implemented at Ferranti, classifies faults by code and use the computer to bring out statistics on the various faults. The fault coding system is

divided into: categories of reject, reject code, description of cause or reject, action and report on one or more causes, and a column specifying the authority requiring the report. With the solutions given, the user can then apply their experience to future inspection planning for subsequent batches.

With modern technology, the use of computers with expert system is becoming increasingly popular. A computer assisted fault diagnosis system (CAFD) which allows the early detection and localisation of process faults during normal operation or on request is developed by Isermann & Freyermuth [153]. The system, which forms an on-line expert system, consists of an analytic problem solution, a process knowledge base, a knowledge acquisition component and an inference mechanism.

Very often, when the traditional statistical control chart cannot be used by the company for their quality control, modification to the control charts are developed. One such modification in the form of quality index, a composite chart, is developed by the Martin-Denver quality department [19a]. This quality index chart, intended for 'quick look', is supplemented by related trend charts that measure all plant operations affecting the quality of the product. The trend charts are complimented by an Alert Program, a computerised data collection network, claimed to achieve quality, zero defects and cost reduction.

Another such modification is that of combining multiple process charting into a Group Control Chart [59]. One group chart is used to control four processes instead of requiring four separate conventional control charts. Kelton et al [168], Hart and Hassan [136] and Jaehn [156] have also modified control charts for their own respective purposes.

This research work modifies the control principles of the control chart to determine the state of a measurement, see Chapter 7. Unlike the conventional method of determining the control limits, the user of the modified control chart is allowed to determine the control limits according to the tolerances specified. A detailed description of this

analysis is illustrated in Chapter 7. The research does not use any of the other techniques but this does not rule out the possibility of implementing them to the data feedback system.

The use of statistical decision theory to locate faults in the support system for a vertical turret lathe is also considered by Gupta [134]. This is achieved by establishing an inspection procedure to specify a definite action for each symptom. The action is derived by asking a series of questions such as faults, symptoms, probabilities and payoffs.

Chapter 4 :

The Integrated Design and Manufacture Environment

4.1 Introduction

This chapter presents the background and the requirements for product modelling in an integrated design to manufacturing environment. The chapter focuses on the key issues, the structured data modelling, the significance of emerging data standards and the relationship to the product life cycle. The key role of data integration is emphasised and the chapter concludes the requirement and role of the project information support system.

4.2 Computer Integrated Manufacture

Computer Integrated Manufacture (CIM) represents the systematic integrated application of computer technology to the manufacturing system, from product design through the manufacturing process itself, and finally on to distribution of the product shown in Figure 4.1 and 4.2 [112, 69, 130, 268, 10, 129, 214, 12, 119, 320]. Although a number of definitions have been put forward, no strong agreement has been reached on the scope of CIM. The definitions stress 'integration' as the main issue [302, 71, 320, 130].

The evolutionary process towards CIM comprised of four stages: mechanisation, point automation, islands of automation and subsequently computer integrated manufacturing [69]. The three approaches to bridge these islands of automation are top-down integration, bottom-up process and a vise-grip approach [249].

Islands of automation represent the majority of the current state of manufacturing integration within the contemporary factory. These islands of functional automation, which have been designed in isolation, have given rise to the CIM problem as these islands are

beginning to overlap and compete with each other. The areas of concern identified are: software transportability; system objectives; goals and rationale; identifying system activities and interrelationships and data/software interfacing with existing systems [10].

In the early 1980's, the MAP/TOP open network standard [107] had to be adopted by all vendor companies into CIM-system hardwired integration [182, 302]. The disadvantages of using this approach was the focus on 'applications' or 'islands of information'; whilst it functioned well within a department, it failed between departments [302]. There is usually some redundancy of data to fit islands of automation applications running on mixed hardware platforms in mixed operating systems and language environments supplied by different vendors [125]. These systems cannot really address the full spectrum of CIM data needed today because of their lack of adequate software for interpreting and handling the context of the image information they store and process [268].

'Top down integration' is derived from the company's long term strategic plan. It requires specification of all interfaces between sub-systems and the tasks to be performed by these systems. The actual implementation process generally involves the entire plant. The disadvantages of such an approach lies in its resource intensive situation and requirement of a large number of specially skilled people. Only when an entirely new plant is installed will such a top-down approach usually be possible.

The 'bottom up' approach is characterised by a patchwork of stand-alone automation. They are initiated at a lower level of management and try to solve immediate short term problems. It is a low-risk investment and requires no major changes in the organisation. The applications are usually between directly related operations, for example, CAPP feeding process data to robotics etc. The disadvantages of this approach are that the automations are suboptimal and integration at a later stage will be very difficult if not impossible.

The vise-grip approach combines the top-down and bottom-up approach to establish a comprehensive and coherent framework allowing automation to fit in this framework and getting as much participation as possible from the operational level. It combines the advantages of the top-down and bottom-up approaches.

Other approaches implemented by other researchers are reviewed. The concept of I-CIM (interorganizational CIM) includes organisational strategy such as interpersonal, political and management aspects as well as technological aspects in the integration of CIM [130,6]. This allows a more vertically integrated business unit to be achieved.

The Burbidge approach to CIM involves simplifying the material transformation and management system (the 'IM') before the computer system (the 'C'). The terms used for such an approach are 'simplification' and 'synthesis' which allows regulation and control to be designed in order to produce the final and unique (CIM) system for a factory [71].

A major cause in all these approaches lies in the difficulty of managing large amounts of rapidly changing and shared data [119,268,302]. The vision of 'data-integrated manufacturing', a shared neutral-format database through which all systems would exchange data for minimum redundancy of entry and storage as well as for maximum accuracy and consistency, is still an unfulfilled dream.

In an idealised world, there are essentially two methods of overcoming this difficulty [125]. Firstly, the use of a single central database consisting of a single set of data which must be suitable for all functions of a company from management, information and control system [119, 125]. Secondly, the single set of data must be capable of being viewed through different filters relevant to each application module [125].

Recent research has also been directed towards a 'data-oriented' approach includes that by Allen [7], Alting [10], Cole [84], ESPRIT [112], Flatau [119], Gane [125], Madison et al [197], Salzman [268], and Stephenson [302].

4.3 Integrated CAD/CAM

An intersection of the two domains of design and manufacture is the technology of computer-aided design and computer-aided manufacture (CAD/CAM), shown in Figure 4.3. This represents an efficient, accurate and consistent method to design and manufacture high quality products. CAD/CAM are now being combined into integrated CAD/CAM systems, with which a design can be developed and the manufacturing process can be monitored and controlled from start to finish with a single system [132].

The main purpose of CAD is to produce a definition of the part or system to be manufactured in the form of geometric database, or a drawing derived from this database. This will then establish the physical configuration of the part or system. On the other hand, the purpose of CAM is to translate this definition into tangible hardware based on that database. The basic premise of CAD/CAM is that individual functions in design and manufacturing are computerised and that these functions are tied together through a central shared database [52].

4.4 The Product Cycle and CAD/CAM

The product cycle begins with a concept or an ideal for a product. An idealised product cycle is shown in Figure 4.4. This concept is cultivated, refined, analysed, improved and translated into a plan for the product through the design engineering process.

The integration of CAD/CAM is the starting point for CIM implementation and the instantiation of a new product. The success of this implementation lies in the design and manufacturing databases [188] to act as the 'central' data [183]. This is to represent all the necessary information concerning the product for and during the design and manufacturing phases [174]. As a result, integrated in this context means that all information, put into and processed by the computer, is also available to all other sub-systems which may require it at any time. This gradually builds up the 'product model' which behaves as an information carrier through all the phases of the product creation process [54, 238]. Whilst a geometrical

model functions well in describing the shape of a product, it has limitations in conveying the technological and functional information. The concept of a 'product model' as opposed to geometrical model is developed as it is able to plug the limitations of the geometrical model. The 'product model' has since been a research topic for many researchers such as Althoff [9], Faux [116], Roy and Liu [262], Spur [295] and Tattersall [316].

4.5 Product Modelling Issues

Product modelling refers to the activities related to representing and utilizing information related to a complete product, its design and manufacturing processes and its production management.

The goals of product modelling are to integrate the separate design, planning and manufacturing functions of a company together to form a whole entity where the same product information can flow from one function to another with minimal friction and no loss of information at any stage [203]. Essentially, the four factors to be considered in achieving the goals are design and manufacturing process, geometric models, feature models and simultaneous engineering, see Figure 4.6.

4.5.1 The Design and Manufacturing Process

The design and manufacturing phase involves: specification (functional design) of the product; conceptual design of the product; detail design of the product; manufacturing process planning; manufacturing of the product; testing of the product and documentation of the product, see Figure 4.7. Ideally, a design and manufacturing system based on product modelling should be based on 'understanding' the nature of these phases and should followed the constraints that limit these phases and the solid engineering principles, see Figure 4.8.

4.5.2 Geometric Modelling

Geometric modelling is essential in solving the geometric aspects of product modelling as well as forming a solid basis for producing effective CAD systems for product design, see Figure 4.9. Geometric models can lead to the problem of over-specification which makes it difficult to interpret the results of the phases.

The geometric model that a designer creates represents the basic geometry of the object being modelled. When drawn by hand, this model can be represented as a traditional multi-view drawing. In a CAD system, this model is the computer's internal representation of the system. Designers normally create their geometric model at a terminal using three types of construction method. The first is used to create the basic geometric elements such as points, lines, circles etc. The second type of construct is used to scale, rotate or transform the basic constructs in some way. The third type of construct allows the designer to combine two or more shape elements into one item.

The workpiece that the designer creates can be represented internally to the computer in several methods. The most basic of these methods is called a wireframe model which consists of simple lists of lines and curves. Today's wireframe system consists of 3-D space curves which are being employed in a variety of applications including NC code generation. However, these systems have some serious limitations. In geometric modelling, there is a move from 2-D wireframe representation, surfaces modelling or free-form surface modelling to 3-D solid modelling. They can be ambiguous and permits representation of 'nonsense' workpieces. The deficiencies of a wireframe representation is overcome by the introduction of surface modelling and solid modelling[55a, 164, 254]. Surface models were introduced to deal with sculptured surfaces. These free-form surface modelling techniques are mostly based upon surface patch techniques such as B-splines, Bezier splines and other parametric surface descriptions. These provide ways of representing complex local characteristics of the surfaces being modelled, for example displaying shaded images.

Solid modelling contains information about the closure and connectivity of the volume of solid shapes. They represent a complete model of component rather than a number of contours or surfaces. It permits the automation of any geometric application such as fully automatic finite element mesh generation and process planning with its unambiguous representation of solids. The most important types of solid model are the boundary solid models or B-rep and the set-theoretic or CSG (constructive solid geometry) [55a, 113, 232a, 253, 254, 341].

In B-rep, the part is represented by its faces, edges and vertices. The relations and the interconnections of these (often termed the topology of the object) are usually held explicitly within the data structures and are useful for producing drawings. In CSG, parts are constructed from primitive solids such as blocks, cylinders and cones which may be merged together, subtracted or intersected by means of Boolean operators. The primitives making up an object are usually stored in the form of a binary tree, together with the set of Boolean operators that define how these primitives are combined.

4.5.3 Feature-Based Design

Feature models are currently being suggested as an alternative modelling technology, see Figure 4.9. They represent parts not in terms of 'pure' geometric primitives, but in representations that bear a clear engineering meaning. The advantages of using features are threefold [203]: it provides a more natural vocabulary for expressing the design object; it gives rooms for dividing the geometry into feature types and geometric attributes of features which allow geometric details to be unspecified and; it offer a good basis for modelling the various manufacturing planning information.

There is no one definition of feature as each definition is related to its purpose and application. However, the traditional definition of a feature defines it as a region of an object's boundary that has significance for a specific activity [252]. A feature can also be defined as a set of information related to a part's description [278, 279]. It may be described

as a characteristic of a component produced by a process. A feature also carries the notion of both the resultant part geometry and a variety of non-geometric or geometrically related information [83a]. Features can be classified into form features, precision features, material features, technological features or assembly features. There are essentially two reasons for using features: geometry is best recognized by certain geometric features of objects to provide knowledge in assisting machinability and other downstream issues and; the inability of the traditional CAD system to capture the designer's intent [232a].

Features can be defined and supported by either of three approaches [74]: Firstly, a human-assisted feature definition where users can interactively group geometric entities to define features. This approach is cumbersome resulting in inappropriate features which cannot be understood by some CAM programs. Secondly, by feature recognition and extraction where a pattern recognition algorithm is applied to the geometry database. This approach makes algorithms for simple features complex and allows room for misinterpretation. Finally, by feature modelling where features are incorporated right from the very beginning of product definition. The final approach is chosen for this research work as it is capable of solving both the abstraction problem and the information deficiency problem.

4.5.4 Simultaneous Engineering

Simultaneous Engineering involves the concurrent design of a new product by the process of designing for design, manufacturing and inspection [120]. A key aspect of simultaneous engineering is involving manufacturing, quality and design engineers in the design engineering stage so as to receive contribution from everyone before finalising the design [79]. It requires that the enterprise be viewed in a more integrated manner [80]. The one problem in implementing simultaneous engineering is getting these engineers to speak the same language. The product modelling concept is the key to fulfilling simultaneous engineering practice since a single design representation will be used for all the functions. Valisys has been identified as a software tool for implementing simultaneous engineering

principles as it provides a common language for all engineering disciplines [79]. Madsen reviews some of the latest simultaneous engineering projects implemented at ABB Robotics,Inc [198].

4.6 The Product Model

Product Modelling plays an essential role in the integration of CAD/CAM systems and acts as a platform for fulfilling the needs to share the same information from an integrated and complete model, see Figure 4.10. The heart of the integrated CAD/CAM database is the product model. The product model of a component consists of the entire body of information necessary for the design and production of that component [186]. Such information are product structure, geometric topology, geometric representation, design logic and results of certain manufacturing processes. The environment in which the product model resides consists of description of attributes and decisions, visualisation or user interface for directed dialogue between the user and the model, and interfaces to the product model for information retrieval. This is a geometric description of the product that is input to the CAD/CAM system by the engineering design function. Product models are required to represent the same kind of information as these engineering drawings. It is also used for other engineering functions such as equipment layout, detail design/draughting, engineering analysis and technological illustration. The product model is important for two reasons : it provides a base line for all forthcoming activities which determine the product cost and; many other manufacturing constraints that influence the design of the products.

Now a host of manufacturing applications make use of the existing product model information and add to the growing CAD/CAM database. Factory production analysis applications such as group technology help optimise manufacturing flow based on part geometry and manufacturing description. The product model can also be used to support finite element analysis and other testing procedures in evaluating the product. The same CAD data set, when finalised, could be used to generate NC tapes and process-plan for both

manufacturing and assembly. The design data can be used as input into a number of computerised activities which would support the design of production equipment and facilities. In turn, the process plan in conjunction with the facility design and capability provide the base line for the scheduled activities required to produce the amount of product anticipated by the marketing analysis.

Product models or engineering databases are integrated models that combine representations of geometry, semantic knowledge and engineering models [118]. They are models of objects to be designed and manufactured by utilizing the 'clever' system which can understand and handle various basic scientific and engineering concepts [172].

4.7 Structured Data Modelling

Two main types of data models available to store and manage data are the database system and the knowledge-based system [292]. The design of the product models is greatly influenced by these technologies. A database system is basically a computer-based record keeping system of large volume of operational data such as product data, planning data and account data. The knowledge domain in the database is represented by the structure of the database. The actual contents of a database are the facts, data or information rather than the knowledge. Knowledge-based systems essentially contain the facts and heuristics that make up the expert's knowledge. The knowledge about the problem is represented in the knowledge base by methods such as rules of thumb, computer programs, theories and other approaches to compute a solution to the problem.

The design of the data model is categorised by its data structure. Five categories are evident for structuring data within these models. These are hierarchical, network, relational, object-oriented and semantic [146, 288]. The hierarchical data structure is a collection of record types connected by a collection of associations with each association linking between two distinct records. Since there is only one association, there is no self-referencing link.

The network data structure is a collection of records types connected by a collection of named links. The links define sets that consist of owner and member records. Links can represent one to one and one to many associations. Like the hierarchical, there is no self-referencing link and the record type cannot be both the owner and a member of the same set type. In the relational data structure, there are no explicit links between record types. Links can be represented by one or many to one or many.

These three approaches, very often known as the traditional approaches, concentrate on the physical structure of the data model without due consideration given to the user's perception of the data. The hierarchical and network data structures offer the user the means to navigate the data model at record level, thus providing operations to derive more abstract structures. The relational data structure adds a data structure level, eliminating the necessity of performing primitive record level manipulations of the data model. The former approach might be considered as operational, whereas the latter might be considered as structural. Modelling capabilities with these traditional approaches are still closely related to the record structure of the data model.

The emergence of semantic data structures are due to two important issues addressed in data modelling [146]. The first is data independence in which the user should be free from the details of the physical structure of the data model and able to model the data in a manner similar to the human perception of the application. The second involved capturing additional semantics in the data modelling process. Semantic models were developed in the middle seventies to provide a higher level of abstraction for modelling data, allowing database designers to think of data in ways that correlate more directly to how data arise in the world. Unlike the traditional models mentioned earlier, the constructs of most semantic models naturally support a top-down, modular view of the schema, thus simplifying both schema design and database usage.

The three most prominent models of the semantic family are the entity-relationship model, the functional data model and the semantic database model. The entity-relationship model is a natural graph-based representation consisting of types and relationships interconnecting these types. The functional model is centred around the functional relationship or attributes. The semantic database model uses the grouping constructor and the support of derived schema component for specifying derived attributes and subtypes.

The object-oriented data structure places emphasis on objects as entities that combine the properties of procedures and data to perform computations. It consists of class to represent a data type, the values as its instance variables and the operations as methods which the class responds to. Essentially, semantic models encapsulate structural aspects of objects, whereas object-oriented models encapsulate behavioural aspects of objects. There are three principal features of object-oriented models. The first is the explicit representation of object classes or types. Objects are identified by surrogates rather than by their values. The second feature is the encapsulation of methods or operations within objects. Users are free to ignore the implementation details of methods. The final feature is the inheritance of one class to another.

4.8 Emerging Product Data Standards

Product data exchange is becoming an important and necessary function in the improvement of integration between product design and manufacturing information, see Figure 4.11. The most widely available way of data exchange is the standard neutral format [18, 19, 56, 63, 165, 175, 218, 229, 231, 346]. The first neutral format for exchange between CAD systems is IGES (Initial Graphics Exchange Specification) adopted in 1980 by the ANSI (American National Standards Institute). Its goal is to provide a foundation to permit the compatible exchange of product definition data used by various CAD/CAM system.

The Product Data Exchange Specification (PDES), sponsored by the United States National Institute of Standards and Technology and International Standards Organisation, is intended to supersede IGES. PDES combines the various elements of graphical data with

manufacturing descriptive data for the classification and arrangement of product model. A new neutral format for product data known as STEP (Standard for the Exchange of Product Model Data) is being created by the ISO Committee TC184/SC4/WG1. STEP is based on data modelling and a formal definition language which will support different implementation forms. It is intended to take over IGES and is receiving input from PDES. As a result, a new international standard known as PDES/STEP for exchanging product information has emerged. PDES/STEP is a major extension beyond IGES and is used for the exchange of a complete product model by CAD/CAM systems. This standard is being co-ordinated with international standards groups and is likely to be adopted internationally by industry, designers and researchers [118].

Product data standards have had a great impact on the communication link between manufacturers and their suppliers and customers. Equally these data standards have also influenced the level of integration within an organisation.

4.9 Current Research in Product Modelling

Current engineering database systems are not capable of meeting all the requirements of the product model concept. This results in a growing demand for a new approach oriented towards constructing a product modelling database and other CAD/CAM databases. There are three categories of database: information administration database; engineering database and; product-modelling database [186]. These are grouped into a total product model consisting of relationships such as product structure, geometric topology, shape and binding, dimensions and tolerances, technical properties, design rules and standards and user dialogue and operation sequences. The product name structure is used to bridge all the relationships.

A engineering database with a flexible database configuration, using a three-dimensional geometric models as its nucleus, has been developed in a design and manufacturing environment [174]. The database is constructed into various entities consisting of core

information, product specification drawing, process planning and manufacturing environment. The benefits of using such a database are: information can be managed consistently; improvement in design and manufacturing productivity; reduction in manufacturing lead time and; improvement in accuracy of analysis and reliability of information.

Boeing is also developing a comprehensive system servicing all design and manufacturing functions where a shared common database forms the foundation of the system [45]. The shared common database includes the computer-based product definition data that comprise the master product data, targeted to replace the engineering drawing as the ultimate design authority. All applications use the common database directly or transform data into a secondary form.

The move towards a product modelling database to describe the machine product information is evident in a integrated CAD/CAM system, CIMS (computer-aided integrated manufacturing system) [155]. This modelling technique was proposed to represent the geometric and technological information about the product. The geometric information is described by both the hierarchical relations among the product, sub-assemblies and parts, and the solid models of the individual parts. The technological information about the material, the surface roughness and the accuracy is described separately and is attached to the geometric shape element of the products. A kinetic simulation system, based on the product model, simulates the product kinetic movements.

The importance, usefulness and requirements of product modelling is studied by Kimura et al [172]. A new representation framework for product model consisting of an object concept called frame, relations among frames and attributes is proposed. It can also incorporate the existing solid modelling package GEOMAP-III into the framework for machine products.

Extensive efforts have been made to show a framework of product modelling. Sata [272] proposed the concept of product modelling as a representational framework for engineering information and showed a basic framework for product models with a combination of the first-order predicate logic and an object oriented method which exhibits a powerful capability for representing machine assembly structures. This description method also deals with geometric constraints such as dimensions, tolerances and assembly. With the aid of first order logic, relations that appear in machine assembly are manipulated in terms of geometry. An object-oriented approach helps to represent attributes of objects in an abstract way.

Kimura et al, [171] considered the process of creation and manipulation of product models in terms of constraint propagation and satisfaction. This method is applied to variations in product design where products are designed and are modified according to the given constraints. One of the advantages of the method is that some of the designer's intention about products can be explicitly represented and manipulated in the form of logical constraints. Kimura et al [173] uses the concept of variational geometry to deal with flexible shape generation and manipulation. The shape is determined from various kinds of logical constraints depending on the product requirements and its applications.

Imamura et al [149] uses the object-oriented product model to represent the geometry and dimension of machine parts. The characteristics of the object-oriented concept are effectively utilised for the two and a half dimensional geometric representation. The designer's intention in shape definitions are described in the data structure of geometry. The dimension data are represented without referring to vertices which results in the simple algorithm of treating dimensions. Sufficient and non-redundant dimensioning is realised by treating logical variable flags assigned to geometry objects. The constraints propagation method makes it possible to realize the flexible interlocked modification of the geometry by changing the dimensions.

A prototype variational product design system which formulate design and manufacturing processes in terms of constraint propagation and satisfaction concept to variational product design in product modelling is developed by Kimura et al [172]. This allows the designer's intention or design requirements to interpret into the form of constraints description with each design process receiving these constraints and decomposing them into several small problem to be solved.

A process planning system, X-MAPP has been developed using product models of machine parts, workpieces and other objects in process planning with form features representation [150]. Process plans of machining operations are generated using knowledge of process planning methods and constraints with product models. X-MAPP consists of two major modules: plan generator, which is a rule-based expert system, is used for process plan generation; model manager to manage product models in process planning.

Domazet & Manic [100] describe CADROT, a product modeller and CAD module for integrated CAD/CAPP/CAM systems for rotational parts. CADROT sees the part as a collection of form features which provides a logical connection of geometrical primitives. The CADROT database allows easy extraction of all part features simply by reading their code numbers and data . Tolerances, surface informations and construction lines parameters enables fast and easy dimensioning as well as dimensions modifications. The database also contains all necessary and accessible product informations for manufacturing process planning.

The product model uses the information layer technique for organising information [296, 297]. The layer syntax of the product model consists of three layers: information layer which described how information can be generated and structure; information-link layer which connects information of same or different semantics and; the organisation layer as the global entry of all informations to an object.

Besides product modelling, a combination of artificial intelligence (AI) techniques and geometric modelling techniques are used as a basis to integrate computer-based support of engineering design process [290]. This is to meet the requirement of an engineering design support system and to provide an effective degree of automated reasoning and consistency in management. This approach models design as an accumulation of a coherent body of knowledge about a particular product. The knowledge represents both descriptions and specifications of possible design and their manufacturing activities.

4.10 The Information Support System Research Goals

The objectives of the total project research is to develop an information support system for design and manufacture (ISS). The ISS has been defined as a set of software tools that assist a company in managing its resources: these resources may be people, data or pieces of software and hardware which perform specific functions [208]. It is designed to address two problem domains: facilitating the integration of existing and new pieces of software applications and; providing tools which support the control of data used by specific software application. Figures 4.12 to 4.14 show todays practice, the role of the ISS in tomorrows possibility, and the what the future might hold respectively.

The ISS, shown in Figure 4.15, is capable of supporting all phases of design and manufacturing processes and it also provides several levels of integration: common data base schemas and communications capability (sharing data); common application programming interfaces giving access to this shared data (sharing software); common user interfaces (having similar screens and keystrokes) and inter-working capability with existing systems in a variety of ways [98].

The product data model, shown in Figure 4.16, is at the heart of the system. The product data model is a combination of the project meta-structure, shown in Figure 4.17, and an instance. The project meta-structure defines the form of the data and the instance of the project meta-structure will contain the data needed by the applications at run-time with slots

provided for storing the data they produced. The project meta-stucture consists of a project framework meta-structure and individual application meta-structure, shown in Figure 4.18. The application meta-structure describes the data structure required by the application. The integration of the data structures allows individual applications to develop meta-structures separately. The framework provides slots for the fitting and integrating of individual meta-structure. Database data, such as company specific data which already exists, will form part of the framework and is global to all the application meta-structures. Since the project meta-structure is modular, the work of individual applications will not disrupt or interfere with each other.

The ISS integration process consists of four phases: pre-integration where all data needed to support individual application is defined in the individual meta-structure; comparison of the schemas where slots are determined in the project meta-structure; conforming to the schemas where any deficiencies in the inter-relationships between individual meta-structures are noted and; merging and restructuring where the individual meta-structure and the framework will be merged and restructured when necessary to produce the ISS meta-structure [206].

The two objectives of the ISS are: to build and experiment with a Product Description System (PDS) and to demonstrate the work through an Integrated Design to Manufacture Experiment. The PDS is build to support the data structure that describes the product and its methods of manufacturing. The use of the PDS to fulfil the second objective will be discussed in Chapter 6. The two purposes of PDS are: firstly, it provides a product modelling environment as the main vehicle for the design and manufacturing activities and; secondly, the use of product data model definition as the means to achieve integration. The three facilities that form the foundation of a PDS are data description, visualisation and integration.

The product description system is intended to define the various data generated through the product life cycle from specification through design to manufacture and back to design.

It supports the product data in a structured manner to complement human structural insight. A PDS is used to produce a description of a single version of a single product. In contrast, an ISS is used to describe the interfaces between different products and other data which is not directly related to a single version of a single product. An ISS can also be used to identify a product and use its data for locating files and checking user authorisation.

The Structure Editor, described in Appendix II, is used for implementing the PDS by defining the detailed design and product realisation levels of the product data [57, 207]. It is a software tool for editing structured data and building interfaces to pieces of software that uses that data. The structure editor can also be used for visualising and manipulating data structures as well as describing other engineering data.

Chapter 5 :

Data Feedback in Contemporary Manufacture

5.1 Introduction

The purpose of this chapter is to discuss the data feedback issues in providing for the manufacture of a product from its specification to its production. This chapter draws on the survey of contemporary literature, available decision support aids and the requirements for integrated design to manufacture, all documented in the preceding chapters.

The chapter moves from highlighting the role of data feedback in the life cycle of a product; to the problem of building a manufacturing data base; through to assessing how one can achieve the product design objectives; the requirements to 'closing the loop'; the current emphasis on process control; the quality control issues in the total quality control environment and; finally to a discussion on the trend towards data integration. This chapter provides the backcloth for the following chapters and a discussion of the research work.

5.2 The Role of Data Feedback in the Product Life Cycle

The life cycle of a product begins at the specification of the product and cycles through inspection and decision on the prototype, through design to manufacture and code generation, and back to design. The product then continues its life from the prototype stage to production.

The three essential levels, shown in Figure 5.1, which are evident in the product life cycle are the prototype phase, the mature product phase and the short-term quality cycle of the mature product. The prototype life cycle revolves around the design to manufacture environment. The prototype will only be considered for production after achieving its specification. The mature product life cycle, in established production, usually requires minor

updates in its design to meet changes in market requirements and to fulfil the company objectives in reducing costs. The short-term quality cycle, which resides within established production, assists in sustaining the quality of the mature product.

The Data Feedback system in this research plays a dual role in the product life cycle. The primary role is to close the loop from manufacture to design in the prototype life cycle. The aim of closing the loop is to maximise the impact of the feedback loop to ensure that a quality prototype is produced. The secondary role deals with the manufacturing problems effecting the quality of the mature product. The two types of analysis, dimensional and process, of the feedback system are applied to achieve the primary role with process analysis also achieving the secondary role. The feedback system is discussed in Chapter 6.

5.3 A Generic Approach to Capturing and Assessing Manufacturing Knowledge

Manufacturing embodies two main types of knowledge: the product/process knowledge and the machinists know-how or expertise, shown in Figure 5.2. Product and process knowledge are required for the manufacture of a product. The use of machinist's knowledge is dictated by the type of manufacturing system employed. In traditional manufacture such as jobbing, the machinist's knowledge is required for monitoring and rectification of any unforeseen disturbances in the system during the manufacturing cycle. In the more automated situation involving large volumes, very often an incomplete source of knowledge results from the use of automated manufacturing equipment, and sometimes from the installation itself. This incompleteness is overcome by having the system partially supported by the machinist's knowledge adding value to the use of the manufacturing knowledge bases. This knowledge base must be capable of being elicited, captured and represented in an understandable manner such that it can be assessed and applied for other applications.

The capturing and assessing of the product and process knowledge has been a research topic of interest for a long period of time. The most current concept evolved in representing this knowledge is the 'product model', which is also the project goal, is discussed in Chapter 4.

Currently, there are no adequate solutions to solving the process control domain using machinists knowledge although research is still ongoing. An approach vigourously being pursued is in the use of expert systems [37, 3, 92]. Expert systems are not fundamentally built for manufacturing, but their technology enables its tailoring to suit a manufacturing application. An expert system is a computer program that uses knowledge and reasoning techniques to solve problems that normally require the services of a human expert. The expert system may either emulate the external behaviour of an expert by gathering information and producing solutions to problems or it may attempt to closely model the internal mental processes of the expert by using formalised methods or heuristic search for solving problems. The technology is usually geared towards a single domain, with little evidence of a distributed nature. Also, the lack of provision of interfaces to other applications to form an information network is thought to be an obstacle to its wider acceptance in an industrial environment.

The most significant advantage which differentiates the expert system from the traditional methods lies in its ability to retrieve consistent and all-related knowledge by different users each time. In the traditional approach, the user is often limited by the scope of the knowledge they are called to act upon. Also, the possibility of forgetting some of the knowledge is apparent especially when making a hurried and lurid judgement. A major input to the expert system comes about in the knowledge elicitation process which is discussed in Chapter 11. The expertise cannot be captured simply in the form of rules. More significantly, it is not a trivial task in extracting the knowledge from the machinist and the same knowledge cannot be captured easily by the expert system. Another area of concern arises when there is more than one expert which then often results in a conflict of solutions.

There are two approaches available to assess the use of manufacturing knowledge: technology-centred [126, 331] and human-centred [50, 51]. While the technology-centred approach can be applied to the product/process knowledge, it poses a limitation to the machinist knowledge. These limitations are that: although there is sufficient sensor technology to capture the information on the process, the capability of interpreting such information has not been fully developed; also full elicitation of visual and audio knowledge has also been researched, but the problem again lies in the representation of this knowledge. Although expert systems have been offered as a solution, the flexibility of the system is still restricted as explained above. Complete automation and unattended operation is still a development objective as long as these hurdles need to be overcome. Humans are still needed to provide valid judgements on improving the quality of the product from the available captured knowledge.

The modern use of statistical process control (SPC) is under challenge. Some researchers argue that the way ahead in SPC is towards attaching expert systems [53]. They claim that complete automation can be fulfilled by introducing SPC with embedded knowledge on a particular process in a rule-based system. Others take the Japanese view of 'zero defects', a different approach to controlling manufacture, which can make SPC unnecessary and inappropriate. However, the balance of this issue shifts in emphasis from application to application as the manufacturing tasks are varied and various. Despite these suggestions, the human operator still plays an essential role in machining as long as the interpretation of information cannot be done automatically [60, 103]. The two issues that need consideration in the human-centred approach are: visualisation, which dictates how information should be presented to the user and; the level of technology, which dictates what information should be presented to the user such that the user can understand the information (discussed in Chapter 10).

The data feedback system presented in this research embodies the learning from the technology inherent in expert systems to develop a coherent information support system

which links design to inspection, through manufacture, and back to design level. The data feedback system employs a rule-based approach supported by product model based knowledge, which acts as the backbone and covers the various stages of the manufacturing cycle. Unlike an expert system which is 'generic' in application, the data feedback system in this thesis is generic only in manufacturing application. A generic approach is adopted in the structuring and managing of knowledge where this knowledge can be captured in a form suitable for any manufacturing process. The ultimate aim is to develop a system as an island that can bridge to other manufacturing applications and engineering databases.

A 'forward-chain' algorithm is implemented in the data feedback system which simulates a human decision system permitting the tracing of faults to causes then actions. The benefits of this approach in comparison to using an embedded expert system is that this rule-based decision tree is an integral part of the overall information support structure, transparent to the user and which permits chain links to other applications such as dimensions and tolerances, machine planning, inspection and geometry evaluation permitting a powerful solution to the problem. The structuring of data to represent knowledge and data managing is presented in Chapter 8 and 9 respectively.

5.4 Achieving Product Design Objectives

Achieving product design objectives implies fulfilment of design requirements by inspection and results in customer satisfaction by providing good product. Although programmable co-ordinate measuring machines (CMMs) have improved the inspection process by replacing micrometers and gauges, they cannot interpret the tolerances specified leaving it to the quality inspectors to decide whether the part will work as designed.

Basically, there are two levels, shown in Figure 5.3, to be considered in achieving the product design objectives. At the higher level are Simultaneous Engineering [79, 80], a soft-gauge approach and the Information Support System (ISS). At the lower level are decision

analysis techniques [195] such as Failure Modes and Effects Analysis (FMEA), Quality Function Deployment (QFD), Taguchi methods, statistical process control (SPC) and Poka-Yoke.

Simultaneous Engineering is now the leading edge of technology in achieving the product design objectives where product can be designed with the knowledge of its manufacturing and inspection capability. Soft-gauge allows the same CAD database to be assessed by design and inspection and allowing inspection results to be fed back to the CAD system for comparison. The ISS, described in chapter 4, is another way of providing information for the complete design to manufacture environment. Manufacturing Data Analysis (MDA), which is a component of the ISS and the research objective, ensures that the design objectives are met by ensuring dimensional accuracy through feedback, and process integrity with human assisted feedback to the machine or design level in a product model environment. A detailed description of the MDA system is explained in Chapter 6.

To achieve the design objectives, a dimensional analysis system is offered based on modified SPC and influence diagrams to assist human operators in tracing faults in a defective product (discussed in Chapter 3 and 7). In this research, the term fault clustering is used in a way which is similar to the application of group technology in that, grouping of faults by an identifying characteristic is carried out. An example of such a cluster is the grouping of all tool faults into a fault cluster of type 'tool'. The fault cluster assists in product and process control in either of two manners. The first is use in the dimensional analysis process to trace the fault(s) from defective product. The user has to follow the line of reasoning from finished component dimensions to identifying the possible fault type(s). The second is a 'short-circuit' process [292] where the user can pre-empt the occurrence of a fault during the machining cycle (discussed in Chapter 7 and 8). He is immediately able to consult the relevant fault cluster directly without following the procedure described.

5.5 Closing the Loop in an Inspection System

The main aim in closing the loop in an inspection system is to prevent defective product from arising. There are three main areas of development: hardware dominated essentially made up of CMM's [193, 324] and sensor developments [160]; software and communication standards such as MAP/TOP [107] and Dimensional Measurement Interface Standard (DMIS) [42] and; data-integration technologies [118].

Advances in touch trigger probe technology and the developments of CMMs have extended the applicability of CMMs. CMMs have moved from the role of standalone end-of-line inspection to being more closely integrated within the manufacturing process.

The current trend in industry is towards small manufacturing cells which call for the design of flexible inspection systems (FIS) [58, 121, 247]. The FIS must be able to provide the same flexibility as the cells and measure a wide variety of parts. The design of the FIS can range from a standalone CMM to multiple CMMs serviced by material handling devices and controlled by one supervisory computer. Advances in computer technology have resulted in powerful control systems, communication standards such as MAP/TOP, ease of statistical analysis of data and database management systems. All of which make the implementation of the flexible inspection system (FIS) feasible. An essential element in closing the inspection loop is the provision of real-time feedback capability for process monitoring. The effectiveness of this real-time feedback facility depends on the integrity and promptness of feeding the inspection data back to the machine to keep the process within specification.

Advancements being made in achieving real-time feedback in a FIS include: statistical monitoring without human involvement to improve inspection efficiency; and a control system that can be fully integrated in a flexible manufacturing cell or system. Furthermore, these advancements enable large volumes of data to be processed, many peripherals to be controlled and versatile software to be produced to meet the dimensional inspection demands of the flexible manufacturing environment.

Another major step towards closing the inspection system loop is the introduction of Dimensional Measurement Interface Standard (DMIS), an interface standard, which allows interfacing between CAD and CMMs. This allows inspection procedures to be created from the same CAD database and allow quality information to be sent back to the same CAD system for design evaluation. Such a system can be found in the software approach of Valisys [81]. Currently, there is no evidence in the literature of end user experience in closing the loop in an inspection system. None of these systems has the apparent capability to identify manufacturing errors from the inspection results.

As seen above, closing the loop is two-fold: the first is through hardware and communication protocols and secondly through effective integration of information and data around the loop. The main thrust of this research work centres on the latter. A data feedback system, shown in Figure 5.4, is provided which supports the human operator in reaching a decision on a defective workpiece or in predicting errors in the process. The loop in this instance is closed when the data is fedback either to the machine level or up to the design level. A description of this system can be found in Chapters 6 and 10.

5.6 Process Versus Product Control

In the contemporary factory today, quality is and can be seen as an important concept in achieving an accurate or a 'zero defect' product to the satisfaction of the customer. The broad emphasis in achieving quality is either on product control or process control. Product control inspects the parts or products after they have been built. Defects can only be detected after they have occurred but does not prevent their manufacture. In contrast, process control influences the process itself by preventing the defects from occurring. The main trend in achieving quality is in process control [128, 325] a better alternative for controlling quality in a manufacturing environment.

The three approaches [284] which are evident for achieving 'zero defect' manufacture are 100% inspection at individual station representing different stages of manufacture,

individual manufacturing process station control using statistical process control (SPC) and 'designing-in' the production line. The first two approaches are classed under product control and the latter process control. Fully 100% inspections, although ideal for the detection of defects, entail considerable time and trouble. It is the best method of assuring quality but is feasible only in the process industry, automated assembly lines and flexible manufacturing systems. It is however, often not feasible in batch production due to its distributive and disruptive nature which may cause bottlenecks at the end of each operation in the manufacturing cycle [49].

Although the techniques and approaches of SPC are well documented, they are usually variable in their effectiveness for use in most manufacturing processes. Also, companies are still not fully versed in SPC and this demands a need to train operators in statistical techniques before they can be implemented. Many attempts have been made to modify SPC to increase its relevance to a manufacturing application. Improvements to overcome such deficiencies by using process specific expert system-based SPC to assist the operator in the control of the process have also been implemented [161, 232]. However, this approach has access only to a localised or specific domain and not to a wider base of manufacturing know-how. Nevertheless, SPC is still a good starting point in building quality into the process and product and towards achieving a 'zero defect' target.

Much of the literature has been directed at process control. The notion of 'designing-in' for manufacture predominates. Many quality theories have been put forward especially the concept of 'zero quality control' to achieve 'zero defect'. They are philosophies for defect prevention where the belief is to ensure quality rather than to produce defects or measure quality. The 'zero quality control' concept also gives rise to 'poka yoke' which is a technique preventing defective products from being produced. Many researchers have embarked on this same route by building quality into the process or product [64, 128, 137]. Although process control reduces the costs associated with product testing, inspection and waste; the beneficial economical aspects have to be balanced against product control.

Currently, industrial practice is based on statistical process control rather than being geared to 'zero quality control' (ZQC). The pioneers of 'zero quality control' have promoted the concept as a preventive technique but sadly, it has not been fully understood. This has resulted in the continued and extensive use of SPC. SPC shares the same broad objective as ZQC but ZQC still remains the ultimate goal. The overall concept of product, process and ZQC gives rise to total quality control which formalises the implementation of these practices.

In this research, a dimensional analysis system is offered, which retains SPC related techniques to analyse the inspection results, to identify those manufacturing errors which have contributed to bad product. The use of SPC in this research involves the modification of control limits. Also offered in this research is a process analysis system, which in line with the objectives of a preventative type system, focuses on anticipating those manufacturing errors which if not resolved, will result in bad product. The two options offered by the process analysis are: verification checks to provide the best machining conditions and set-up, with the information support system providing access to a wide base of manufacturing and inspection knowledge, to fulfilling the design to manufacture objectives. Fault clusters are provided for organising similar manufacturing errors together for a quick and easy error identification. In addition, a fault library, which consists of manufacturing errors and their solutions, is offered to bridge the two systems. A discussion of these systems is deferred to Chapter 7.

5.7 The Total Quality Environment

The concept of having a centralised quality function has now evolved to total quality control (TQC). TQC has reinforced this decentralisation by devolving responsibility in maintaining quality to the man at the shop floor. Whilst Simultaneous Engineering emanates at the design level by considering design for manufacture and inspection, TQC encompasses every stage of production from design to marketing. Thus TQC provides a wider organisational quality framework [76, 89, 148, 191, 228].

Total Quality is a competitive imperative for the 1990s [328]. TQC is the system which achieves the goal of designing, manufacturing, marketing and maintaining quality at the most economical costs which allows for full customer satisfaction [227]. A powerful TQC capability is one of the principal managerial and engineering strengths for a company today providing a central hinge for economical viability. It permits TQM to cover the full scope of the product and service life cycle from product conception through production and customer service [117].

The breakthrough in total quality has been the acknowledgement of processes. The power of total quality is that it is built on an awareness of the many processes which interact to make a company function. Taking a process view, total quality is achieved when all of a companies processes operate with zero defects measured against the requirements of the customers of those processes. Practically, it is hard to attain zero defects but total quality uses this concept to drive continuous improvement.

The power of the process approach lies in the fact that processes can be defined, measured, analysed and improved and these improvements can in turn drive a new cycle in a closed loop. A closed loop is required to eliminate defects in the process and to comprehend changing requirements. For example, take the prototyping process, we measure the effectiveness of the process by the quality of the prototype. As we measure we compare the results to what was required. In so doing we may discover a deviant quality aspect. The next step is to analyse the deviation using tools as suggested in this research, for example influence diagrams. By identifying a factor and making a correction we may refine our process. In continuing with the cycle comparing results with requirements (design), analysing and then refining those requirements we drive continuous improvement.

It is vital to recognize that this process loop does not take place in isolation. Thus, although the fault may occur in manufacturing, the effects will be felt elsewhere and the corrective action possibly even implemented in the design application. This functionality within the product data model has been the benefit of the project design to manufacture

environment. Futhermore, this enables a process to be defined, and a cross application approach to be activated, which can draw on all relevant disciplines to work on that process. This integrated approach is necessary to eliminate the no-mans land between applications.

The TQC concept will be achieved with the support of an integrated information system. Such a system is the project 'Information Support System' where an integrated data structure is provided to allow the exchange of data between different functions in an organisation. No one application operates as an island. The data feedback system, discussed in Chapter 6 and 10, in this research is aimed at bridging these applications by feeding back data and thus closing the loop from manufacture to design. This data integration, the heart of CIM, hence allows these applications to be structured through a 'product model'.

5.8 Towards Data Integration

The key theme in the 'Factory of the Future' will be 'data integration'. This will be towards automating the information flow and maintaining a coherent data structure which is able to support applications.

The technology for running 'unmanned' is here but problems such as those discussed above in section 5.3, relating to hardware, communication and human involvement, make achieving the 'Factory of the Future' a distant objective. As reviewed in the literature, current CIM installations are now directed towards a 'data-oriented' approach aimed at providing a single set of data for all functions relating to the manufacture of a product.

The role of data in an integrated design and manufacture system has been emphasised as an important factor in the support of information flow . This emphasis has led to the concept of 'product modelling' aimed at representing data and information of a product. The ISS project is designed to support all the phases of design and manufacture process with the 'product model' at the heart of its architecture, discussed in Chapter 4 and 6.

The data feedback system proposed in this research is a cornerstone in achieving an integrated design and manufacture system based on a single set of data. This then represents a cohesive view in the provision of information back to the design level. Such a view is presented in later chapters.

Chapter 6 :

A Framework for the Data Feedback System

6.1 Introduction

An overview and scope of the framework for the design and operation of the data feedback system is presented in the context of an integrated design and manufacture system. The framework is based on the 'product modelling' concept presented in chapter 4 and the decision support aids presented in chapter 3. It provides for the structuring, organising, management and interpretation of data each of which is described later in more detail. The purpose of this chapter is to describe the overall project, set the scene for the research and to then briefly describe the visualisation of the prototype software. Finally, the competitive status of the research work is also discussed.

6.2 The Integrated Platform for Supporting Data Feedback

This research work is one of a series of related research carried out under the umbrella of the Information Support System (ISS) [1, 151] experimental structure shown in Figure 6.1 There are two distinctive inputs contributed by the project to this research. The first is a very sophisticated information platform for information and data flow between design and manufacture. The other is the ability to process information and data for a particular application which offers a fluency of power which could be difficult to achieve in a lower grade environment.

The integrated information platform is based on a product description system (PDS) which provides a product modelling environment, shown in Figure 6.2. The product data model (PDM), residing in the product modelling environment, is the means to achieving integration through the structured sharing of data. This unique environment then works with either loosely or closely coupled applications. Loosely and closely coupled applications may coexist in this environment. The loosely coupled applications are usually the third party or

proprietary software. The closely coupled applications, in the context of this research, refer to the work on generation of machine code (MCG). It should be borne in mind that other closely coupled applications also exist.

The generation of machine code, shown in Figure 6.3, is centred on 'machine plan and code generation' [347], 'inspection plan and code generation' [88] and 'analysis and feedback of data', this research work. The power of the integrated platform can be demonstrated by the interaction between these applications. Each of these applications could draw and return data to the product data model. This data flow capability could also be supportive of the other applications such as 'dimensions and tolerances' [339]. The latter is an essential input to the three mentioned applications. The flow of information and data for each of these applications is shown from Figure 6.4 to 6.6. To appreciate the nature of the integrated environment and to understand the context within which the data feedback system is to operate, the two related closely-coupled applications are described briefly below.

'Machine plan and code generation' (MPCG), shown in Figure 6.4, has its core activity directed at achieving the generation of machining code. The three phases of this core activity are set-up planning, operation sequencing and code generation. The results of set-up planning is to identify the set-ups to be used for machining by integrating fixturing strategies with technological and geometric information. Operation sequencing provides information on the operations and tools to aid in the code generation. The MPCG is supported by information on raw materials, design specification and manufacturing information. This model interacts with the product data model thus enabling other applications to have access to its constituent modules. For example, the data feedback application can have access to the information on set-up and the machining process information.

The 'inspection plan and code generation' (IPCG), shown in Figure 6.5, has its main activity directed at manipulating the inspection machine, CMM. Two outputs derived from this main activity are the inspection plan and the resultant measurements of a finished

workpiece. These resultant measurements form the basis for the data feedback application. The inspection plan describes the part positions and orientations, probe configurations, fixturing requirements and all the measuring and probing operations that are required for the inspection of the part. This work is supported by information on the designed component, manufacturing information and inspection requirements.

The 'analysis and feedback of data' (MDA), which is the result of this research and shown in Figure 6.6, has its core activity directed at the provision of feedback for data correction. This activity is supported by the design specification from 'dimensions and tolerances', manufacturing information on set-up and machining process of the part from MPCG and finally on the measured component data obtained from IPCG. The integrated platform thus provides an environment in which all of the above research can coexist and be performed in parallel.

6.3 The Scope of Data Feedback in An Integrated Environment

The aim of this research work is to provide a data feedback facility within the integrated design to manufacture environment described above, see Figure 6.7. The scope of the facility extends to the analysis of manufacturing data, error reporting and error correction.

Contemporary feedback systems are directed mainly at resolving faults in specific domains within the machining environment, with no recourse to global product information. Many of these system operate for fault diagnosis and are expert-based [44, 103, 142, 201, 241, 294, 336]. The scope of this work thus not only includes the machining environment, embracing a number of domains, but also includes communication with all the intermediate functions upto design. The design to manufacture environment in this thesis is represented by a product data model which holds all information pertaining to the design and manufacture of a product.

From an integrated product data viewpoint, the challenge to achieving data feedback is five-fold. Firstly, to design a domain-independent feedback facility based on a single

source of data. Such a position is realised by the product data model which is the core of the project information support system. Very few, if any, other systems are apparent that offer such a facility in an integrated data environment. Two systems, without evidence of feedback, but worthy of mention are the Quick-Turnaround Cell [77, 78, 219] and the Alvey Design-to-Manufacture demonstrator [115].

Secondly, the challenge is to provide adequate visualisation to support user interaction and involvement. This approach is supported by the human-centred design thinking and the move towards more human involvement in computer integrated manufacture [50, 51, 66, 87, 263, 286, 287]. Visualisation in the data feedback facility must account for data presentation, data manipulation, data integration and data interaction. Visualisation has been implemented through HORSES [96,97] on a SUN Microsystems workstation using ADA [266, 337]. This permits feedback data to be displayed and viewed through menus in a window environment.

The third challenge is to provide a facility to provide explanations and correction of any deviations in the measurements of a prototype workpiece. As this research focuses upon a prototyping environment, it can be assumed that, if the machine is capable of manufacturing a quality prototype, then with the support of this facility repeatability in manufacture will ensue [211, 317]. Included in the data feedback system is also a facility for consultation of remedies for process deviations in the manufacturing cycle. This falls in with the current emphasis on process control [64, 128, 137, 325]. The data feedback system is thus intended to produce a quality prototype by upgrading the generated machine code, that is the machining and inspection code, through human-assisted verification and correction of design and manufacturing faults. This process is essentially carried out by responding to erroneous parameters in the process of manufacture of a workpiece and/or through data analysis of the inspected critical measurements of that finished workpiece. The former is performed through process analysis and the latter by dimensional analysis.

Fourthly, the data feedback system must provide for data interaction and channelling of information not only within an application, but also between applications and between an application and the user. To reiterate, as this environment is centred upon the product data model, these applications include machine plan and code generation, inspection plan and code generation and the data feedback facility itself. Currently, the system does not provide for automatic correction but includes the necessary interfaces should a need be anticipated in the future. Also, considered in the light of the literature concerned with the time lapsed in communication between a co-ordinate measuring machine and other systems [108], the data feedback facility in its integrated environment, should ease the problems encountered in communication.

Some difficulties were encountered in implementing such a novel approach. Firstly, the focus on the product data model meant that all the applications which were being developed in relative isolation now had to be data integrated. This integration with the inclusion of data feedback meant that applications now had to communicate with each other. This task was further complicated in that the environment and the applications themselves were being concurrently progressed, as they themselves were prototype applications. a further difference arose in approaches employed, for example, the approach adopted by the inspection application (developed in parallel) was geared to geometrical analysis. An approach necessary to inspect to the design intentions. The feedback application, on the other hand, had a requirement to reflect the manufacturing process capability and thus had to opt to follow the approach implemented in the machine planning application. A compromise external facility was implemented to perform transactions between the inspection and feedback applications. The role of this facility was to manipulate the inspection results to reflect the dimensions of individual features.

Finally, the requirement on the data feedback facility was to retain a level of independence in usage. Furthermore, its should be applicable to any particular process in that a generic approach to the capture and representation of data can be implemented. The challenge

to this generic product model approach is mainly in the contending technology of expert systems. Although the latter systems are perceived by industry as complex and characterised through their low level of acceptance. The facilities implemented for data feedback in the product data model include a decision network, a fault library, fault clusters, and verification checks. The structure provides a significant advantage in that data manipulation can be managed efficiently.

6.4 The Operational Data Feedback Framework

The data feedback framework is structured to achieve efficiency in data processing and in data reduction. The nature of data feedback demands a large amount of data relating to design, measurements, fault, cause, action, process parameters, set-up, machining condition, cutting tools and machining know-how to be held in a data framework. The integrated environment provides an ideal facility for structuring these data in a form appropriate to the feedback process.

The feedback process is structured into dimensional and process analysis centred upon a fault library and shown in Figure 6.8. In dimensional analysis, faults are detected as a result of any deviations in the workpiece dimensions from that expected and which may have risen within the manufacturing process or at the higher level design stage. Process analysis, on the other hand, suggests causes for errors which have occurred in the manufacturing phase but which are not dependent upon the workpiece dimensions. It advises the user on the causes and hence corrective actions to undertake to eliminate suspected errors during manufacture. The process of manufacture includes set-up and machining as part of the whole manufacturing cycle. These two analyses are presented in the following chapter.

Although, in dimensional analysis, it is possible to derive measurements from other sensory devices, only the co-ordinate measuring machine (CMM) is considered in this research. The measurements received from a CMM are compared with the expected values and if a deviation is found, the analysis will pursue its logic to conclude a fault type. The

action suggested or recommended by the model can then form the basis for user activity. This analysis is applicable to post-machining but may be applied to pre-machining to predict and correct any suspected errors.

The research offers two efficient structures namely a decision network and a taxonomic structure shown in Figures 6.9 to 6.11 respectively. The decision network represents a decision relationship between dimension(s) and fault(s). This structure allows multiple relationships between fault(s), cause(s) and action(s) to be represented. Furthermore, the clustering of faults using the taxonomic structure enables direct access to the appropriate action(s) to be effected by fault type. Verification checks are also able to be constructed in the taxonomic structure and it allows relationships between checking criteria to be clearly defined.

The fault cluster is described with reference to the fault types stored in the fault library which is also accessible to the dimensional analysis. The fault types of a particular class and of similar characteristics are grouped into clusters to assist the user in rapidly selecting the type of fault he may wish to rectify during manufacture. The verification checks are designed such that the user can identify a fault without pursuing manufacture to completion. Attached to each check are task-oriented criteria and a list of verification procedures where the procedures implicitly embody a fault type arrived automatically once the user defines the initial criteria.

The organisation of data in the data feedback system anticipates short range support to a machine operator enabling him to rapidly reach a conclusion, decide on the next procedure or to access the wider information base. The structure also provides for longer range support to the designer in that error(s) in a finished workpiece are reported back to the appropriate application. The research data structure is described in Chapter 8 whereas the building and use of each data feedback facility is described in Chapter 9.

6.5 The User Interface

The product data model (PDM) is created by a Product Data Editor in which a Structure Editor is the main driver. The Structure Editor, developed within the project and described in Appendix II, is used as the main software tool for creating and editing data for the project. The design of the editor is based on the graphical representation of the data using HORSES [96, 97]. The latter is a user management interface system used for browsing of the data model and for the interactive creation and editing of the product data model definitions. The product data model also allows the description of features and geometry, dimensions and tolerances, manufacture of component, inspection of component and feedback data.

The interfaces of the application is written in ADA programming language on the SUN workstations. The visualisation and the facilities provided by the data feedback system are explained in Chapter 10 and illustrated in Appendix II.

6.6 Related Work

It is noted that other research programmes with similar broad objectives are in existence in academic establishments and in the industrial environment. Programmes are found at Brunel University, Minnesota University in joint collaboration with the Software and Electronics Resource Centre and the Valisys Corporation.

The research in the Brunel programme is aimed at investigating an intelligent interface between CAD and CMM system [1a, 35]. The interface establishes a two-way link: checking a physical component against a definitive CAD model and uses a physical component as a means for creating CAD geometry. The system is able to interpret CMM data in terms of higher level geometry rather than points. The information could then be converted to measurement procedures for the CMM. Also, the system is planned to have the ability to update the measurement strategies and to suggest remedies in the manufacturing operations based on results obtained from production.

The second research project is the development of KLUE, a diagnostic expert system tool for manufacturing [163]. KLUE was developed in response to a number of observed problems in using expert systems. These problems are program control and connectivity of the rule base and the requirement of expert maintenance of the rule base. KLUE is a diagnostic expert system tool that addresses these problems by representing the knowledge in the form of decision graphs. Other functions included are: both the program control and the diagnostic strategy are explicitly represented and; domain information is added or modified by direct operation on the decision graph.

The programme in FMC is directed at producing a software package, Valisys [81, 217]. This package uses the CAD model and tolerance standards specified by the part designer to create a 'soft-gauge' an electronic model of the worse fitting part for a particular feature. This is then compared with an electronic model of the actual part measured on the CMM to determine any deviations. Valisys also has the capability to generate inspection paths automatically from the part model taking tolerances into consideration. Finally, there is no need to build custom fixture for part as Valisys is able to orient itself on the actual part.

6.7 The Competitive Status of the Research Work

The two pieces of work, Brunel and KLUE, and the research work reported in this thesis encompass two approaches, that is the use of expert systems and product modelling. The use of an expert system by Brunel and KLUE were possible because the research was targeted and aimed at a particular domain. The data feedback system in contrast is a sub-project of the total information support system, described in Appendix II. It had previously been decided to embark on product model based approach implemented in ADA. This somewhat narrowed the possibility for using technologies other than this high level language supported by the powerful structure editor.

The Brunel system set out with the same objectives of linking CAD and CAM as did this research work. This view is formed on the basis of what is gathered from their literature.

The Valisys system is a convenient intermediate software tool which enhances the use of limited data processing from the CMM. It can be viewed as complementary to both the Brunel and the data feedback system in interpreting the CMM data, shown in Figure 6.12.

This research work can be perceived to have a three-fold advantage over the Brunel approach. Firstly, it is set within a product model thus not only permitting a bridge between CAD (design) and CAI (inspection and CMM) results but also allowing access to CAM (machine planning). Secondly, this research task enables a generic approach towards representation of manufacturing knowledge about any product. This implies that the data feedback system can be used either as a stand-alone domain-oriented module or in the context of greater product knowledge in an information support system. Finally, the data feedback system is geared up to react to any fault, cause and action relationships and to consult the product model.

The KLUE system is domain based with its only direct relevance being, as far as one can deduce from the literature, being in the use of decision graph. This approach could be in contention with that employed in the data feedback system. A drawback of KLUE over the data feedback system is that KLUE reacts to a constrained manufacturing problem domain without apparent access to other applications.

Chapter 7 :

Achievement of Product Design Objectives in a Prototyping Environment

7.1 Introduction

In a contemporary manufacturing environment, a product graduates from being a successful prototype to full batch production. Success at the prototyping phase is measured against the product's fulfilment of its intended design. The research work focuses on this prototype phase of the product life cycle. It is intended to provide support such that a quality prototype will emerge from this first phase of the life cycle. Two tasks have been identified to realise the design objectives. Firstly, to ensure through dimensional analysis, the products dimensional accuracy and secondly, through process analysis, the process integrity. These tasks and their procedure and configuration are discussed in this chapter.

7.2 The Tasks in Achieving a Quality Prototype

In a total quality organisation, there is a fundamental requirement to design and ensure quality at the prototyping phase before the prototype can proceed to production. To achieve a quality prototype, two important concepts usually found in batch or mature product manufacture have to be considered. The concept of product control has been the main focus in many manufacturing organisations. Recent research, though it acknowledges product control, suggests that the emphasis should be shifted towards controlling the process which then in itself will prevent defects from occurring rather than taking action after a defect has been detected [137, 325].

In a prototyping environment, unlike batch production, the focus is mainly on a single or a set of 'first-off' products. This far narrower focus enables a wider base of measurements to be controlled. Thus, unlike a batch environment where volume necessitates statistical control to limited critical parameters, prototyping enables the scope of investigation of assignable causes to be more thoroughly investigated. This in-depth investigation is usually

very human-intensive and requires a great deal of localised expertise, time and cost. The challenge in this research has been to provide a data feedback decision support system in an integrated design to manufacture environment. Very little data feedback research is evident in the literature in the prototyping environment area and practically none is product model supported. This computer-assisted feedback, assessed through an industrial case study, leads to increased operator productivity in this prototyping phase.

The data feedback system is provided in the form of recall facilities for providing expert knowledge, a maintainance facility for increasing knowledge and finally edit facilities for updating knowledge. Experience in the industrial case study has proved the relevance of providing such a facility in a prototyping environment. This is crucial in ensuring repeatability in manufacture. The provision of a bank of ready data for the non-expert is crucial in proving a robust part program.

The data feedback system is aimed at making effective use of embedded expertise to produce a prototype to its specification. It is also aimed at maintaining the quality of the mature product in production. The system is generic in approach to the capture of machinist, designer and machine planner expertise. This leads to a system that can interact easily with other applications in the information support system environment.

The data feedback process provides for dimensional control of the prototype as well as control of the manufacturing process through the provision of process analysis. The data feedback process channels information between manufacturing, inspection and design. This closed loop is based on a single set of structured data, that is, the product data model. Within the framework of this information support system, quality may be ensured at every level through the implementation of the decision network for dimensional control and the clustering of faults and provision of verification checks for process control. This total quality cover is

provided through the implementation of data feedback and is significantly enhanced by access to an integrated product modelling environment. All of which makes for a powerful data feedback facility.

7.3 Dimensional Assurance in the Prototype Life Cycle

Dimensional analysis is used to explain and conclude any deviations in the dimensions of a finished workpiece. These dimensions are compared with those specified in the respective workpieces' 'dimensions and tolerances. Measuring the dimensions of the part during the machining process is the optimum approach to assuring dimensional integrity. However, the dimensional data will usually include machine errors and consequently lengthen the machine operation cycle. These parts are therefore most practically measured remote from the machine, usually on a co-ordinate measuring machine.

In applying dimensional analysis to a workpiece, it is usually a matter of selecting an appropriate technique rather than writing off one technique against another. The bottom line is to improve quality and productivity on the shop floor and thus inspection need to be as close to the process as possible to provide real time feedback, or near real time data for prompt correction of adverse conditions. The objective of dimensional analysis is to confirm design requirements or offer a solution for those deviations so as to prevent them from recurring.

Dimensional analysis can be applied in either a prototype or in a batch production environment. Prototype manufacture is essentially a tape-proving exercise verifying the information contained in the part program. It is at this stage that any amendments to the part program are made either by the machine operator at the shop level through the machine controller console or fed back via production engineering department to the part programming facility.

A number of factors affecting the analysis process need to be considered. The first set of factors decide the important features that have to be assessed. These features are the

dimensional errors, errors of form, tool wear, material integrity etc. The second set decides the methods of control such as dimension, shape, position or surface finish. The third determines the methods of measurement such as contact, non-contact, absolute measurement, sampling control and automatic gauging. Other factors such as critical temperature, effect of clamping, effect of machine forces, tool wear, machine vibration and cutting liquids are also considered.

The results of the analysis may require that the part program be altered and this will often relate to the machine tools, types of cutting tools, tool offsets, feeds, speeds, datum setting, NC code, drawing and fixture design. Design and fixtures changes are essential for the prototype phase but not usually valid for first-off of batch production. The proving of tape is typically verified by inspection of the first workpiece or by operator observation of adverse machining conditions. Dimensional analysis is thus a critical aid in assisting the operator to dimensionally control the workpiece at this machine level and, if necessary, report to the design level.

First-off manufacture is usually the production of the first component during the production stage after the completion of the prototyping phase. Amendments made at this phase usually involve changes in tool offsets, datum setting, feed and speed. The application of prototyping and first-off varies with the company policy. In a 'batch of one', or small batch manufacture, the first-off is also the prototype of the component.

Manufacture in a batch production environment usually follows successful completion of the prototype phase. The batch sizes usually involved in this environment make application of statistical control techniques feasible. Use of statistical quality control techniques such as the familiar Shewhart average and range charts, cusum, trend analysis and correlation find favour in this environment. Dimensional analysis can also be applied in this area by offering explanations for out-of-tolerance workpieces detected from use of these statistical techniques. The application of dimensional analysis in this case will not differ significantly from its

application in the prototyping phase. It is often not economically feasible in a batch production environment to fully inspect a workpiece at the machine. It would in some cases be beneficial to transport an offending workpiece to a co-ordinate measuring machine for a more thorough and accurate investigation. This research work has considered the applicability of dimensional analysis to this environment but deemed it more advantageous to pursue with a prototyping environment.

7.3.1 Workpiece Representation

Dimensional representation of the workpiece is an essential element of dimensional analysis. This representation must include the dimensions and the relationship or influences between these dimensions such as squareness, perpendicularity and flatness. The dimensional analysis focuses on the critical dimensions and intentionally excludes the non-critical dimensions. Critical dimensions are those that affect the functionality and/or aesthetics of the workpiece. The workpiece may be represented either through geometric modelling or feature-based modelling.

Contemporary geometric modellers, whilst good for representing the details of a particular solid object, cannot be integrated with computer-aided manufacture because of an incomplete database which does not contain information such as dimensional tolerances, surface and material attributes. Furthermore, the data is at a very low level of abstraction which is not meaningful to manufacturing [278,279]. There is a need for representing possibly higher level spatial entities, called features, for the CAM programs. CAD/CAM users desire product models which contain not only geometry but also functional and manufacturing data [184].

Dimensional analysis employs a feature-based approach. The three main benefits of this approach, borne out by the industrial case study, are that: the design intent can be better expressed by manipulating features directly, eliminating tedious intermediate steps; Secondly, feature databases allow reasoning systems to perform tasks such as heuristic

optimising and manufacturing analysis and; finally, features can contain knowledge to facilitate NC programming, machine planning, inspection planning and in this research, feedback data. Ideally, if all the features generated in production are inspected as soon as they are machined and the results processed to given management criteria, degenerative quality phenomena can be immediately identified before defective parts are actually turned into products.

Feature-based workpiece representation falls under two distinct groupings: the dimensions of an individual feature, and the dimensions between features. The method of expressing the critical dimensions and the relationships between these dimensions requires some form of directed graph. The technique employed in this research for expression of such relationships is based on the use of an Influence Diagram as a decision support aid. The Influence Diagram is translated in the prototype software to a Decision Network and is discussed in Chapter 9. These representations have led to 'If-Then' rules being drawn out of the branches of the Influence Diagram (analogous to a ruled-based approach). The antecedent or 'if' part of the rule being formed in the direction of the link between the circular intersection nodes and the consequent or 'then' part of the rule being the decision rectangle at the terminus of the network or sub-network. In some cases these terminal blocks may form the antecedent of a further sub-network leading to chaining.

The critical design dimensions represented in the decision network are compared with the dimensions of the finished component. The dimensions of the finished component are stored in a measurement graph and the explanation of any deviations in dimensions, are stored in a historical analysis data library (Chapter 8). This analysis is similarly applied to analyse the dimensions between features, but differs in the sense that each feature and its critical dimensions are compressed into one node in the Influence Diagram as opposed to previously being expressed as a whole sub-network. Whereas previously the relationship between critical dimensions of one feature was expressed in its own right in a sub-network, we are now at a level where the critical dimensions of one feature are expressed in relation

to the critical dimensions of another feature. For example, the dimension of one face of a feature is expressed in relation to the face of another feature. This logic is also applicable to expressing the relationship between features in a subjective visual mode as opposed to an objective measured comparison. For example, each circular node in the influence diagram may now represent feature type and each square or decision node the subjective result.

7.3.2 The Research Approach to Dimensional Analysis

The dimensional analysis system is classified in levels under the following: data classification, decision making structure, data analysis and supporting module, the fault library.

7.3.2.1 Data Classification

Control limits, based on statistical process control principles, are derived and modified from the available design dimensions and tolerances for classifying the measurements. The control limits, shown in Figure 7.1, are classified as 'Upper Action', 'Lower Action' and 'Satisfactory'. Above or below the action limits are classed as macro errors and these require immediate attention by analysis and diagnosis. These two banded areas are used explicitly in the prototype environment and are focused on in the dimensional analysis. The satisfactory band, lies within the action limits, and has results deemed acceptable and requires no further action. The warning limits are not considered necessary in this research. The equations required to derived the macro error band are shown below:

The four types of tolerance considered are plus/minus, minus/plus and maximum/minimum and limit dimensions:

Under plus/minus (+/-) tolerance:

If $D_A > D_{ND} + t_+$ Then State = UA

If $D_A < D_{ND} - t_-$ Then State = LA

If $D_A =< D_{ND} + t_+$ or $D_A >= D_{ND} - t_-$ Then State = S

Under minus/plus (-/+) tolerance:

If $D_A < D_{ND} - t_-$ Then State = LA

If $D_A > D_{ND} + t_+$ Then State = UA

If $D_A =< D_{ND} + t_+$ or $D_A >= D_{ND} - t_-$ Then State = S

Under maximum/minimum (max/min) tolerance:

If $D_A > D_{ND} + t_{max}$ Then State = UA

If $D_A < D_{ND} + t_{min}$ Then State = LA

If $D_A =< D_{ND} + t_{max}$ or $D_A >= D_{ND} + t_{min}$ Then State = S

Under limit (l) dimensions:

If $D_A > l_{max}$ Then State = UA

If $D_A < l_{min}$ Then State = LA

If $D_A =< l_{max}$ or $D_A >= l_{min}$ Then State = S

where:

D_A = the actual measurement

D_{ND} = the nominal dimension

t = the tolerance

UA = Upper Action/Upper Fault

LA = Lower Action/Lower Fault

S = Satisfactory

The tolerances can either be the design tolerance or the process tolerance. The design tolerance is decided by the designer and determines the functionality of the

workpiece. The process tolerance is usually less than the design tolerance and determines whether the process is capable of manufacturing to the design requirement. The use of either of the tolerances is decided by the requirements of the workpiece and the degree of control required during manufacture.

7.3.2.2 The Decision Making Structure

The decision making structure selects the hypothesis or goal to investigate depending upon the results arrived at in the data classification level. Two sub levels provided are the relational and the decision levels.

A. The Relational Level

At this level, the design dimensions comprise of three factors: state, decision and goal. The state represents the result. The decision represents the interrelationship between the dimension within the feature and the goal represents the possible fault. The relationship between these factors are pre-defined by the designer using manufacturing knowledge. An example to illustrate this relationship is to take that of a pocket of a workpiece, shown in Figure 7.2.

The pocket is made up of length (L), width (W) and radius (R). A possible relationship (rule) from a branch of the influence diagram network, shown in Figure 7.3 and 7.4 may be:

L(UA) + W (LA) + R (S) -----> result of deviation

Each component of the left hand side of the equation is a state. The right hand side is the goal achieved from the left hand side of the equation, the decision. This is analogous to:

IF (antecedent [condition]) THEN (consequent [goal])

A network of these rules are represented within a decision network in the prototype software.

B. The Decision Level

The dimensional analysis system can be viewed as a four level structure. The lowest level (Level 1) identifies the product type; Level 2 identifies the assemblies level; Level 3 identifies the component type; and Level 4 identifies the features within the component. The decision network and measurement graph for an individual feature is stored at Level 4. The subjective approach for relationship between features and the decision network for the relationship between features is stored at Level 3. A detailed description of these levels is given in Chapter 8.

7.3.2.3 The Data Analysis Level

The analysis and interpretation of the outcome of the dimensions of the finished workpiece are performed at this level. These dimensions are analysed and classified into the appropriate bands for each feature using the data classification technique described above. The analysed data are then compared with the rules contained in the decision network. This analysis results in the identification of fault(s), the cause(s) of such a fault and the possible remedy to be taken via the user.

7.4 Process Error Prevention in the Product Life Cycle

Process Analysis is used to explain and conclude any process problems that occurred during the machining cycle, that is, it can be viewed as the progression from raw data about a process to conclusions or interpretation about process problems. With complex prismatic parts machined on a machining centre, error correction is very complex because the reason for the error is usually not known. For example, if the error is caused by tool wear, there might be one correction. On the other hand, if there are set-up or fixturing errors, there would be other corrections. If there is a machine positioning error, it might require a third approach.

Process analysis is applicable to both the prototyping and the batch production environments. The difference between these two environments lies in the corrective actions required. In prototyping, the corrective actions are related to the design and manufacture applications. The aim is to achieve the design specification so that the product can then continue its life in production. In batch production, the aim is to sustain the design specification so that only good quality product are generated. The process in both environments embodies set-up, machining and inspection.

In the set-up phase, the specification, set-up of fixture, set-up of workpiece and tool must be verified before machining may commence. The machinist begins by loading and unloading the workpieces prompted by the process planning system. This involves the positioning of the work with respect to the fixture, the positioning of the fixture on the machine table, and ensuring that the position of the clamps do not obstruct the workpiece and tools.

The verification of the part program and the selection and set-up of the proper tools are guided by the part program. The set-up of tools includes tool pre-setting for correct tool offsets, putting the right offsets in the controller and putting the right tools in the correct magazine pocket. Selecting feed and speed to minimise time without affecting the surface finish and avoiding tool chatter. In addition, pre-requisites such as use of the correct raw material and fixture must be satisfied. The flow of coolant is also ensured to provide lubrication at the tool-workpiece interface and to remove heat generated. Process analysis in this phase ensures that the specification is met, and that efficient part and tool set-up is possible through the monitoring of process parameters.

The machining operation consists of phantom pass, rough cut and the finish cut process, see Figure 2.5. The control and monitoring of these passes are critical and varied. The machinist is alert to all phases of the operation. The two senses used are visual and auditory monitoring. Although visual information is important in the set-up phase, a combination of intense visual and aural information is used by the machinist during real-time machining,

see Figures 2.6 and 2.7. The sound produced by the machine itself and by the actual cutting process is a key to the machinist for evaluating that process. Various noises may provoke concern in the novice but only the machinist is able to determine if a problem actually exists and then to assess, diagnose and remedy it.

The colour, size, shape and condition of the chip, and the condition of the tool are other clues to the efficiency of the machining process. Interpretation of these clues by the machinist may lead to adjustments in speed, feed, tool type and/or tool support. In addition machinists tend to maintain physical contact with their machines during operations. For example, their hands rest easily on tailstock, machine support or other area. Sometimes their fingers lightly brush the workpiece. This perception of vibrations associated with the machine itself and with the cutting process lead to they drawing conclusions about the status of the machining process. The machinists thus literally 'feels' how the job is progressing [103].

The machinist is a bank of machining knowledge but yet very little of this knowledge and experience is formally recorded. This leads one to conclude that the problem may lie in the ability to extract the journeyman expertise. Process analysis captures the knowledge of these machinists to provide a system that can assist the novice as well as the machinists in solving problems occurring during the machining process. It attempts to assist the operator at the machine level to control these problems by providing compact solutions and the reasons for such occurrences backed up by access to product data model.

7.5 The Research Approach to Process Error Prevention

Process analysis assists the machinist by providing him with access to a wider based information support system and maintaining a record of the previous decisions so that the same information can be accessed by other machinists who encountered the same problem.

There are basically three methods of initiating action when a problem arises in a process. These methods are essentially human-centred. In the first, action is initiated if the machinist

thinks that the process has deviate. In the second, the machinist takes action only if he envisages that the process is moving out of control. Finally, he may be warned of impending deviations or prompts to initiate corrective action. The system is designed to cope with these situations.

Process analysis is designed to operate in the set-up and machining phase of the machining cycle. The inspection phase has been described within dimensional analysis. The two phases are set within a prototyping or a production phase. In a prototyping environment, the concern is in getting a good first product. Process analysis assists in the production phase in maintaining good products over a sustained period of time. With the current move towards human-centred engineering, process analysis is designed with this view in mind. As previously discussed in Chapter 2 and 5, there is a lack of adequate means of transferring the machinist's knowledge to the expert system. Also, with a technology-centred approach, the knowledge is not necessarily represented in a logical manner to assist the machinist. This thus inhibits the design of a complete design to manufacture system which has access to a wider information about the product, manufacturing and inspection.

The research seeks to provide data feedback supported by the product modelling environment. The product model in this environment holds a complete set of information relating to the product design, manufacture and inspection as well as the feedback data. In contrast, an expert system holds localised information to support a specific domain of the machining process.

The process analysis system is configured to include several forms of usage. The first use provides for verification of a fault. The two instances that prompt the machinist to utilise this facility are: firstly, he suspects or predicts that a fault is about to occur and; secondly, he wants to enquire to confirm the existence of a fault in which he has no substantial knowledge. This system hence provides a check-list type procedure to be followed in order to arrive at the fault type with its cause(s) and the necessary action(s).

The second use allows a fault to be accessed directly by the machinist. This is utilised in either of four ways: firstly, to cater for an experienced machinist who is consciously aware of the fault type but not experienced enough to know what action has to be initiated or what decision path has to be taken to remedy the fault; secondly, to assist the machinist in confirming his diagnosis and; finally to make available the knowledge or experience of several machinists locally.

In the third use of the facility, the fault group with all the related faults is identified. For example, the machinist is aware that a particular fault is related to tool, he can then examine this group, shown in Figure 7.5 and 7.6, visually by scanning the list of faults. A guess can be made or he can run a verification procedure to confirm the fault.

The facility also caters for making specific changes. For example, if the machinist knows that the speed and feed require to be changed, he then has access to other applications within the product model, such as machine planning, in order to gain an insight into what has been planned and recommended before he can exercise his own experience to make the changes. Alternatively, he could recommend the change to be implemented in the appropriate application. The user is also allowed to seek for more information regarding the product. The user can access other parts of the product model or other applications. The system also provides for adding, retrieving, updating and recording of the fault's information. Action taken by the machinist at the machine level can then be reported to the appropriate application for correction to be initiated at the design level so as to prevent the fault from recurring.

Finally, the process analysis caters for special applications where the user may chose to ignore the system and wish to create a new check-list to suit his manufacturing purpose. The system defines a skeletal structure where the user can construct a data feedback system based on his own knowledge domain. The data structure which supports this analysis is described in Chapter 8.

Chapter 8 :

Structured Data Modelling for Data Feedback

8.1 Introduction

This chapter presents a structural view of the data feedback system within the context of the integrated design and manufacture environment. This environment provides an ideal facility for structuring, storing and manipulating data in a form appropriate to data feedback. The functionality and the data model of the data feedback system is presented against a backcloth of other contending data structures. Two main data structures highlighted in the product data model are namely a decision network and a taxonomic structure. These structures provide the framework to support the dimensional and process analysis. The use of each structure is detailed in Chapter 9.

8.2 Prerequisites for Data Model Specification

The main task involves the provision of data structure for the feedback system in order to store, manipulate and manage data efficiently. The prerequisites for the data structure are firstly to express the data in an ordered manner to reflect the human decision making process [146]. Secondly, the data itself must be able to be retrieved, then transformed and processed [94] to accommodate the dimensional and process analysis, and finally to transact data between applications. All of these needs must be accommodated with minimal duplication of data from a single source, that is the data structure of the feedback system must be an integral module under the umbrella of the product data model [206].

Some competing technologies available and to a large extent being employed by other researchers have focussed on the application of artificial intelligence and or the development of knowledge-based systems [290]. A vast literature base in Chapter 2 typically supports the

application of this technology to diagnosis. Some authors have also adopted a database approach [45, 174]. This latter approach is mainly centred on some form of relational data structure.

The research work has examined each of these approaches. In the first instance, a knowledge based system approach was pursued by developing an 'expert system' in a conventional program to store rules in an ordered rule base. Several problems arose not the least of which was data integration with the product data model. A relational database was not considered a viable proposition for reasons elaborated below. Finally, the choice was narrowed down to the product data model. This was by far the most complex to grasp. Once one gets familiarised with the 'look and feel' of the data model and the powerful facilities provided, it was discovered that it outclassed the others. Thus, the data model was the ideal candidate although at first it is an awesome task to comprehend such a massive structure. During the course of the project, it become more and more apparent that this was the data model to pursue.

The definition of the product data model is based on a semantic modelling entity-attribute approach [281, 282]. A semantic model is used because it allows the application program to model the data in a manner close to the human perception of the respective application. The entity-attribute approach permits a natural graph-based representation consisting of types, and relationships interconnecting these types. The product data model had three facilities directly relevant to data feedback. Firstly, it possessed all the capabilities expected of a database. Secondly, it had the ability to organise data hierarchically as well as logically. Finally, the software was able to generate dummy interfaces in ADA code. The latter facility enabled many applications to be generated relatively easily.

The data structure of the feedback system is essentially represented by a decision network, measurement graph, historical analysis data and the associative and taxonomic structures. The taxonomic structure organises feedback information on fault, cause and action

relationships stored in the associative structure. Both structures actively serve the decision network. The decision network which stores information on deviations is used for comparing the measurements stored in the measurement graph. The results of the comparison are stored in the historical analysis data. Each of these can exist in any or all of the four levels of the product data model. These four levels are product, assembly, component and feature. Each collective structure is specific to each level and provides for data storage, manipulation and hence feedback between applications in the integrated design and manufacture environment.

8.3 Feedback in an Integrated Data Model

The main focus in this research is on the product data model and in communicating between the various applications. A product may be described by either an assembly or a component. An assembly may consist of one or more components or as an integrated assembly. Each component in turn can be described either geometrically or through a feature description. In geometric terms, the component can be represented by its solid, surface, curve or points. Through features, the component can be represented by the features and or the interrelationship between these features. The product data model shown in Figure 8.1, consists essentially of four main levels: product, assembly, component and feature. A data structure pattern consisting of entity name, entity definition attributes and entity actual attributes, is repeated at each level but the data stored within each pattern will vary.

In the repeated pattern, shown in Figure 8.2, each entity is identified by its name and comments. Furthermore, at a level beneath this, the structure holds the data entity, its specification and its actuals. This data entity could either represent a product, component, assembly or feature. Moreover, the entity definition itself also consists of name, attributes and comments. The data entity, data about data, includes the part number, the version information and references, if any. This entity specification consists of a list of requirements which the actual entity must satisfy. A second repeated pattern holds the definition attributes data structure. This is the same for all product, assembly, component and feature entities but differs in its information content.

At the component level, the definition attributes are made up of a description, a relationship graph, planned processes, a decision network and finite element analysis. The description of the component along with its dimensions and tolerances are presented in the description and the relationship graph. The method of manufacturing a complete component is given in the planned processes. Finite element analysis is also present at this level. At the feature level, the information that relates to each feature is its description, dimensioning, its manufacturing data and the approach directions identified for its inspection.

The root of the framework consists of a product range, an associative and a taxonomic structure as well as the manufacturing information. The product range data structure is the node that leads to the first repeated pattern structure. The associative data structure exists as a common base for all relevant information identified as a parametric function. The taxonomic structure is a formalised structure for organising related data. The manufacturing information includes manufacturing rules, company-specific data, manufacturing methods for process planning and a decision network to assist in the planning processes.

8.4 The Data Characteristics Set of the Data Feedback System

It is essential to understand the data characteristics when designing and constructing data structures for the feedback system. The data characteristics in semantic modelling which have relevance to the feedback structure are unstructured objects; relationships; abstractions such as classification, generalisation, aggregation and association; networks or hierarchies; derivation/inheritance; insertion/deletion/modification constraints; degree of expression of relationship semantics and dynamic modelling [233, 281, 282]. The data feedback employs the structure editor for defining, storing and managing this data. This goes further than its contemporaries to include sharing and parameterization.

The entities utilised in this research are atoms, number atoms, name atoms and string atoms which are also referred to as unstructured objects. Atoms are at the end of each branch of the data structure and can either be a number, a name or a string or null (nil atom). Number

atoms are real or integer numbers whereas name atoms are character strings of up to 16 characters. String atoms are character strings of any length and null atoms are character strings which do not have a value and are displayed to the user.

A relationship can be loosely defined as a link between two objects. The feedback system uses names to indicate this relationship and to serve as labels when navigating the structure. In the abstractions grouping, the entities use 'list', 'collection' or 'selection'. The first two correspond closely to association and aggregation. A 'List' can contain zero or more elements but each element must be of the same type whereas a 'Collection' contains a fixed numbers of elements which can be of different types. 'Selections' are choices from one of the members of elements. Each element is defined as a 'named-node' consisting of a name atom and a structural element from either of a list, collection or selection. The name atom in this instance is a means of classification or naming a type. The 'selection' capability follows generalisation, the last concept in the abstractions, to recognize the commonality between types and this creates a general type into which all candidate types can be entered.

One of the most important properties of the feedback system is the recursive or cyclical nature of the network. This is used in the definition of the data structure at each level of the product data model, and also for extensively defining the rules in the decision network. Derivation is used to obtain those attributes through computation whereas inheritance can mimic through sharing, a unique feature of the system. Sharing in this context refers to the same data being used at multiple points throughout the structure. Other data characteristics include the ability to maintain the validity of the data through the addition of constraints and then by allowing data to be added or modified within the structure. A further important data characteristic is parameterization achieved by a form of lambda calculus [196]. This enables the definition of functions and the return of structures, associated with that function, when invoked at an appropriate point in the structure. This latter ability is of importance in the

development of standard features associated with feedback data and manufacturing instructions and in the definition of fault types. Sharing is also used in the definition of the functions.

8.5 Data Structures Pertinent to the Feedback System

The design of the data feedback system is characterised by the decision network and the taxonomic structure. As is apparent from Figure 8.2 and Appendix II, the decision network is present at every level in the product data model. This reflects the data and process requirements at that particular level. Thus if feedback is to be provided, the system has access to all relevant information pertaining either to the feature, component, assembly or product. Secondly, and by far the most important, the data although inserted at each level is not duplicated at any other level as the feedback data structure transparently holds the common data at a point in the structure accessible by all applications.

At the feature entity level, feature, the decision network provides information relating to any deviations in the dimensions of a manufactured feature. At the component level, the decision network provides information relating to any deviations in the interrelationship between the features. The two types of deviations considered are dimensional and geometrical. The dimensional deviations are the distances between the feature such as length. The geometrical deviations between the features include parallelism, perpendicularity, squareness and concentricity, amongst others.

The decision network for features is implemented in this research, although decision networks are also provided at the component, assembly and product levels. The information provided at these two levels are related to the placing of one component with respect to another in the former and with respect to functionality in the latter. At the root level, the decision network provides a birds eye view of manufacture.

The decision network represents the fault finding decision process that has to be followed when relating a dimension to a state, deciding on what that state ought to be and then relating the state to a fault and cause. The decision network, shown in Figure 8.3, is thus a data structure representing the rules and knowledge used for the dimensional analysis system discussed in Chapter 7. It consists of one or more lists of dimension-state pairs, known also as a 'd-state'. Each d-state consists of the dimension, its state and a decision-node. The dimension in the decision network at the component and feature level is shared by the same dimension used in the relationship graph and description. The state is a choice from upper action, satisfactory or lower action (discussed in Chapter 7). The decision-node is a selection from either a d-state or a fault. The d-state is re-selected for each further dimension with the structure repeating itself. When all the dimension(s) have been considered, a fault will then be identified. The fault itself, a separate structure, reflects the deviations of the dimensions. Once again, if more than one fault is in existence, the next fault is identified by the previous fault structure. Like the d-state, the decision-nodes is a list of decision-node giving access to a number of faults or a d-state. The latter d-state than itself is a collection of dimension, state and decision-nodes, that is the structure up to this point may easily be re-accessed.

Some form of representation has to be realised for storing and describing the fault type. The fault data structure, is shown in Figure 8.4. is used for this purpose. It consists of fault description describing the type of fault and a list of causes which describes the occurrence of the fault. The number of causes ranges from one to many. Each cause is described by one or more cause descriptions and the action required to remedy this cause. A probability factor (weighting) is also given to determine the likely occurrence of that cause. Like the cause, the action can be singular or numerous. The fault data structure is stored as a parametric function at the association list located at the top level in the structure to service all the decision networks at other levels. Like the decision network, the causes structure is once more a list of causes where each action in this cause collection is in turn a list of action.

The measurement graph was implemented to store measurements observed from inspection. The Measurement Graph is a data structure, shown in Figure 8.5, representing the dimensions of a finished workpiece. The Measurement graph is a list of dimension-measurement pairs. The dimension is the same as that used in the decision network. This is achieved through sharing, pointing to the same design data, allowing the same value to be used. The measurement is the dimension of the finished workpiece obtained from inspection. The measurement in this case is defined as real 'number atom'. As with the decision network, the measurement graph is also created for each feature and arranged and stored in a similar manner.

Historical Analysis data is implemented to store results of analysis for further reference. The historical analysis data, held at the component level's 'actuals' entity, has the same data structure as the fault. Results of the current dimensional analysis of a particular component serve as the input to the structure. The results are provided as 'history' and can be retrieved at a later stage during the machining cycle for reference.

There was a need to organise data by similar characteristics. One such example is the fault structure. Since the fault is not related to a specific domain but to a rule, there is a requirement for aggregating these faults and to put it in a special part of the structure, that is the taxonomic structure. The taxonomic structure is used to organise similar faults into a cluster and grouping verification checks procedures for specific verification check. It is stored at the top level to service mainly process analysis but will just as well serve the decision network. The taxonomic structure is shown in Figure 8.6. A taxonomy is a 'collection' of menu heading and menu members. The menu members are a 'list' of named members which themselves are a collection of a name and a member. The member is a selection of a name-value association or a member. The structure terminates with the selection of the former and continues with the selection of the latter.

8.6 Providing for Data Feedback in the Structure

The data feedback loop aims to channel data between manufacturing, inspection and design. The data and information of all these applications including the data for feedback are stored in the product data model. This provides for a consistent set of data throughout the life cycle of the product, that is the data is shared amongst all the applications. The feedback loop is able to provide for three modes of operation: Firstly, it provides for reporting; secondly, it provides for consultation and thirdly, it provides for error correction.

The reporting facility is positioned at the component level. For dimensional analysis, this facility holds information on the measured dimensions, related fault(s), cause(s) and action(s). For process analysis, this facility is positioned at the fault node of either the decision network or the historical analysis data structure also at the component level. This reporting facility provides sufficient information to guide the user in reaching a decision as to what possible action he is required to initiate.

The consultation facility is provided within the structure and directs the user to an area of interest within an application usually pin-pointed by the information contained within the reporting facility output. This facility also provides for that user who wishes to consult, irrespective of the reporting facility, the wider information support system. For example, the action in the reporting facility may suggest verifying feed and speed, information contained in the planned processes structure of the machine planning, sited at the feature level. In the first use of the consultation facility, the user may then walk to his area of interest in the planned processes structure to verify the actual feed and speed against that recommended. In the second use of the facility, the user may pursue his interest further along the structure to verify or confirm his diagnosis.

A third facility is provided for error correction. Errors may be corrected at the machine level by the user but only reported back to the design application or other relevant part of the structure. The advantage of reporting enables other applications to consider the feasibility of their outputs and thus take preventative actions.

A map has to be provided to assist the user to walk through the structure to the appropriate area of applications. This map calls for channels to be constructed for efficient retrieval of data. Currently, all data input is performed manually whereas software is provided for retrieving of data. The feedback facility has been applied to an industrial prototyping environment for error correction. This facility provided a powerful integrating environment in that all data in the product data model was available to a user of any application. This thus allows a user to make the best informed judgement on any errors he may encounter to ensure a quality prototype. Whereas in the past, one would have to retrieve data from many sources, perhaps disjointly. Now through this integrated environment, one has available or is able to make available all possible data for design, manufacture, inspection and back to design.

Chapter 9 :

Organisation and Management of Data

9.1 Introduction

This chapter describes how data is organised and applied for effective feedback. The product data model structure, described in chapter 8, provides the vehicle for data feedback and facilitates the channelling of data between applications. The provision of data feedback requires four main structural components: a fault library, a decision network, a measurement graph and a taxonomic structure. Attention is given in this chapter to the use of each of these components for data feedback in the integrated design to manufacture environment.

9.2 The Requirements for Data Organisation and Management

The requirements for data organisation are many and varied. Firstly, the data must follow a decision path that mimics as closely as possible the human decision making process [146]. Secondly, the data presented to the user must be such that the user is comfortable with the system [124]. Thirdly, the system must provide expert guidance such that confidence is instilled in the reasoning process. Finally, a generic approach must be implemented to capture the machinist knowledge and represent this data in a form suitable to a users situation. This procedure is reflected in the case study discussion in Chapters 12 to 14. All traditional facilities such as data logging, analysis of data and historical capabilities must also be taken into account [36]. The data must be organised such that the user can have direct access to any relevant information he so wishes to consult [70]. This is particularly important in the prototyping environment. The demand on data for provision of data feedback within an integrated design and manufacture environment requires the data to fulfil these requirements.

The data required to build the data feedback system for set-up, machining and first one-off inspection are organised into three categories, shown in Figure 9.1. These categories

are the design specification, fault verification and fault information. The design specification holds the dimensions and tolerances of the component required to act as the 'control' when determining the 'state' of the actual dimensions achieved in a finished workpiece.

The fault information is derived either from machining handbooks or elicited from the machinist, process planner or designer, discussed in Chapter 11. This human-sourced information is obtained through interviewing and/or observations made during the manufacturing process. The fault information includes the nature of the fault, the conditions that gave rise to this fault and consequently the actions required for its rectification. Finally, to complete data feedback, verification procedures are required to confirm the occurrence of a fault. The gathering of information to establish these procedures is carried out in the same manner as that for the fault information.

Bearing in mind the product data model structure, described in chapter 8, and the positioning of the feedback facilities within this environment, it is now of importance to present a view on how this implicit data is organised internally for data feedback. Each of the three categories holds information in particular modules. The design specification is basically held in the decision network and in the measurement graph. The measurement graph also holds the inspection results, thus providing a state for a dimension. This dimension-state pair is related in a decision network to arrive at a fault. The fault information is organised into a fault library and in fault clusters. The fault node in the decision network can lead to consultation of either fault groupings. Finally, the third category of fault verification permits information to be stored as verification checks or even permits direct access to the fault clusters.

9.3 Representation of Fault, Cause and Action Relationships

The fault relationship is given as an error condition relating a fault to a cause and a cause to an action. Thus, the error conditions can be attributed to one or more causes and in turn these causes may require one or more actions in order to effect rectification and hence

elimination of the fault. The approaches available for representing the fault relationship are Failure Mode and Effect Analysis, Quality Function Deployment [195] and Cause and Effect charts [303]. These approaches although powerful in themselves, are essentially paper-based and do not lend themselves easily to procedural change. What is thus required is the generic capture of this learning in a computer-based system.

A generic approach to capturing knowledge in the form of fault relationships is implemented. These relationships are stored together and are known as a fault library. The fault library is at the heart of the decision network, fault clusters and the verification checks. Prior to the implementation of the fault relationships in the product data model, fault coding [185] was used. As the faults were then represented by numbers, there was a difficulty of relating a fault to a fault type. The fault type is now replaced by a fault description. This facility is provided for three main reasons. Firstly, the captured knowledge of one expert is now not only available to the novice but also to other experts. Secondly, the knowledge may be constantly updated with new learning and finally, recurring faults can be retrieved for corrective actions.

The fault library consists of one or many fault types. Each fault type has associated with it its cause(s) and action(s). This combination is represented by:

$$FaultLibrary = \sum_{1}^{n} FaultType$$

Each fault type in turn is represented by:

$$\sum_{1}^{n} FaultType = \sum_{1}^{n} Cause = \sum_{1}^{n} Action$$

This relationship can be expressed in either of ten categories shown in Figure 9.2. The first category illustrates the simplest of relationships essentially a one to one relationship, that is for each fault, there is one possible cause and for each cause, there is one possible action. The use of this strategy within the structure, shown in Figure 9.3, would involve the user commencing at a fault node and walking once through the structure with pointers to the fault, cause and action nodes.

When many factors contribute to a fault and there is only one action to rectify the fault, the second category is used. In this case, the use of the structure is the same as in the first category except now more than one cause is described under the cause node. In contrast to this, that is in category three (see Figure 9.2), if the number of actions needed to rectify the fault is as numerous as the causes, then the use of a cause and action node in the structure is repeated for as many times as required.

In category four, there is only one attributing factor to a fault, but the number of actions required to correct the fault is greater than one. The use of the structure therefore requires that the action node be repeated as many times as the actions required. If there is more than one cause and the number of actions required to rectify each cause is also greater than one, then this relationship will fall under category five. Here, the action node is repeated as many times as is required for each cause and the cause node in turn is repeated as many times as the contributing factors. This category considers only one fault. Where more than one fault is considered, this will fall under a category from six to ten. The difference with this category group as against that described lies in the description of the fault. The use of the structure is similar to that described.

The information or knowledge required for building the fault library is shown in Figure 9.3. The fault library can store one or more faults. Each fault in turn can have one or more causes and each cause one or more actions. The library knowledge will comprise of the factors effecting the fault and the actions required for its elimination. This action will be

initiated by the machinist if he subsequently encounters a similar fault during a machining process. Additional knowledge such as the design and manufacturing plan or set-up information is available for the action mode. This is present, as described in chapter 8, to assist the user in consultation of the fault library.

The entry in the fault library is shown in Figure 9.5. The building of each fault structure, see Figure 9.4, in this library follows one of the ten categories described above. The building process starts at the fault node. The description of the fault at this node depends on the number of faults considered. When this is completed, the cause node is initiated. The description of cause is then input followed by the initiation of the action node. The action node is initiated as many times as the number of actions. Like the action node, the cause is also initiated as many times as required. The process is repeated with the action node and the certainty factor node. When all information relating to this fault is input, the procedure is repeated for a new fault type.

Two major factors need to be considered when establishing the fault, cause and action relationship. These being the confidence in a solution and secondly single versus multiple solutions. Attaching a confidence value to any decision is particularly difficult and often subjective as information about the domain is usually incomplete, expensive to obtain, in some circumstances unobtainable and in others uncertain [135]. Furthermore, when a group of experts are asked to provide a solution, a number of varying or fuzzy responses may be obtained [170]. The best compromise solution is to allow for a numeric factor to be attached to a cause in a scale decided by a company. An example of a suitable choice might be a percentage value.

When a multiple solution exists, the problem might arise as to how one would evaluate the alternatives or even control the reasoning process. Once again, a numeric value could

be attached, say to each cause, but in this case would be used as a weighting factor rather than as a probability. This, thus allows the relative subjective importance of a particular cause to be expressed in relation to the others.

The problems of using probability models are compounded by the fact that the theory is not fully comprehended [135]. An experts estimate of probability is usually wildly inaccurate and difficult to elicit or justify. The other problem is the continual adjustment of odds until the results are reasonable. It is difficult to estimate probabilities with any confidence except for the three cases of impossibility, certainty and complete uncertainty (i.e weighting values of 0, 1 and 0.5). This is comparable to fuzzy logic [170]. The data feedback system has found the attachment of weightings to decisions adequate for this implementation.

An example to illustrate the building of a fault library for a Category 3 relationship is shown in Figure 9.5. In this particular example, one factor effects the fault but requires two actions to rectify it. The fault type is 'wrong positioning of the drill'. The cause type and the two actions are as shown.

The structure begins with the initiation of a fault node. This adds a new list of fault type 'wrong positioning of drill. The cause node is then initiated from this list. One then inputs the cause description shown in the figure. This is only required to be done once, since in this example there is only one contributing cause. The probability attached to this sole cause is user defined as being of value '1'. The building process proceeds with the initiation of the action node from the cause list. Since there are two possible actions required for resolution of the fault, the action node requires to be initiated for each action from the cause list.

9.4 A Decision Framework for Fault Rectification

A framework for representing a human-decision making process is required in reaching a conclusion about a fault type and thus in effecting an action. The most obvious candidate

in this area is the Influence Diagram [216], described in Chapter 3, which was pursued right from the start. The advantage found with this technique is that it can than be turned into a decision graph. It can also lend itself such that each branch of the network can in turn be used as a rule. This early enlightenment led to the rapid building of many Influence Diagrams for an early experimental base of the work. Another advantage of the Influence Diagram is its ability to graphically communicate to a non-expert. However, this use was not pursued to the level of complexity that uses Bayesian theory [196, 220]. Only the first level is used as the same decision process can in turn be represented in a comparative hierarchical structure, that is the decision network. The decision network structure represents each branch of an Influence Diagram network in structural terms as lists, collections and selections. This gave added power to the internal decision making process but some human-decision process relevance is sacrificed. However, this problem was overcome by the work in visualisation, see Chapter 10.

The decision network is used when the manufacturing process has an adverse effect on the dimensions of the component, that is, the deviations in the component are attributable to a erroneous process. The decision network is served by the fault library, described above, for the tracing of faults. The requirements for building the decision network, shown in figure 9.6, include the design specification such as the dimension(s) and tolerance(s) of the component; knowledge of the manufacturing deficiency, stored in the fault library, that effects the accuracy of the component; the Influence Diagrams to graphically represent the relationship between deviations in dimension(s) and; finally modified statistical process control formulae to determine the state of the dimension(s). A detailed description of the procedure for arriving at the state is given in Chapter 7.

The decision network is considered at the feature and at the component levels. At the feature level, the decision network reflects the expected performance and analysis of that

particular feature. The decision network for each feature is stored in an associative structure in the product data model. In which case, the dimensions and tolerances represent the design requirement of each feature.

The decision network for each component is formulated in two ways. Firstly, all relevant features in the defined decision networks are retrieved from the associative structure to represent a particular component. Secondly, the decision network is formulated to gauge the performance of the relationships between features. These relationships can either be the position between two features or the geometrical tolerances such as parallelism, squareness and perpendicularity. Currently, this is not implemented as the number of relationships between the various features is numerous. This requires extensive observations of many components before reliable knowledge can be elicited and used. Instead, the relationship between features is implemented by grouping similar characteristics together using the taxonomic structure. This process is described in section 9.6.

The information stored in the decision network, akin to a branch of the Influence Diagram, actually represents a decision rule. The decision rule is a defined relationship between dimension, state and fault. This relationship can be explicitly defined in more familiar terms as an 'If [dimension and state] Then [fault]'. The dimension and state being the condition and the fault being the consequent. This consequent is also a node in its own right. This consequent node is the condition of a subsequent network (rule), that is the second and subsequent relationships would enable a fault, cause and action chain to be established. This chain permits an effective conclusion (goal) to be attained in the consultation.

The data in the decision network are structured in lists, thus each list is a rule. The power of this structure is two-fold. Firstly, the data in the decision network is generic in that any rules for any manufacturing process conforming to the decision network definition can be represented. Secondly, it allows a whole host of unordered decision rules to be stored. This transparency permits the user to insert, add, delete or modify any rule without affecting

any other rule at this level in the decision network providing, of course, that each consequent (node) at this level maintains a relationship with the antecedent at the lower level. That is, not only is a relationship between state and fault established at one level but also a relationship between fault and cause is maintained. This also applies to the relationship between the cause and the action, thus maintaining the power of inference in the fault, cause and action hierarchical structure.

An illustration as to how a decision network for each feature can be created is shown in Figure 9.7. With the knowledge previously gathered, an influence diagram network is built for representing the relationships. Each branch of the influence diagram network for a feature, in this case a pocket, is shown below and described in Chapter 7:

L(UA) + W(LA) + R(S) --> tool offset

where L is the length, W is the width and R is the radius. The state can either be upper action (UA), lower action (LA) or satisfactory (S).

This branch is then transferred to the decision network. A decision network consists of a list of d-states as described in Chapter 8. The d-state is initiated as many times as the number of dimensions. In the first loop of the d-state, the dimension will be L. This includes the nominal dimension and the tolerances and will be the same as the design specification. The state is selected either from LA, UA or S. In this case, UA is selected as the state for L. Since there is more than one dimension, the loop is repeated with a d-state as the next decision node. In second loop, W will be the dimension, LA the state, and the d-state as the next decision node. Finally, the loop is again repeated with R as the dimension, S as the state and a fault, in this case 'tool offset' as the decision node. This particular branch of the network terminates at this stage. In cases where there is more than one fault type, this cycle will be repeated but with the fault as the next decision node. The process is then repeated for each branch of the network.

The procedure for building the decision network for relationships between features at the component level is shown in Figure 9.8. The building process is similar to that at the feature level except that the dimension is now replaced by the positional or geometrical tolerance.

A control program is required and written for walking the product model from the component level to the feature level and then to the relevant decision network. This control program enables information retrieval from the decision network.

9.5 Determination of an Error Condition

The first process in data feedback is accessing whether an error has occurred, and if an error has occurred, to determine the state of the deviation. A contending approach such as statistical process control (SPC) only monitors known parameter(s) and pursues these rigourously [224, 338]. An approach where a collection of parameters can be monitored and investigated is adopted in this research. This requires a measurement graph to be implemented to accommodate the results of inspection and to use with the decision network.

The requirements for building the measurement graph are the design dimensions, the tolerances and the actual dimensions of the finished workpiece, shown in Figures 9.9 and 9.10. The design dimensions and tolerances are the same as that used in the decision network but the actual dimensions are derived from inspection. The implementation of the measurement graph is at the feature level.

A control program is initiated at the component level of the product model to walk this structure from this level down to the relevant feature level and finally to the inspection dimension(s) in the measurement graph. The aim of this controlling program is to retrieve and then analyse these inspection dimension(s). Also included in the program is an algorithm, shown in Figure 9.11, for comparing the inspection dimension with the design dimensions. The state of the analysed data are either upper action, lower action or satisfactory. The

determination of these states and the tolerance types are described in Chapter 7. The result obtained together with the rules in the decision network constitute an inputs to the dimensional analysis system providing for explanations of deviations in the workpiece measurements.

In the dimensional analysis system the state of the analysed data and the dimension type, described in section 9.4, which form the antecedent of the rule is compared in a search to each antecedent of each rule in the decision network. The search occurs in a left-most-depth-first mode till a match between an antecedent and dimension-measurement is attained. When this happens the forward chain-like process is activated. A pre-condition for this matching process is that each rule construction in the measurement graph is identical to that in the decision network, that is the ordering in the 'condition' or antecedent of the rule must be identical to the ordered condition in a rule in the decision network or the search would be unsuccessful. In which case an error handling routine is activated. The algorithm for the dimensional analysis system for feature-based representation is shown in Figure 9.12.

9.6 A 'Short-Circuit' Fault Identification

Short-circuiting is a term used widely in expert system parlance to relieve the end user of responding to questions that are not needed to perform the analysis [292]. No contending approach is found in the literature on fault analysis. This approach allows faults with similar characteristics or features to be quickly retrieved from clusters.

Clustering is a process whereby items may be ordered, organised or clustered by means of an identifying characteristic or feature, see Figure 9.13. Clustering may be carried out either statistically or heuristically, the choice usually depending upon the number of data item or categories (clusters). In this research, it is not considered necessary to resort to a statistical procedure as the faults are always semantically defined. The user may define faults by alpha-numeric codes in which case some statistical clustering may be practical. The categories or clusters into which the fault types may be classed are pre-defined to match the machinists fault searching knowledge. These categories for example, are tools, fixtures and

so on. In the tool category, for example, it would be possible to locate tool-related faults such as tool offset problems, broken tool, inadequate tool life and so on. This structure permits a company to define clusters as is most suitable to their manufacturing experience and requirement.

Fault clusters are built in the taxonomic structure at the root of the product model, see Figure 9.14. The taxonomic structure is described in chapter 8 and shown in Figure 8.6. The process of building a fault cluster is illustrated in Figure 9.15. The fault cluster is in taxonomic terms a collection of menu-heading and menu members. The menu heading holds the menu title whereas the menu member describes the list of fault clusters. Each fault cluster (list) is in turn a collection of name and member. The name, for example, would be tools. The member is a selection of members or name-value associations. In this case, since the tool cluster holds many tool related faults where each may be considered as a member, one would then return to the initiating node of the structure where the menu heading now holds the title tool cluster with its menu members being a list of these tool related faults. Each tool related fault now has a name-value association, for example, broken tool, which allows one to seek in the associative structure in the product model this fault type.

The name-value association in the taxonomic structure is retained as the associative structure sets up a call to the fault library for this fault. This call then plugs this fault-related information, which is the cause(s) and action(s) relationship information into the retained position in the taxonomic structure. This process is repeated for each fault cluster and each fault cluster-related fault.

The power of this fault clustering structure lies in its ability to share the data of the fault type with the fault library thus avoiding duplication of specification of fault, cause and action relationship in two areas of the structure. The use of the fault cluster is initiated at the fault node at any level in the structure. A control program is written for walking this structure and retrieving the fault information.

A variation on this theme but with the same underlying process is establishing categories where each category expresses a relationship between features, for example between hole and channel or hole and hole. This is an alternative to the use of the decision network at the component level. As in the fault cluster, the menu heading would now be the feature relationships and each cluster's content would hold fault related information explicit to that relationship.

9.7 Confirmation of a Set-Up or an Error Condition

Confirmation of a set-up is usually required in a prototyping environment for a pre-manufacture situation. The challenge is to provide a system such that the user can interact in either of two modes. Firstly, he can interact with the system to confirm a production set-up in a pre-manufacturing situation. Secondly, in a post-manufacturing situation, he may have to run through procedure for confirming an error condition. If he believes that an error has occurred, then he can pursue a procedure to confirm his belief. He can then link up for example to a fault cluster if his reasoning is correct. An alternative but familiar approach which is widely practiced for verification is the use of decision charts, flow charts, or yes/no charts. This chart base was found in the case study industrial environment. This approach firstly, requires a 'yes/no' type decision and then based on the response the user is allowed to pursue his enquiry along the direction of his response.

The choice based typically on what was learnt in the industrial case study is that the paper based decision charts had the disadvantage in the amount of paperwork involved, the inflexibility of adding, modifying and inserting new data acquired through new learning and the tendency to skip or not follow procedure. The challenge was thus to construct a list of verification procedures in the product data model. The advantage of this approach lies in the power of the data handling in the product data model which could be explored to its full potential. This provides an ideal readily available solution to capture the information from these decision graphs, perform database type functions and use visualisation to present the information to the user.

The verification checks are usually expressed in a 'yes/no' decision tree. The advantage in this approach is that specific rules may be built up for each particular situation. This collective decision tree structure would be fairly legible, its execution fast and its maintenance not problematic. The alternative, implemented in this research, which is far more effective is a generic decision structure which separates the data from the decision structure. Thus instead of embedding a large number of specific decisions in a decision tree one builds a recursive generic frame which represents a verification check group. Such a structure, although it loses its direct mapping to a human decision process, has the advantage that new checks may be added, inserted, deleted or modified without disrupting the verification process structure. No time is lost in execution nor is maintenance of the structure a problem.

The verification checks are grouped in process tasks. Figure 9.16 illustrates the building process of verification checks for a process task. Like the fault cluster, the verification checks are created in the taxonomic structure. The procedure begins with the initiation of a a list of process tasks where each task is identified by a header and the initiation of a new list for the storing of check criteria. Like the task, the check criteria are identified by a header and another creation of a new list for the check procedures. The results of the check procedure is a list of faults which are retrieved from the fault library. Each fault is created by using its name-association value. The two process tasks identified are set-up and machining with the criteria as described earlier in Chapter 7. Each criterion will then consist of one or many check procedures which lead to one or many fault types. The process can be represented by:

$$VerificationChecks = \sum_{1}^{n} processtasks$$

$$ProcessTask = \sum_{1}^{n} criteria$$

$$Criteria = \sum_{1}^{n} checkprocedures = \sum_{1}^{n} faulttypes$$

As discussed, the process of building the verification check procedures is identical to that of establishing fault clusters but differs in that the menu-heading now specifies the check criteria and name procedure. For example, in set-up the menu-heading identifies the set-up and the name in the named member list defines the type of criteria such as part set-up or tool set-up. Each of these criteria in turn has the menu-heading describe the check criterion. Thus, if this check criteria is part set-up, then the name in the named member will also be a list of check procedure types. The menu-heading will now hold the description of this check procedure. The name in a name-value association of a named member will now be the related fault types.

Chapter 10:

The Data Feedback Facility

10.1 Introduction

This chapter aims to discuss the requirements and difficulties encountered in the visualisation implementation. The discussion includes the role the structure editor fulfils in data presentation, integration, manipulation and visualisation. Finally, the feedback facilities provided for data feedback which make use of the visualisation and structure editor are presented. The detailed functionality of these facilities are discussed in greater detail in Appendix II. The chapter draws on information previously presented in Chapter 7, 8 and 9. The use of this facility in a case study is presented in Chapter 12 to Chapter 14.

10.2 Visualisation - Requirements and Difficulties

The two requirements for visualisation are firstly, to make a core set or a single set of data about a product available to a number of applications [119, 125]. The single set of data will describe the design and manufacture of a product, whereas the applications may be either dimensions and tolerances, machine planning and code generation, inspection planning and code generation or data feedback. Secondly, the aim must be to maintain a centralised control of this set of data without any duplication of data in any part of the structure [36]. This is fulfilled by providing an arbitrator such that each application has a channel open to access this core set of data, and through it any of the other applications. Further, the visualisation must consider the user as being one of the most important elements interacting with the system [70].

The difficulties in achieving these requirements lies in preserving the dimensionality of the data [119, 268, 302] providing analysis to these data and finally providing communication between these data [70]. These complicating factors make the task difficult and reflects the

still active literature about what constitutes visualisation [124]. Besides, each application may have its own view on this data set without giving considerations for other applications. Furthermore, the data and the content of each application will normally be different.

In this project, each application considers its own view point of the data, its local requirements and the methods of accessing the core set of data for its purpose. The interrelationship and interconnection between the applications was never necessary except to occur at most between two applications. For example, design and tolerance and inspection planning use the same data structure describing the design specification. The difficulty which came about, starting three years prior when this element of the project was introduced, was the interaction of the data feedback application with probably the whole structure and its attachment with other applications. It was necessary to link up to other applications as there was perceived to be a need to consult these applications to preserve the elements of feedback. For example, to consult machine planning with regard to tools employed because the action recommended in data feedback may have suggested that the tool might be the cause of the fault. A detailed discussion is found in Chapter 7, 8 and 9.

Three factors are considered in the design process of visualisation. Firstly, the level of expertise of the operator must be taken into account [66]. Secondly, the system should seek to preserve the elements of a human-centred application [50, 51, 263, 286, 287]. Finally, there should be a balance between the user's involvement and incorporating all knowledge and tasks to be performed by the user in the computer system [66]. This also dictates what part of the structure would be visible to the user. The factors then considered in building the feedback facilities are, how to open a channel of communication between applications and between the feedback application and each of these applications. The implementation must also take into account the time constraints of channelling information to other applications, the software availability, the single set of data (the product data model) and finally the user of the system.

The visualisation of data feedback was achieved on the SUN workstation with the control programmes written in ADA and visualisation in HORSES, see Figure 10.1 and 10.2. The visualisation was initially implemented using the SUNVIEW tools available on the SUN workstation [306]. This was chosen because the user sitting at the terminal would have a ready means of communicating with the system. The real problem encountered with this system occurred when other applications did not perceive the same visualisation as the feedback system. As a result, it was difficult for these applications to fall under the umbrella of the data feedback visualisation. As the project progressed, a user interface management system, HORSES, was made available by one of the collaborators, PAFEC [97]. This availability was then able to provide a suitable context for each application within the same structure. Since all applications could then be connected under the same user interface management system, the work on SUNVIEW had to be abandoned. Thus, the data feedback system is now dictated by the facilities offered by HORSES. To go beyond such facilities would have involved difficulties in implementing SUNVIEW and HORSES in the same instance. The HORSES work is on-going by Dawson [96, 97] and known as the 'product data editor'. The advantages offered by HORSES are firstly, it enables data to be presented graphically in the way the data structures were described, that is in the form of hierarchical tree structure consisting of list, collection and selection as described in Chapter 8. Secondly, the user is assisted by this visual view to walk to any applications within the structure easily.

10.3 The Role of the Structure Editor

Having described the role of visualisation for data feedback, this now has to be combined with the structure editor for data presentation. Data presentation is essential for the generation of application as this application has to understand the presented data in the wider information context, that is the product data model, before any control program can be implemented. The structure editor thus provides a framework which enables an application to experiment with ways of exploring the same data.

Three components of the structure editor play an essential role in the design of the data feedback system. These components are graphics, data ancillary facilities and the infrastructure. The graphical component assists in presenting the data in a hierarchical structure. This allows the user or application to walk the structure from the top level down to particular application as well as the user's application in the 'left-most-depth-first' manner. This graphical view is enhanced by the use of HORSES to present in a pictorial form, see Appendix II.

The data ancillary facilities offered by the structure editor perform three main functions. The first deals with data storage, data manipulation and data organisation. These include deleting, inserting and modifying data. It allows data to be derived from one part of the structure and inserted into another part of the structure. Secondly, it provides a facility to link through data, one application to another. Finally, links are provided for data to be retrieved by an application. The structure editor is the main vehicle in assisting the data feedback process. It allows the system to structure and store data in a form which is comparable to that stored in, for example, an expert system. The information in the data feedback system can thus now be channelled between and to other applications.

Finally, the three main elements in the infrastructure are hardware, software and data exchange. The hardware and software have been discussed. Data exchange exists in three ways; by bridging a link within an application, between applications and finally between an application and the user.

10.4 The Facilities Provided by the Data Feedback System

The Data Feedback System provides two main purposes. Firstly, it controls the quality of the component during the manufacturing process. Secondly, it investigates the deviation from the intended design specification of a manufactured component. The facilities offered by the data feedback system to fulfil these objectives are assisted by the use of the structure

editor and the HORSES user interface management system. It is designed to perform data manipulation, pre-manufacture verification, in-manufacture control, post-manufacture analysis and provides a consultation facility for feedback.

In data manipulation, the user will be able to input and edit data into the structure. This would include building the fault library, decision network, organising data into clusters and arranging verification procedures according to verification checks. The input facility also includes inputting of inspection results into specific positions in the structure. The user will also be guided to a point in the structure where comparisons can be made between the inspection results and the rules in the decision network. He will then be redirected by the explanation provided for such a deviation to the required actions. The whole structure also enables the experienced user to change, modify, add and delete data. Facilities for constructing these structures are discussed in Chapter 9. The tasks to be performed by the user physically sitting at the keyboard are discussed in Appendix II.

Pre-manufacture verification is provided to the user who wants to consult or ensure that set-up is performed correctly, correct tools are available and so on as discussed in Chapter 7. The facilities offered for pre-manufacture are the verification checks. Verification checks ensure that the user is guided as to what to do next by the verification process.

In-manufacture control is employed when the user suspects that the process is in error or that the process is going out of control. The user can then stop the process at anytime to run the consultation facilities which are provided through two menus: verification checks and fault clusters. The former is used when he is unsure of the fault, and the latter when he knows what the fault is but wants to have more information. The ultimate aim of the two facilities is to provide him with the fault description, the causes of this fault and the actions that have to be taken for its rectification.

Post-manufacture analysis allows the user to evaluate the accuracy of a manufactured component by determining any deviations in the measurements from that intended in its design dimensions. It also provides the reasons for such deviations. Interactive facilities are provided at the feature level of the structure for the input of inspection results for each component. The analysis is then performed on the respective component. Facilities for performing this analysis are described in Chapter 9 and illustrated in Appendix II.

Consultation facilities are provided for both the semi-skilled and the skilled operator. The three modes offered for the semi-skilled operator are firstly, to report any changes he has made during the manufacturing process to the design level. Secondly, the system provides manufacturing prompts for taking any actions and finally, the data feedback make available knowledge of highly skilled operators to the unskilled or semi-skilled operator. For the highly skilled operator, facilities are also provided to check the wider information model in regard to the manufacture of a product, and enable changes to be made to the product design or just to report changes.

Chapter 11 :

Knowledge Elicitation Methodology

11.1 Introduction

This chapter introduces the reader to the process of knowledge elicitation for the data feedback system. This chapter moves from an analysis of requirements to the methods of acquiring the knowledge. The emphasis is placed on the interview technique as this method was employed for knowledge elicitation in the case study presented in the succeeding chapters.

11.2 Requirements Analysis

Requirements analysis is the first stage of the development process. The aim is to provide sufficient information about a problem to be solved such that initial development decisions can be taken [2, 292].

A good starting point for the analysis is to consider the tasks that the data feedback system is to perform, and the setting or context in which the system would be employed. Performing a task analysis permits definition of the input information that must be provided, the output that the system must produce and finally, the capability that it must provide to an end-user. An adequate requirement analysis would include interviews with the decision maker, the prospective end user and the expert. The decision maker is usually the funding authority, for example, Renishaw management and the Department for Trade and Industry.

A. What the System must do?

A discussion of the objectives required by the case study is given in Chapter 12. The external requirements identified by the analysis may probably required the system to perform more than one service and also perceived to be used at a variety of level.

B. Determine what Knowledge Sources are Available?

After analysing the requirements demanded of the data feedback system, there is a need to determine what knowledge sources are available. This identification of sources is crucial to the development of the data feedback system. The knowledge sources must provide the facts and reasoning that make it possible to construct the manufacturing rules and to select the appropriate representations such as decision networks, fault clusters or verification checks, discussed in Chapter 8 and 9. Thus, the issues that must be addressed are the availability of domain knowledge either from diagrams, database or the individual's with expertise.

C. Characterize the End User

The end-user provides the input that the system uses when making decisions. The issues to be addressed include the familiarity of the end-user with the domain, how much information he can supply, to what level of details he can supply these inputs and finally, with how much certainty he can answer the requests for information. The end-user level of sophistication directly affects the design of the visualisation, discussed in Chapter 10.

D. Identify the 'Real World' Context

The context in which the data feedback system will be used must also be considered. The context issues to be addressed include the type of hardware, the run-time, the requirements and standard of graphics and the speed of delivery of solutions. Some of these points are discussed in visualisation, Chapter 10.

11.3 Acquiring the Knowledge

The most crucial task in the development of the data feedback system is the acquiring of the manufacturing knowledge [37, 108, 135, 196, 223, 292]. During this task, interaction with the experts (or other knowledge source) is required to extract information about the specific problem the system is expected to solve, and the reasons by which the solution is developed.

There is a poor understanding of the nature of expertise, a limited number of techniques available and little evaluation of the effectiveness of these techniques. Numerous methods have been suggested and used for knowledge acquisition. These include the use of interviews, graphical representations, and protocol. Interviews may be unstructured or structured, protocol analysis involves think-aloud, taping, retrospective verbalisation and discussion [2, 135]. Another well used technique is the use of a repertory grid, shown in Figure 11.1, which is the representation of the expert's view of a particular problem [135]. The focus in this chapter is on the use of structured interviews. This elicitation technique together with some retrospective verbalisation was employed in the case study.

Unstructured interviews are usually carried out at the initial stage with the expert in control. This type of interview is difficult to direct but is an excellent forum for airing of views. The structured interview, on the other hand, works to a list of topics which makes it easier to extract information. In the case study, structured interviews were conducted based on the pro-formas and flowcharts illustrated in Chapter 13. The approach taken to an interview will depend on a particular expert and the knowledge domain. What is required from the interview/elicitation stage is a complete and correct description of the expert knowledge and the way in which he handles that knowledge in the specific area of expertise which is being investigated. The pro-formas were designed primarily for use in data collection in the prototyping environment described in Chapter 12. Each pro-forma was thus intended to capture the complete fault knowledge as well as act as a basis for discussion and implementation.

At a simplistic level, knowledge can be regarded as facts and rules, but in practice, this is far too simplistic; knowledge is more complex involving intermediate states of believe, conjectures and assumptions. It is the way in which the expert handles and manipulates the knowledge which is important; in particular, the way in which he deals with incompleteness and uncertainty. Figure 11.2 shows that data consists of facts which are always true and

assumptions which are normally true. Answers that are input can override assumptions. The rules combine all the data to give a resulting decision. This knowledge is displayed in lists and rules shown in Chapter 13.

The points to be learnt, in interviews are, firstly, to be specific and not general as the experts may find it difficult to recall all rules or concepts. Secondly, do not impose unfamiliar tools, that is the experts should be encouraged to provide information in a way which is more natural by making maximum use of graphical or pictorial aids. Thirdly, the expert should not be interrupted. The aim is to get the expert talking despite the fact that he may digress or repeat himself. Fourthly, a means of recording information should be planned as often a throw-away remark can turn out to be of fundamental importance. The knowledge elicitation process in the case study employed taping to ensure any aside remarks are recorded and analysed. Finally, it is not just facts, theories and heuristics which are important. The elicitor must listen to the way the experts use and manipulate knowledge. This includes points such as the order in which he approaches problems, the relative importance attached to different items and the ways in which he weights evidence.

11.4 Feedback to Expert

Once the knowledge has been elicited in raw form, it has to be analysed and refined until the knowledge is in a suitable format. During analysis, the raw information is also edited and reorganised. Feedback to the expert is very important to confirm the accuracy of the knowledge. The feedback process may be done through intermediate representations such as rules, flow charts, diagrammatic aids or prototype diagrams. This enables the experts to discuss tentative results and to offer constructive criticism [135].

11.5 Engineering The Knowledge

There are many different ways to engineer the acquired knowledge. The choice depends on the results of the requirement analysis, the knowledge domain, the time and personnel

available and the organisational issues [2, 135, 292]. If the knowledge engineer and domain expert is the same person, the classification and implementation of the knowledge can then be proceeded immediately. However, as in the case study, if the domain expertise is from another source such as Renishaw, the process of familiarisation with the domain vocabulary is essential before obtaining the detailed information from the expert discussed above. This then requires the knowledge to be understood and then implemented.

Regardless of the approach used in acquiring knowledge, an important role is played by the prototype. The data feedback prototype is built to ensure that it functions as required. It is less costly to build and modify the prototype in the early stages then to commit major resources and later discover that the development efforts were off the mark. A functioning prototype is a good foundation on which to add the details and in special cases, to represent the complete data feedback application.

The results of requirements analysis should be borne in mind as one goes through a series of development as the data feedback system is refined. The implementation of the data feedback system is discussed in Chapter 13 and the assessment given in Chapter 14.

Chapter 12 :

The Renishaw Prototyping Environment

12.1 Introduction

The industrial case study prototyping environment is described in this chapter. The data used to illustrate the research methodology is supplied by Renishaw Metrology. The major aspects to be covered include the industrial context, the prototyping cell design, the components to be manufactured, the current prototyping procedure and the requirements demanded of the case study system.

12.2 The Industrial Context of the Case Study

The prototyping cell case study is introduced in order to bring the established data feedback system under a serious test with industrial data in an industrial environment. The emphasis of the test is to evaluate the relevance of the research approach, the benefits that can be derived from the computer-assisted application of a data feedback system and finally to assess the robustness of the software.

12.3 The Prototyping Environment

The Renishaw prototyping environment, shown in Figure 12.1, consists of a prototyping cell, located in the machine shop, and linked to the Group Technology Centre which comprises of design and production engineering departments. The design department provides the component's design dimensions and tolerances to production engineering. The latter's function is to design the fixtures required and the part programs necessary for machining the component in the prototyping cell. A dividing line is drawn between production engineering and production. Prior to successful 'prove-out', all activities are the responsibility of production engineering. Responsibility for activities subsequent to 'prove-out' is attributed to production.

The prototyping cell comprises of two Mazak VQC-15/40 vertical machining centres and a Bladechecker coordinate measuring machine (CMM). Currently, the machining centres in the cell are neither linked nor automated. Each machining centre is capable of accommodating up to 30 tools in the tool magazine. The numbers of parts that the machine can accommodate varies according to the design of the fixture. A typical example, that of the PH9 top housing, holds 12 parts at each set-up. The machining centre uses the Mazatrol CAM M-2 controller for loading and manual editing of unproved part programs designed by the production engineering department.

The Bladechecker is a three-axis coordinate measuring machine with an accuracy of +/- 8 micrometer. The x and y axes are capable of moving upto 205mm and the z axis up to 360mm. It can measure up to nine components in one set-up. The Bladechecker uses the PMS3-10 (Part Measuring System) controller for input of part programs and output of inspection results.

12.4 The Component Range

A series of components, all specific to PH9 and PH10 probe heads, MIH manual indexing heads and MP11 machine probes, have been considered for inclusion in this case study. A typical component and the PH9 probe are shown in Figure 12.2. The process details of a specific component, that of the PH9 top housing, are documented in Appendix III. This aluminium alloy component machining cycle consists of a set-up time of 0.5 hours and a run-time of 0.13 hours respectively. A typical route is from material store, to machining centre, on to the deburring station, then on to inspection and finally back to store.

12.5 The Current Prototyping Procedure

The Renishaw prototyping procedure, shown in Figure 12.3, is set out in two phases. Phase A, which is essentially the design discipline, consists of activities 1 and 2. Phase B, which ranges from activities 3 to 11, consists of machining, inspection and error correction.

Phase B is in turn set out in three stages. The first step, activities 3, 4 and 5, establishes the repeatability of measurement. The purpose is two-fold: to establish the viability of the CMM program and secondly, to establish the viability of the machining process to produce features which are able to be repeatedly inspected. The second step, activities 6, 7 and 8, determines the repeatability of manufacture. The aim of which is to establish that the production process is able to give an acceptable level of repeatability on each feature of the component.

Finally, the third step which consists of activities 9, 10 and 11, establishes acceptable repeatability of manufacture on all features. The objective in this final phase is to arrive at a situation in which all the features have a repeatability spread of 50% or less of the allowable tolerance. The features are identified as type T and type P features. Type T features are addressed individually whereas type P features are inter-related. A Renishaw specific process analysis sheet is given in Appendix III and is used within this phase for two purposes. Firstly, it is used for documenting the non-capable processes found during the 'prove-out' cycle, another term to describe the prototyping exercise. Secondly, the process sheet is used to highlight the relationships between the features. The detailed advanced 'prove-out' procedure and flow chart, restricted to multi-fixturing, for the three steps is given in Appendix III.

The aim of this exercise is to produce a logical fault-finding solution to assist in problem-solving during the prototyping cycle. The current process of providing data feedback is a very labour intensive process which is essentially paper-based. The case study is targeted mainly at the second step of phase B.

12.6 The Case Study Activity Cycle

The case study or test and trial, shown in Figure 12.4, reflects the research focus on dimensional and process analyses. The trial commences with observations of the iterative prototyping process. This has been focused on a set of workpieces. The observations conclude

when a workpiece achieves its design requirements and is able to be repeatedly manufactured. The series of observations concentrate on the manufacturing methodology, fault-finding element and the manufacture capability.

An early need was identified for a pro-forma to capture the results of observation in a form acceptable to the part programmer and the prove-out operator, see Chapter 11. The pro-forma thus primarily designed for data collection had the added function of documenting all findings and conclusions. This recorded knowledge elicitation is the basis of structuring a fault-finding flow chart. Alternatively, the knowledge may be directly recorded by experienced personnel in a logical fault-finding flow chart without resorting to the use of the pro-forma.

The data so documented forms the basis of implementation of the fault library, decision network, verification checks and fault clusters in the data feedback system. This implementation is discussed in Chapter 13. This initial system then had to be subjected to an industrial test and trial. The potential benefits and limitations are then explored critically within the test and trial. A critical discussion is given in Chapter 14.

12.7 The 'Restricted' Activities

The case study is restricted to the specific activities of the Renishaw Prototyping Environment. As such, a list of 'restricted' assumptions made to support the case study is as follows:

1. This task is dedicated to the multi-fixtured machining.
2. The design in question has been challenged so that the workpiece is 'designed for manufacture'.
3. The workpiece definition uses a feature-based approach.
4. The units used throughout the observation are metric.
5. Only prismatic part operations are considered.

6. Two types of machining are identified, that is machined 'all' over and 'partial' machining.
7. The material type considered is aluminium.
8. The raw material is in 'rolled' or extruded form.
9. The tool types and clamping methods used are adopted from Renishaw's tool assembly manual.
10. The speed and feed used initially depend on the maximum metal removal rate.

Chapter 13 :
Design and Implementation
of the Renishaw Feedback System

13.1 Introduction

The design and implementation of the feedback system for the Renishaw prototyping environment is described in this Chapter. This chapter moves from describing the objectives of the case study, through the process of gathering data or knowledge elicitation, to how this knowledge is organised and embedded for data feedback in the Renishaw context.

13.2 The Objectives of the Case Study

The scale of the case study is restricted to an important part of the Renishaw activity, that is it is aimed at checking the validity of a part program before it is issued to the production, see Chapter 12. This activity is also known as the 'prove-out' phase. On the other hand, the prototyping life cycle commences at design and progresses through machining, inspection, improvement and back to design. The 'prove-out' phase, which is the particular focus of the case study, is that activity which encompasses machining to inspection and the analysis of results. Thus a successful 'prove-out', in Renishaw terms, implies that the process is capable of producing every feature of a component, that is the spread of the measured data is within 50% of the allowable design tolerance. The objectives to be met for enhancement of productivity at 'prove-out' are to:

1. Shorten the time-scale of the 'prove-out', that is, to reduce the number of iterations required for each 'prove-out' activity.
2. Establish acceptability and repeatability of manufacture on all features of a component, that is the determination of a course of actions to be undertaken to make a feature repeatable.
3. Increase the understanding of manufacturability by providing guidelines for the designer through ascertaining machining centre capability.

4. Determine the best way of manufacturing a product from past data captured in the data feedback system.

5. Provide a consistent problem-solution framework, such that problems can tackled at an early phase before a component can mature to production. This framework encapsulates a logical fault-finding solution.

6. Establish communication between design and production engineering departments such that a closed loop is achieved back to design from manufacture.

13.3 Knowledge Elicitation Formalism

In order to effectively register observations on 'prove-out', it was found necessary to design pro-forma to formalise the data input. The pro-forma is the primary sourcing of data which permits the recording of auditory, visual and physical problems. This recording is achieved when the personnel encounters a problem during the 'prove-out'. This is used as the basis for the interview method of knowledge elicitation described in Chapter 11. The design of the pro-forma required many iterations and discussions with the prove-out personnel before the design could be finalised and used in data collection. This design allows for three main factors. Firstly, it encourages the user to fill in all the information of the occurrence of a fault as completely as possible. Secondly, an explanation of all causes and the necessary actions for rectifying a fault is given at source. Finally, the purpose and usage of the form must be on approval by the user. Whilst the pro-forma shows the linking between faults, it nevertheless does not permit a global picture to be captured of any one scenario. It is more a reference catalogue of fault, cause and the successful actions taken to rectify the fault. All and all, it provides documentary evidence for future consultation in the event of recurrence of a similar fault.

Building a more global picture is made more possible through the use of flow charts. This decision aid not only shows the sequence of expected faults, but enables one thread of logic to be followed through to conclusion. Thus, any specific branch or part of the flow chart may either be derived from operator experience or compiled from the pro-forma. These

branches may be collated to become a fault reference for prototyping of a particular workpiece. Alternatively, each branch may be likened to a sub-routine in a software program and sub-implemented as prototyping knowledge for other workpieces. The set of data elicited from the Renishaw's experts are shown in Appendix III.

13.4 Knowledge Elicitation for Process Analysis

The elicitation of knowledge for process analysis is best described through the use of the pro-formas and flow charts and how this information is then represented by the software as shown in Figures 13.1 to 13.5 respectively. The same fault type, that of 'position of drill', is used for this illustration. The pro-forma, problem-solving sheet 1 shown in Figure 13.1, records the problem number and any other problem(s) which have direct relevance to the cross reference number. The fault type is then recorded on the 'problem identified' row. The likely causes in this case will then be that 'the spot/centre drill position might not be in line with the drill position'. The corresponding actions will either be: 'move spot/centre drills in program because the position of the two drills did not tie up'; or 'move both drills in actual xy position because they are in the wrong position' respectively. The machining and design information is documented in problem-solving sheet 2, see Figure 13.2. Furthermore, a more complex problem may be pictorially represented through problem sheet 3, see Figure 13.3. The same set of information documented in the pro-formas is also shown recorded on the flow chart in Figure 13.4. This flow chart is a sub-network of the series of charts given in Appendix III. Here, the actions are the terminus of the flow chart's decision node. Each branch is thus analogous to a cause. Finally, the software representation is shown in Figure 13.5. The representation is made more explicit by describing the fault, cause and action relationships in a structured form.

There are three routes available for transferring the expert's machining knowledge to the data feedback system. These are shown in Figure 13.6. All three routes require an interpreter for interpreting this knowledge into the form required by the system. In the first, the knowledge is recorded directly on the pro-forma and transferred to the system. The

second route requires the user to record the knowledge on the flow charts before the data is input into the system. Finally, the knowledge can first be recorded on the pro-forma, then transferred to the flow charts before allowing the data to be transferred to the system.

13.5 Knowledge Elicitation for Dimensional Assurance

The knowledge is elicited from the data collected based on the Renishaw perception on process analysis. It was perceived that any errors contributed by defective workpiece or feature are attributed to the choice of manufacturing method. The manufacturing method determines how the feature is made with respects to the choice of tools, speed and feed. These choices are also influenced by its design dimensions and tolerances. The tolerances in turn are classified into 'Grade A' or 'Grade B'. The 'Grade A' tolerance is the most desirable feature to design and manufacture and has the highest process capability confidence level. These are represented in the form of charts, one of which is shown in Figure 13.7, with a list of criteria to satisfy in order to qualify as 'Grade A' feature. Currently, the focus is 'Grade B' tolerances with data collected only on 'hole' as the amount of data collected and required is considerable. Data was collected based on twenty components, shown in Figure 13.8. This was considered sufficient to illustrate the research concept. More data for other features can be collected in the future and implemented in stages.

The data provided by Renishaw for dimensional assurance are based on ranges of dimensions, ranges of tolerances and the manufacturing method as a solution, shown in Figure 13.9 which is a subset of that shown in Appendix III. Renishaw adopted this method because, they believed that the right manufacturing method used in the first instance will guarantee the integrity of the workpiece. Renishaw at this stage had no intention to pursue the fault, cause and action relationships as in the research approach. However, the two approaches are analogous but the research approach allows a greater insight into the problem than that of a bird's eye view Renishaw approach. The research approach employs the same data but

will require more investigation in order to completely build the Influence Diagram, Figure 13.10. However, the elicited data can be accommodated easily in the decision network, see Figure 13.11, as well as the taxonomic structure, see Figure 13.12

An example of the design diameter of 'less than and equal 3.1 millimetres' with tolerances of 'greater than and equal to 10 micrometers to less than 20 micrometers' are used and shown in Figure 13.9. This is represented graphically by an Influence Diagram shown in Figure 13.10. In this case, the influence diagram is applicable for any diameter and tolerances within the above range. This information is then transferred to the software in two ways. It can be represented in the decision network or in the taxonomic structure. Currently, it is implemented in the taxonomic structure of the data feedback system.

13.6 Organisation of Knowledge for Data Feedback

The organisation of data is influenced mainly by the workpiece representation. The workpiece is represented by features and not by geometrical analysis. Each of the features within the workpiece is in turn correlated to the type of tool used. The feature is then represented by its attributes such as size, depth and position. The features are considered in insolation as well as with reference to a datum or to another feature. Currently, only 'hole/bore' features are considered for dimensional analysis as a substantial data collection is necessary. On the other hand, for process analysis, features such as hole/bore, boss, slot/step, face and profile are considered.

In process analysis, the set-up phase is assumed to be satisfactory and the focus is on the machining phase of a particular feature. This is based essentially on checking the accuracy of machining and the programmed parameters generated by a particular tool. The inspection of the workpiece is to verify the accuracy of the workpiece.

Dimensional analysis, on the other hand, has the dimensions and tolerances classed in ranges. These dimension and tolerance ranges can be directly attributed to a manufacturing method. The feature in question is used either as a datum or non-datum feature.

From the above, the classification of data is based on the appreciation of the Renishaw workpiece representation and on their perception of dimensional and process analysis. The research approach can then be enacted to formalise the Renishaw approach into the familiar data feedback implementation. The implementation consists of building a fault library, providing a verification checking facility and fault clusters.

The knowledge implementation process for each of the data structures is given as:

1. Take a self-standing branch, such as the hole produced by drill, shown in Figure 13.4. Every decision point which is identified by the node is then examined.
2. Identify all contributing attributes such as size, depth and position of the hole.
3. Examine each attribute decision point such as position.
4. The terminus of each decision point can itself lead to a decision point or terminate with a result. In this case, the position of the hole has a decision point which enquires whether all drills used are in line. The answer to this decision terminates with the action to be taken.
5. Decide on the appropriate structure to be used for representing all these decisions.

13.7 Implementing the Data Feedback System

The software implementation of the data feedback system must consider the knowledge extracted from the case study, and then decide on the structure in which to embed this data. A first pass of the data revealed a discrimination between manufacturing method and faults in dimensional analysis. What this entails, basically is that in the research approach, the fault, cause and action relationship is implemented based on a particular dimension of feature. The case study implementation now demanded an approach based on a feature's dimension and tolerance range coupled with the respective manufacturing method.

The power of the generic approach in capturing and representing data in the data feedback system, within the product modelling environment, still permits the Renishaw data to be adequately represented. This representation is in a form understood by Renishaw and retains all the essential elements of data feedback in the product data model. The implementation of process analysis on the other hand was straightforward in that data was provided by a more conventional method, that is through a flow chart. A closer examination of the flowchart reviewed that some manipulation of the data was still necessary before it could be readily configured for data feedback. Each of these particular implementations is discussed.

13.7.1 The Main Menu

The research approach, provided for process analysis and workpiece measurement analysis, is now discussed in the context of the case study. Embedded within the process analysis system were verification checks and fault clusters. These now demanded a slight change in emphasis to cater for the industrial needs. The emphasis was placed on providing a fault-finding solution and a manufacturing method selection. These are analogous to the facilities provided for process analysis and dimensional analysis respectively. This new implementation in relation to the prior is given as:

MDA:
menu header : MDA
menu elements :
Manufacturing Process Analysis:
menu header : Process Analysis
menu elements :
Fault Cluster:
...
Verification Checks:
...
Workpiece Measurement Analysis:
menu header : Relationship between Features
menu elements :
Relationship between Hole and Hole:
...

Relationship between channel and hole:

...

Relationship between block and hole:

...

Relationship between block and channel:

...

Renishaw Case Study:

menu header : Renishaw Data Feedback system

menu elements :

Fault-Finding Solution:

...

Manufacturing Method Selection:

...

Fault Cluster:

...

13.7.2 The Fault-Finding Solution

The implementation of the fault-finding solution is influenced by the feature type, the machining method, the feature characteristics and the factors contributing to a fault. The software implementation of the overall structure is shown graphically in Figure 13.13 to 13.14. The construction of the software structure is described in Chapter 9. The data representations for the fault-finding solution are shown progressively below.

A. The first process identifies the feature types. The fault-finding solution focuses on 'hole/bore', as shown below. Other features are also included as shown.

Renishaw Case Study:

menu header : Renishaw Data Feedback system

menu elements :

Fault-Finding Solution:

menu header : What is the feature?

menu elements :

Hole/Bore:

menu header : How is the feature produced?

menu elements :

...

Boss:

...

Slot/Step:

...

Face:

...

Profile:

...

B. Secondly, taking the hole/bore in particular, the methods of generating this feature are shown below. This can either be produced by using a drill, reamer, boring bar, end mill or form tool. A similar approach is also implemented for boss, slot/step, face and profile.

Fault-Finding Solution:
menu header : What is the feature?
menu elements :
Hole/Bore:
*menu header : **How is the feature produced?***
menu elements :
Drill:
menu header : What is the feature attribute?
menu elements :
...
...
Reamer:
menu header : What is the feature attribute?
menu elements :
...
Boring Bar:
...
End Mill:
...
Form Tool:
...

C. Thirdly, taking the drill in particular, the implementation is based on the attributes such as size, depth and position as shown below. This implementation is repeated for reamer, boring bar, end mill and form tool.

```
Drill:
menu header : What is the feature attribute?
  menu elements :
    Size:
      menu header : What is the size?
        menu elements :
          ...
    Depth:
    ...
    Position:
    ...
```

D. Finally, all factors leading to a fault for varying sizes are considered. Currently, only two sizes, that is oversize and undersize are implemented. The power of the data feedback system permits structures to be added or modified with ease. It is possible to implement other categories of size by simply adding a new element. Also, as in oversize, the structure permits additional checks to be added before confirming a fault. The fault structure is described in section 13.7.4.

```
Size:
  menu header : What is the size?
    menu elements :
      Oversize:
        menu header : Check Run-out   ----> verify
          menu elements :
            Run-out is not within limit:
             menu header : Problem is due to
              menu elements :

                collet size == ... ----> fault type

            Run-out is within limit:
             menu header : Confirm check
              menu elements :

                drill diameter(large) == ... ----> fault type

      Undersize:
        menu header : Confirm check with micrometer
          menu elements :

            drill diameter(small) == ... ----> fault type
```

13.7.3 The Manufacturing Method Selection

Manufacturing method selection is based on the way the 'hole/bore' is generated, that is, the type of reference, the diameter and tolerance ranges. The software structure is shown in Figure 13.15. The structure has been tailored to suit this particular application using the generic approach for capturing and representing the data. The data representation for the manufacturing method selection is shown progressively below and in Appendix II.

A. The two types of referencing, shown below, are either datum or non-datum. When the hole/bore is used as datum, all dimensions of other features are measured with reference from this datum. When it is used as a non-datum, its dimension is then dependent on the datum hole/bore. This positional error is the deviations from the datum. In this case, a positional error of less than or equal to 0.2mm is permissible.

Manufacturing Method Selection:
menu header : ***How is the hole referenced?***
menu elements :
As Datum:
menu header : What is the diameter range for hole used as Datum
menu elements :
...
...
With Positional error of le 0.2mm:
menu header : What is the positional error range?
menu elements :
...
...

B. Highlighting the datum as reference for the hole, the diameter ranges are as shown.

Manufacturing Method Selection:
menu header : How is the hole referenced?
menu elements :
As Datum:
menu header : ***What is the diameter range for hole used as Datum***
menu elements :
diameter is le 3.1mm:
menu header : What is the tolerance range for diameter le 3.1mm

menu elements :

...

...

diameter is gt 3.1mm to lt 4.0mm:

menu header : The manufacturing method recommended for gt 3.1mm to lt 4.0mm dia is

menu elements :

...

diameter is ge 4.0mm to le 10.0mm:

menu header : The manufacturing method recommended for ge 4.0mm to le 10.0mm dia is

menu elements :

...

...

diameter is ge 10.0mm:

menu header : What is the hole types?

menu elements :

...

...

C. Taking a specified diameter category such as 'less than or equal to 3.1mm', this can be further split into tolerance ranges as shown. Progressing down, the manufacturing methods can then be reached for each of the tolerances range.

As Datum:

menu header : What is the diameter range for hole used as Datum

menu elements :

diameter is le 3.1mm:

menu header : What is the tolerance range for diameter le 3.1mm

menu elements :

tolerance is ge 10 micrometer to lt 20 micrometer:

menu header : The manufacturing method recommended for ge 0.010mm tol is

menu elements :

B/dia le 3.1/tol ge 0.010 to lt 0.020 == ...----> selected mfg method

tolerance is ge 20 micrometer:

menu header : The manufacturing method recommended for ge 0.020mm tol is

menu elements :

B/dia le 3.1mm/tol ge 0.020mm == ... ----> selected mfg method

D. The implemented manufacturing method for a particular diameter range and a particular tolerance range is given below. 'B' represents that the tolerance is a 'Grade B'

tolerance (see Chapter 12), 'dia le 3.1' indicates the manufacturing method for this particular diameter range and similarly for the tolerance. A detailed description of the manufacturing method is given in section 13.7.4.

diameter is le 3.1mm:
menu header : What is the tolerance range for diameter le 3.1mm
menu elements :
tolerance is ge 10 micrometer to lt 20 micrometer:
menu header : The manufacturing method recommended for ge 0.010mm tol is
menu elements :
B/dia le 3.1/tol ge 0.010 to lt 0.020 == ...----> selected mfg method

E. Other factors that influence the choice of manufacturing method are the types of holes considered. Taking the diameter 'greater than 10.0mm', then two types of holes considered are through and counterbore holes. In this instance, only the manufacturing methods are given but it is not dependent on the tolerance range.

diameter is ge 10.0mm:
menu header : ***What is the hole types?***
menu elements :
Through bores:
menu header : The manufacturing method recommended for through bores is
menu elements :

B/dia ge 4.0 to le 10 and gt 10.0mm == ...----> selected mfg method

B/dia dia ge 10.0/Boring == ...----> selected mfg method

B/dia gt 10.0/0.8 rad == ....----> selected mfg method

To depth or c/bore:
menu header : The manufacturing method recommended for To depth or c/bore is
menu elements :

B/dia ge 4.0 to le 10 and gt 10.0mm == ...----> selected mfg method

B/dia dia ge 10.0/Boring == ...----> selected mfg method

B/dia gt 10.0/0 rad == ...----> selected mfg method

F. The positional error, as a reference for the hole, consists of the positional errors range. Each positional error range is in turn directly influenced by the diameters range or by the tolerance range. This is shown below.

With Positional error of le 0.2mm:
menu header : What is the positional error range?
menu elements :
Positional error range is lt 0.1mm:
menu header : What is the diameter range?
menu elements :
...
...
...
...
Positional error range is ge 0.1mm:
menu header : What is the tolerance range?
menu elements :
...
...
...

13.7.4 The Fault Library

Currently the fault type and the manufacturing method are represented by the fault structure described in Chapter 8. These data structures are stored in the fault library and are retrieved when appropriate. The same fault type or manufacturing method can be used either in the fault-finding solution or the manufacturing method selection. The software implementation of the fault structure is shown in Figure 13.16 . The data representation for both structures are shown below.

A. The implementation of the fault, cause and action relationships of the fault, shown below, is a one to one mapping relationship with the data. Taking the fault type that of positioning of spot/centre drill as an example, the data representation reflects the actual cause and action.

positioning of spot/centre drill ==

FAULT:

fault description : *"position of spot/centre drill is out of tolerance"*

causes :

cause description : *"actual xy position of spot/centre drill does not ties up in program"*

actions :

action description : *"adjust spot/centre drill position in program (confirm with specs)"*

probability :

prob : *100.0*

cause description : *"actual xy position of spot/centre drill in program ties up with design spec"*

actions :

action description : *"move both spot/centre drill and xy position in program"*

probability :

prob : *100.0*

B. The fault structure is also used for representing the manufacturing method as shown. As the structure was tailored and improvised to accommodate these data, the fault description gives a brief statement on the manufacturing procedure. The cause description describes the machining parameters and the sequence of that particular operation. The action description gives a list the appropriate tools to be used for a specific diameter.

B/dia le 3.1/tol ge 0.010 to lt 0.020 ==

FAULT:

fault description : *"The procedure is in sequence"*

causes :

cause description : *"First use centre drill with 10000rpm and 500mm/min"*

actions :

action description : *"If dia is ge 3.0, use dia 2.5 centre drill"*

action description : *"If dia is ge 2.0 to lt 3.0, use dia 1.6 centre drill"*

action description : *"If dia is lt 2.0, use dia 0.5 centre drill"*

probability :

prob : *100.0*

cause description : *"Second, use drill to reamer with 10000rpm and 500mm/min"*

actions :

action description : *"If dia is ge 3.0, use dia 2.9 microdrill"*

action description : *"If dia is ge 2.0 to lt 3.0, use dia 1.9 microdrill"*

action description : "If dia is lt 2.0, use 0.9 microdrill"
probability :
prob : 100.0

cause description : "Third, use reamer with 500rpm and 500mm/min"
actions :
action description : "If dia is ge 3.0, use dia 3.0 reamer"

action description : "If dia is ge 2.0 to lt 3.0, use dia 2.0 reamer"

action description : "If dia is lt 2.0, use dia 1.0 reamer"
probability :
prob : 100.0

13.7.5 The Fault Cluster

In this implementation, all similar fault types are grouped together. The building procedure is similar to that used previously in the building of the fault-finding solution and manufacturing method selection. The fault types are those stored in the fault library and are shared with the two analyses. The software implementation is shown in Figure 13.17.

A. Currently, four clusters are defined within the Renishaw's environment. These are cutting tools, feature, manufacturing method and cutting tools accessory.

Fault Cluster:
menu header : Fault Clusters
menu elements :
Cutting Tools:
...
Feature:
...
Manufacturing Method:
...
Cutting Tools Accessory:
...

B. Taking the cutting tools cluster as an example, some examples of the types of fault are as shown below.

Cutting Tools:
menu header : Tool Error
menu elements :

drill diameter(smaller) == ...----> fault type

drill diameter(too large) == ...----> fault type

positioning of spot/centre drill == ...----> fault type

length offset/design spec == ...----> fault type

13.8 The Software Trial

The data feedback system, implemented at Renishaw Metrology, was subjected to a test and trial for the prototyping phase of a particular workpiece. The activities involved in setting up and running the test are shown in figure 13.18. The manufacturing method selection of the data feedback system is put to the test by assisting the designer in correctly defining the processes for manufacture of the component. The fault-finding structure is used to solve any problems that may arise in prove-out. Furthermore the time taken for these exercises using the data feedback system is to be subjectively compared with that prior to this implementation to assess productivity and most importantly to obtain a critical assessment of the value of the data feedback system

The other factors to be considered during the test and trial phase were to examine the consistency and completeness of the knowledge, the user-friendliness, and any limitations imposed by the software. The system was to be closely monitored during this period and the industrial comments taken into consideration to further enhance the prototype. The critical assessment and conclusions drawn from the case study are described in Chapter 14.

Chapter 14 :

A Critical Assessment of the Data Feedback System Based on the Case Study

14.1 Introduction

A critical assessment of the research work and its implementation within an industrial environment is discussed in this chapter. The discussion centres around the measure of achievement of the general case study objectives presented in Chapter 12. In a wider context, the value of the research methodology in relation to the underlying principles of dimensional and process analysis is also discussed. The general conclusions are presented in Chapter 15.

14.2 Reducing the Lead-Time in 'Prove-Out'

The Renishaw prototyping cycle consists of sixteen activities with their expected time dependence shown in Figure 14.2. Many of these activities are run in parallel with some activities contributing to a critical path. These activities in the process critical path give a realised lead-time of approximately 30 days, shown in Figure 14.1, although there is a desire to reduce this to the expected 18 days, shown in Figure 14.2. The activities of the two main phases had been described previously in Chapter 12. Thus, the objective is to realise the planned time of 18 days by enhancing productivity. The overrun of 12 days, that is from 18 to 30 days, is contributed mainly by step 1 and step 2 of the Phase B activities.

Currently, the two stages, step 1 and step 2, are repeatedly applied because when a problem arises, there is no documented persistent logical fault-finding solution. Thus, a 'new' process of investigation is initiated at each occurrence of a fault irrespective of its past detection and cure. This rectification could also be complicated by the fact that different personnel of varying levels of expertise may be involved. Thus, the degree of confidence between different personnel in problem solving is relative. The data feedback system

addresses this problem by offering a computer-assisted problem-solution framework which embeds a 'consistent expertise' and makes it available simultaneously to any 'prove-out' personnel.

The lead-time may then be substantially reduced through the application of data feedback. This can be achieved because the system has embedded within it a considerable body of knowledge which may be interrogated rapidly to offer explanation or give advice on corrective actions. This in itself acts as a ready source of problem-solving data with only tried and tested knowledge embedded within the system. Thus, it will effectively reduce the number of iterations needed to detect the effectiveness of a solution. Secondly, the data feedback system embodies a wider base of knowledge usually and frequently beyond the skill of any one person. Thus, the accessible knowledge is not only with respect to a solution of a prevailing problem but also in a product modelling context. Thirdly, the data feedback system permits a learning capacity in that new problems or updated solutions may be added, modified or deleted at a single source thus making this 'new knowledge' immediately available to all interrogators.

Alternatively, to reduce phase one activities, the principles of dimensional analysis could be applied. This application allows access to the manufacturing method in the product data model which would assist the designer/planner in providing the best manufacturing method to assist in the production of reliable NC part programs.

14.3 Ensuring Manufacturability

The aim of this case study was also to assist in establishing the manufacturability and inspectability of a feature or part. The Renishaw prove-out procedures are shown in Appendix III. The procedure for ensuring repeatability in manufacture is essentially to make ten components and then measure the first component ten times. This then indicates the process capability of measurements for each feature, that is its inspectability. The ten components are then measured and their results analysed. This generates the system process capability

for each feature, that is the manufacturability. The aim of determining manufacturability is to arrive at a situation in which all the features have a repeatability spread of 50% or less of the allowable tolerance band. If the spread is greater than 50% of allowable tolerances, then the process is concluded as not capable. The focus of attention in this research is given to Renishaw's requirement for a 'book of rules' to document the knowledge regarding the manufacturability of the features. Thus, a system is required to store and retrieve rules which offered explanation of expected deviations, and to capture the 'prove-out' experience of manufacturing. This will then address the process capability and the variables that affect the manufacturing of features.

The data feedback system offered an approach which documented the manufacturability of features through fault, cause and action relationships. These relationships derived from the prototyping experience represents the knowledge shown in Appendix III. The feedback system permits: Firstly, a means of documenting the prototyping experience of manufacturing; Secondly, it alerts the designer to the process capability of the machine and the reasons for deviations. Thirdly, it provides a consultative facility whereby if a feature lies within a particular tolerance range, then its machining method may be consulted to provide the best manufacturing method so as to minimise or eliminate the problem at production. This prevents the design of a process which is incapable and provides an understanding of what must be done to make the process capable.

14.4 Providing a Logical Fault-Finding Framework

The provision of a problem-solution fault-finding framework has been the main contribution towards the Renishaw prototyping environment. This approach, particularly within the product modelling environment, is at the very heart of all the analyses. By ensuring a structured methodology and by constraining knowledge to within its boundaries, a system is achieved which enhances productivity at 'prove-out'. This, thus realised the Renishaw requirement in reducing the lead-time in the prototyping life cycle.

The research methodology has provided a taxonomic structure which embodies verification checks and fault clusters, and a decision network which reflects the fault, cause and action relationships. These are all implemented within the product modelling environment which provides for inter-communication between design, manufacture and inspection. The verification checks have provided Renishaw with a ready means of implanting their knowledge regarding prototyping. This enables a logical route to be followed when interrogating the facility for explanation of deviation.

In relation to data input, the logical structure forces the input of information in a manner which is consistent. The core of this structure, that fault, cause and action relationship, may generically be accessed by all relevant features and applications. In a 'prove-out' situation where the user knows exactly what fault to expect and does not wish to use the interrogative facility, he can then directly access the fault cluster capability of the software. This will then guide him in determining the course of action to be taken for a particular fault.

The decision network although it provided a powerful dimensional analysis framework, had to be adapted to the Renishaw scenario. Renishaw had invested a considerable effort in building knowledge based on dimensions and tolerance ranges with respect to the machining methods. Thus, as discussed in chapter 13, even though the research approach could be applied in its original form to the Renishaw scenario, the company requirement was to pursue a path in the direction of machining methods. This has provided an insight into an alternative method more applicable to the case where the concern is not on explanation for the deviation in a particular dimension but on a range of dimensions. The research work has benefited from this approach as the number of rules required are then substantially reduced.

14.5 Closing the Loop Through Inter-Function Communication

Currently, in the Renishaw prototyping environment, communication is only established between design and production engineering when a problem is deemed sufficiently serious to merit immediate attention by the design personnel. At all other times, the majority

of manufacturing decisions are undertaken within the confines of the production engineering department. Furthermore, the experience gained in the production engineering department is often not conveyed back to the design department. Thus, because of the misapprehension of the design personnel in relation to manufacturing, persistent errors are encountered and resolved in production engineering. Effective feedback through software provides a means whereby this matter may be addressed. This is then achieved by reporting manufacturing problems and process capability directly to design, to avoid a design that contributes to the same manufacturing defects. It is thus important to realise that data feedback should not just take place just within the production engineering department but also between departments. Very often, the biggest problem faced by any company is the 'white spaces' in the organisation chart, that is the no-man's land between departments.

The data feedback system sets out to close this loop or bridge the 'no-man's' land by allowing the production engineering department to log the manufacturing methods and the problem-solving solution. The system then permits designers access to this information base through the product data model environment. Thus, enabling them to consider the problems in perspective during the designing or planning process.

14.6 Achieving a Good Quality Prototype Through Data Feedback

Achieving a good quality prototype implies a successful 'prove-out', manufacturability and inspectability of feature, capability of machining process, effective data feedback to design and maturity into production. This process can be guaranteed by providing in the data feedback system a computer-based basketful of knowledge. This then allows information to be drawn for reducing prototyping lead-time and more specifically, the time taken to resolve manufacturing issues.

The key to the success of the data feedback system lies in its ability to use past knowledge to make present correction and to suggest improvements for future design. Thus, a facility which provides a generic approach to capturing and building manufacturing knowledge in a

logical manner ensures preservation through data feedback. This captured information is then disseminated to all concerned parties so as to achieve design for manufacture, right first-time and finally an increase in product quality. Such a facility, which is integrated at data level and with a high speed of making changes, provides a powerful system for supporting the production of a quality prototype.

14.7 Data Collection

The experience gained through the industrial case study has shown that the gathering of data can prove to be an enormous task. This exercise has proved to take a significant portion of time. The implementation of the data feedback system requires a massive body of information to be acquired before the system can be fully adopted. The process of acquiring this knowledge could take many man-months. A methodology for knowledge elicitation, such as the use of pro-forma, developed with this thesis contributed significantly to: the documentation of fault-finding; the provision of useful guidelines for user in the collection and collation of data for feedback, and finally to the final implementation of the system.

14.8 The Case Studies

Two case studies have been considered within the scope of the thesis. Prominence has been given to the work with Renishaw which was done outside of the integrated environment of the Information Support Systems (ISS) project which allowed a first large scale test of the value of the research by placing emphasis on the building up of fault libraries based on knowledge elicitation from company personnel. This is considered to be a most important aspect of the work and the proof that a first application can be carried through satisfactorily is considered to be significant.

There is, however, a flaw in solely relying on this case study to vindicate the efforts spent on the research. It is considered that a more balanced view can be gained on the assessment of the work by considering both the Renishaw case study and the work presented in Appendix 2F which is a case study considering a Glacier top plate bearing component.

This latter piece of work was carried out within the integrated environment of the ISS and is a less complex example than the Renishaw application. The reduced scope of this case study makes it more possible to critically evaluate the effectiveness of both the central argument of the thesis and of the prototype software. As the case study is dealt with relatively briefly in the appendix it is necessary to extend the discussion beyond the scope of Appendix 2F so that a balanced assessment can be made of both the value of the research and the applicability of the experimental software.

14.9 The Glacier Top Plate Bearing Study

The Glacier top plate, consisting of a channel and four holes, was used as an example to illustrate the use of the decision network and the measurement graph. This allows the illustration of the analysis of inspection data by utilising the rules stored in the decision network. The knowledge used for building the decision network is based on data collected from the experiment on a bolster plate in the University environment [194]. The rules for each feature of the bolster plate were considered to have the potential to generically represent the Glacier top plate. The particular rules considered were those relevant to the channel and hole of the top plate. Taking the channel in particular, the rules to represent a particular route of the decision network are shown below.

D-STATE:

dimension reference : width plus/minus

process tolerance : (0.125 mm)

state : satisfactory

decision nodes :

D-STATE:

dimension reference : depth plus/minus

process tolerance : (0.25 mm)

state : lower fault

decision nodes :

tool wear/worn

tool length offset

Each d-state consists of a dimension with its tolerances, a state and a decision node which in turn can be a d-state or fault types. In the first set of d-state, the dimension is the width of the channel utilising plus/minus tolerance type. The tolerance chosen is that of process tolerance. The state given is satisfactory. Since there is more than one dimension, the second set of d-state is chosen for the decision node. The dimension is now the depth of the channel with the same type of tolerances chosen. The state given is lower fault. As there are no more dimensions, the decision node chosen is the fault types. That is, if the dimensions are of the given condition, then the fault types are due to tool wear/worn or tool length offset. More rules for representing the decision network for a channel and a hole are given in Appendix 2F. The structure of the decision network is given in Figures 2A.6 to 2A.10.

An example of the measurement graph of the channel is shown below.

linear dimension : width plus/minus

process tolerance : (0.125 mm)

measured dimension : measured width

linear dimension : depth plus/minus

process tolerance : (0.25 mm)

measured dimension : measured depth

Each measurement list consists of a linear dimension with its process tolerance and a measured dimension. In the first list the linear dimension is the width which is also the same dimension as that in the decision network. This is achieved through the process of latching and sharing. The measure dimension contains the inspected width of the channel. As with the decision network, since there is more than one dimension, the second measurement list will contain the depth of the channel. The measurement graph is shown in Figure 2A.16.

The analysis process begins with the comparison of the design dimensions against the measured dimension. This will then return with a state of either the upper action, lower action or satisfactory described in chapter 7. The control program will then continue its analysis by retrieving all the rules in the decision network and data in the measurement graph. The process of analysis is described in Chapter 9. If more than one feature is involved, the analysis will process one feature at a time. The result of the analysis will be as given below.

Begin Analysing Feature

Measurements

the name : width

nominal value : [value]

tolerance value : [value]

measured dimension : [value]

.....

FAULT : the fault type(s) with its associated cause(s) and action(s) will be given

Analysing Feature Complete

14.10 Concluding Comment

The Renishaw case study demonstrated two important points: the focus on reducing the number of 'prove-out' iterations in order to ensure workpiece manufacturability and inspectability and; secondly, the effectiveness of employing past experience to the current prototyping process. The data feedback facility addressed both these issues, firstly, by providing information not only back to design but also to other personnel involved in 'prove-out'. Secondly, by offering a computer-based facility with full feedback functionality in a product modelling environment.

The Glacier case study gave a complementary insight into the establishment of the data feedback facility in an integrated environment. The value of using a decision network for individual dimensions, described for a Glacier top plate, as opposed to that adapted for the Renishaw case study is that there is a deeper focus on relating deviant dimensions to a fault type.

Chapter 15 :

Conclusions

15.1 Introduction

The general conclusions presented in this chapter are drawn from the research work and the experience gained from the industrial case study. The research focus on rapid prototyping in a data integrated environment is valid as it is in this domain that a large number of problems require to be solved.

15.2 Access to Product Information

The data feedback system set within the product modelling environment is a powerful feature of the integrated design and manufacture system. This powerful tool allows access to the product data model for product information. Such information can be the part design's dimensions and tolerances, the manufacturing information on the set-up and machining process or the measured dimensions of the part. As reflected in the literature on Valisys, the power of interrogation and deduction of this research work is in contrast with Valisys. The latter is said to be that of acting as a software template against the processing of data.

15.3 Representing Manufacturing Knowledge with Features

Experience from the case study has shown that this approach has proved to be of value in associating manufacturing knowledge, such as the fault-finding solutions and the manufacturing methods, with features. This approach was also adopted by the research work on Dimensions and Tolerances, and Machine Plan and Code Generation in the information support system project and in this case, the Renishaw Case Study. The result of this approach permits an easier and more meaningful representation and bears a clear engineering meaning.

15.4 Modelling Collated Data with Influence Diagrams

This technique has been used to show the relationships between measurement(s), their machining states and their associated fault type. However, the case study revealed an interesting competition between the use of the Influence Diagram and the conventional flow charts. The Influence Diagram found its most effective use when the data was collated whereas the flowcharts were most effectively used for raw data collection.

15.5 Classifying Measurements with the Use of Modified Control Charts

Experience from the case study has shown that modifying the traditional statistical process control chart to the three bands: Lower Action, Upper Action and Satisfactory, was sufficient for this implémentation. This is possible since the focus of analysis is on prototyping where no trend analysis is required.

15.6 Providing a Detailed Level of Information with The Decision Network

The use of decision networks to represent branches of an Influence Diagram has proved to be of great value in those circumstances where the focus is on the individual dimension or the relationships between dimensions within a feature or even between features, and their subsequent control. This analysis has provided the most detailed level of information required in a prototyping environment. The value of this work was proven through dimensional control of a bolster plate in the university laboratory [194].

15.7 Error Identification with The Dimensional Analysis Algorithm

This dimensional analysis algorithm considers a collection of critical parameter(s) within a feature or between features. This is unique and differs from the statistical process control approaches which monitor only known and commonly single parameter(s). In addition, the algorithm permits direct error identification.

15.8 The Generic Characteristic of the Fault, Cause and Action Relationships Structure

Experience in the case study has proved that the structure is very powerful and versatile and able to cope with variations, such as the use of the manufacturing method as an alternative to expressing a fault, cause and action relationships. The full power of the generic approach was drawn and brought to light in converting the Renishaw case data into a feedback system for dimensional analysis.

15.9 Decisions Based on 'Weightings'

The difficulty of using the probability models are compounded by the fact that the theory was often not well comprehended. Also, an interviewee's estimate of probability is usually inaccurate and difficult to elicit or justify. Problems arose when attempting to use probability in the case study. Thus, the data feedback system has found that attaching 'weightings' to decisions are more than adequate.

15.10 Versatility of The Taxonomic Structure in the Organisation of Data

This structure is used to support the verification checks and fault clusters. The versatility of the structure allows data to be formulated and organised to the needs of the user. Such versatility is reflected in the case study for the building of fault-finding solutions and manufacturing method selection framework.

15.11 A 'Short-Circuit' Fault identification

Since the data feedback system involved a substantial amount of data, the research approach of using fault clusters, has proved to be of great value especially to the experienced user. This allows the user to arrive at the fault type immediately without having to respond to unnecessary questions. This approach was met with great enthusiasm in the industrial environment.

15.12 'Closing' the Loop in a Product Modelling Environment

The research was foreseen to occur through the channelling of data within the product data model. The experience borne out of this work proved the validity of this aim in the prototyping life cycle. The provision of feedback facilities, such as decision networks, verification checks and fault clusters, at different levels in the product data structure ensured that corrective action(s), undertaken at manufacturing, with data recorded in the same model, was available to all other functions thus achieving a 'closed' loop. The value of this approach in an industrial environment can almost be said to be analogous to the achievement of crossing of several traditional departments boundaries for information and support.

15.13 Preserving a Single Source of Data

The structures provided within this research work are implemented within the product data model of the Information Support System. Similar to the product data model providing a single source of data in an integrated design to manufacture environment, an associative structure is provided in this research for the fault library in the overall data feedback system. The power of the structure was illustrated through its accessibility to all other functions, its visibility to the user and a common point for data entry.

15.14 Human-Centred Data Feedback System

The provision for human-centred data feedback is catered for by visualisation and the structure editor. The visualisation permits user interaction through data access through an overall information support system, that is by the provision of walking facilities, the user is able to visibly interact and communicate between functions.

The value of this work has been shown through the project integration between dimensions and tolerances, machine plan and code generation and inspection plan and code generation. Also drawn out of the user's experience of the prototype software, particularly in linking with the HORSES User Interface Management System [96, 97], was the limited

user-friendliness. However, the human-centred approach adopted within the software was well-received and through the use of visualisation, permitted the user to participate with the learning and understanding process.

Chapter 16:

Recommendations for Further Work

It is recommended that further work be undertaken in the following areas:

16.1 Providing of Facilities for Automatic Correction

The facilities provided in the data feedback system are essentially human-centred. This approach is based on the current emphasis on human involvement. Some form of facilities for automatic correction in other functions, such as the updating of tool types and machining conditions relating to the manufacture of a part, must be explored to provide an enhanced information support system.

16.2 Enhancing the Implementation through Case Studies

The research work implementation would benefit greatly from many more case studies. The case studies are required to complete the data feedback system evaluation to provide a comprehensive base of knowledge for prototype design and manufacture.

16.3 Enhancing the User Interface

Embedding and integrating the learning and knowledge within this thesis within industrially accepted technologies should be further investigated. The user-friendliness of the software also requires to be enhanced. Emerging technologies such as multimedia which considerably enhance the user's acceptance of systems should be explored for use in data feedback. This technology combines the use of audio, video and graphics to provide highly interactive visualisation. One such multi-media system may be TACIT [390], exhibited in October at CIM 1990. This company has expressed interest in furthering this work.

APPENDIX IA.

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APPENDIX 1A :

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APPENDIX IB.

FIGURES

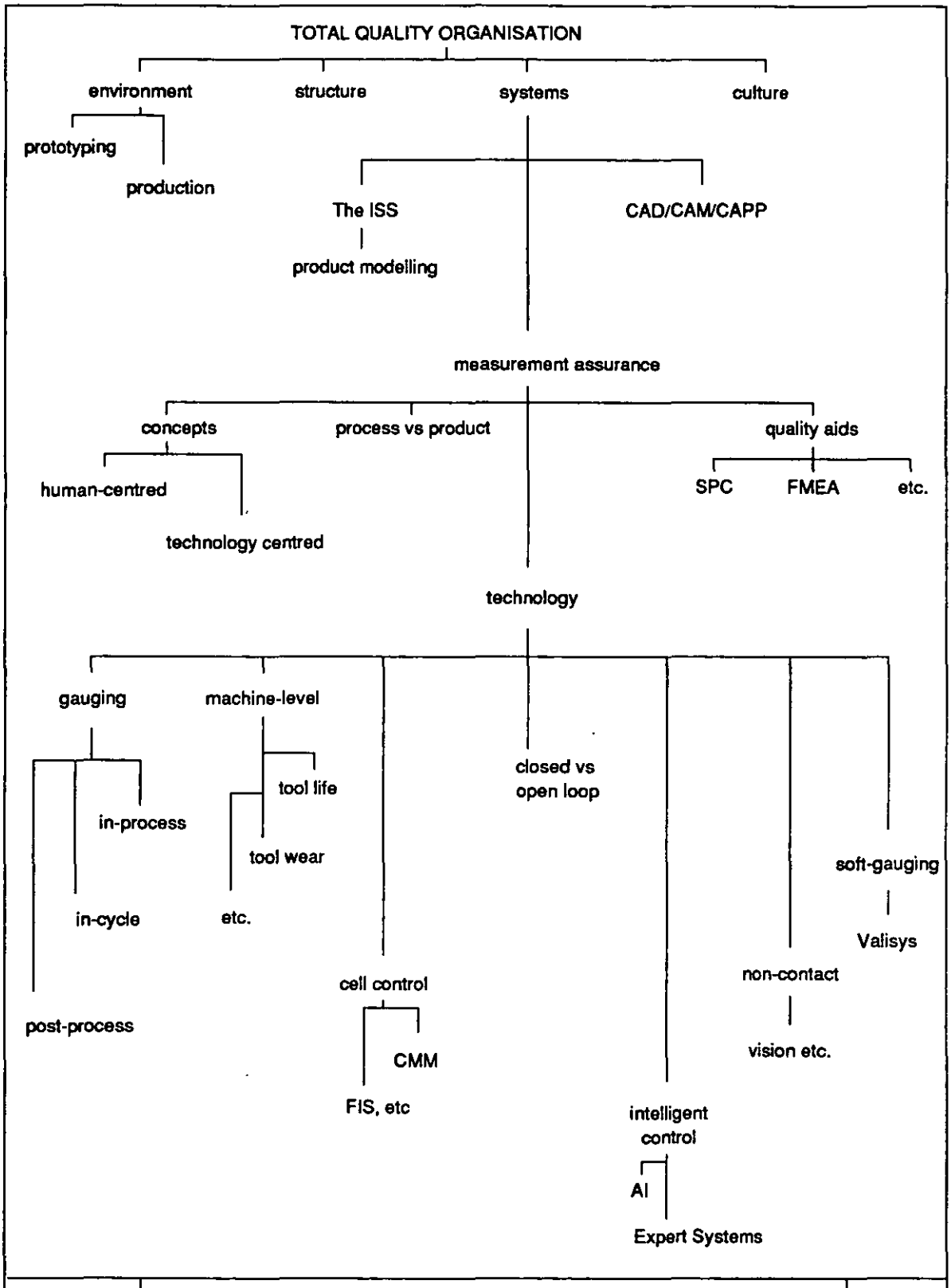


Figure 2.1 TECHNOLOGIES IN THE CONTEMPORARY FACTORY

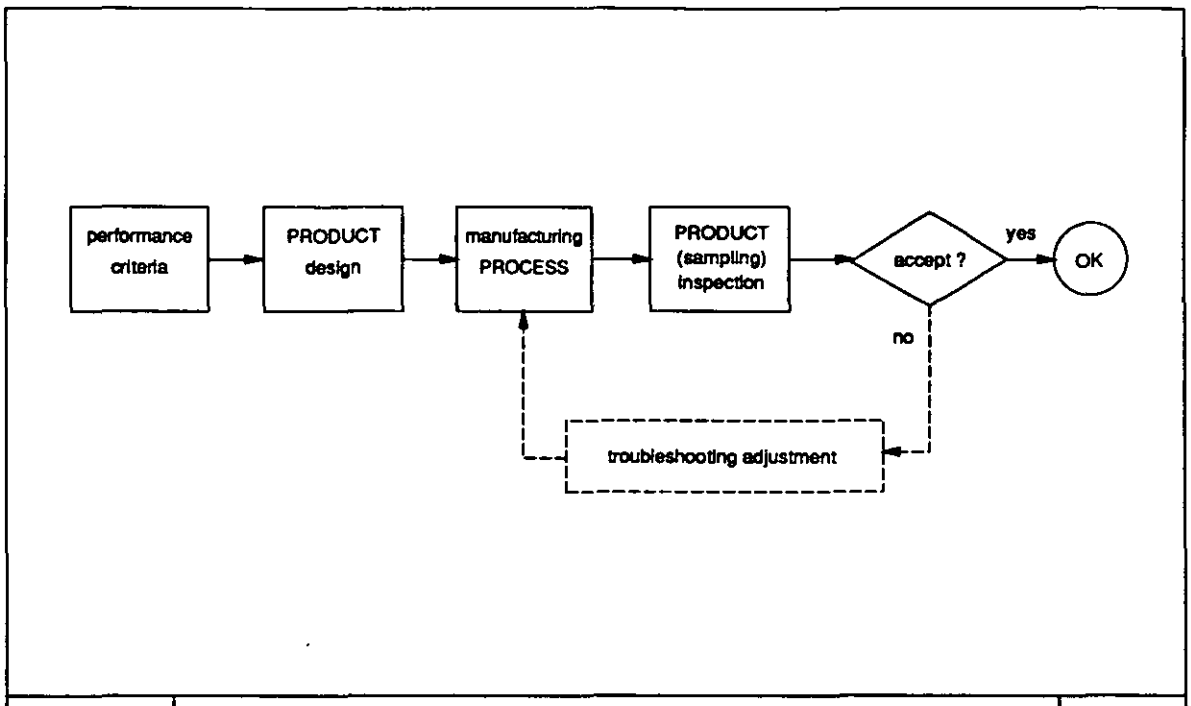


Figure 2.2	QUALITY BY FAULT DETECTION	Ref. 128

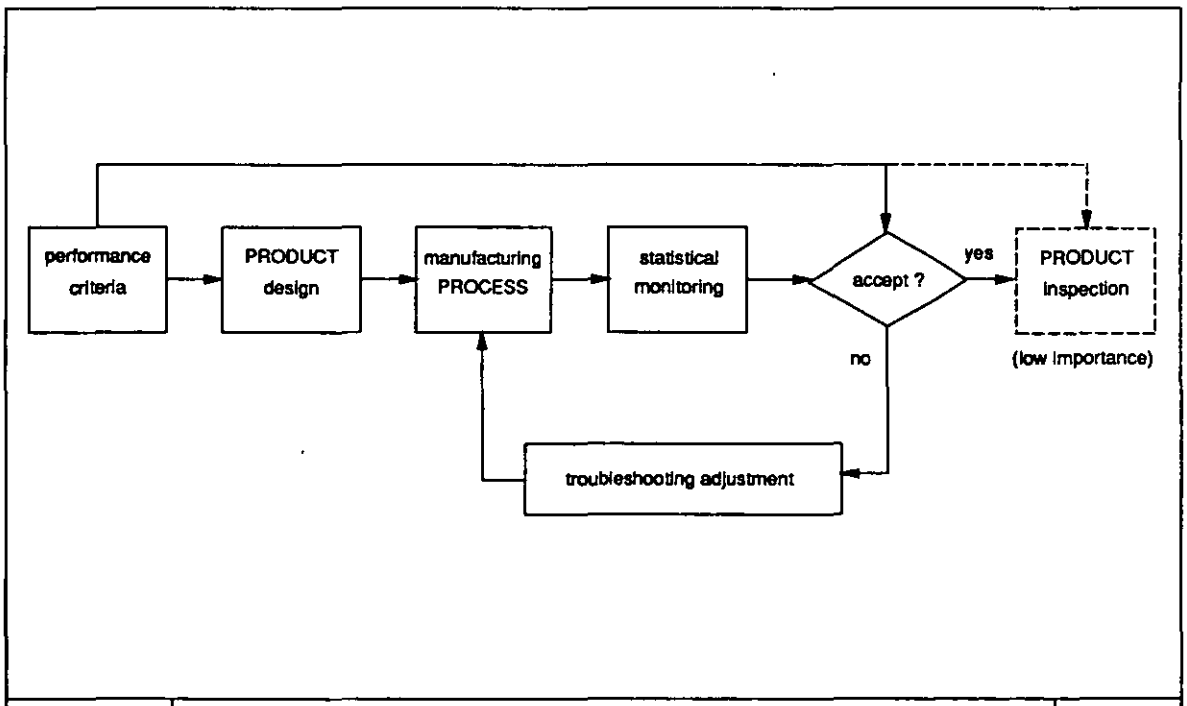


Figure 2.3	QUALITY BY FAULT PREVENTION	Ref. 128

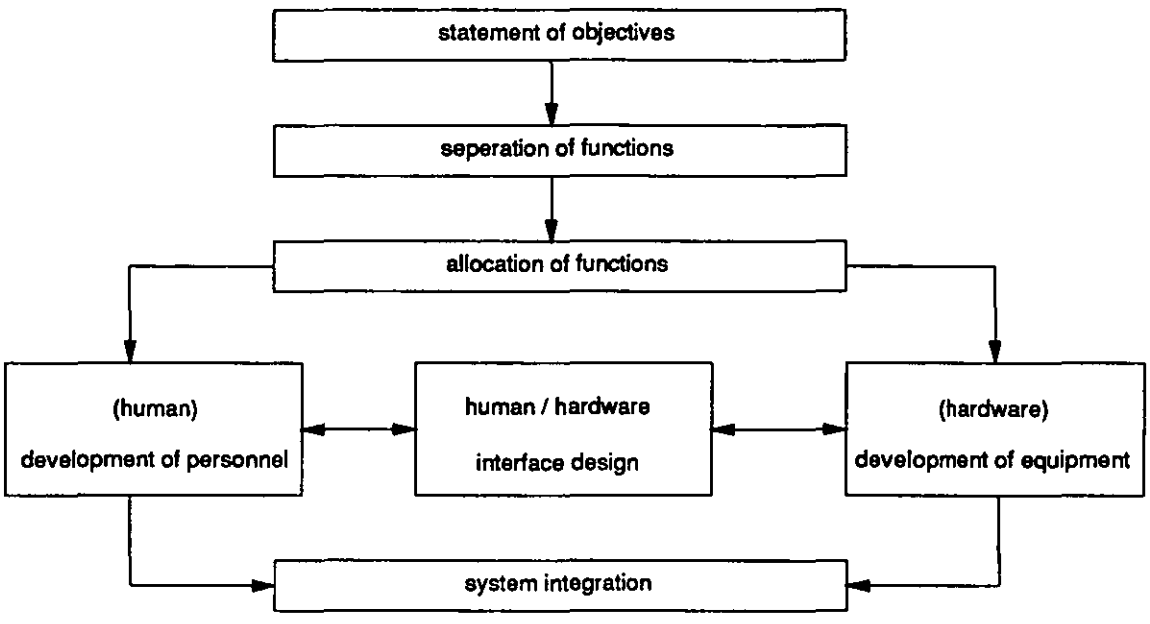


Figure 2.4	HUMAN-CENTRED APPROACH TO SYSTEM DESIGN	Ref. 287

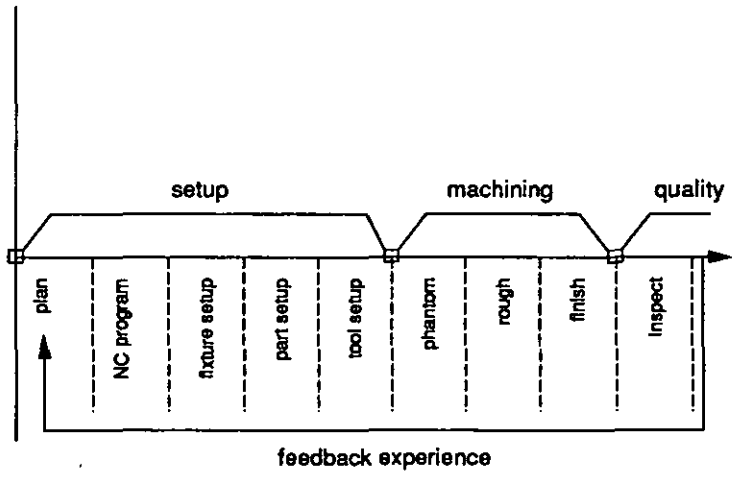


Figure 2.5	9 PHASES OF THE MACHINING TASK IN PROTOTYPING	Ref. 60

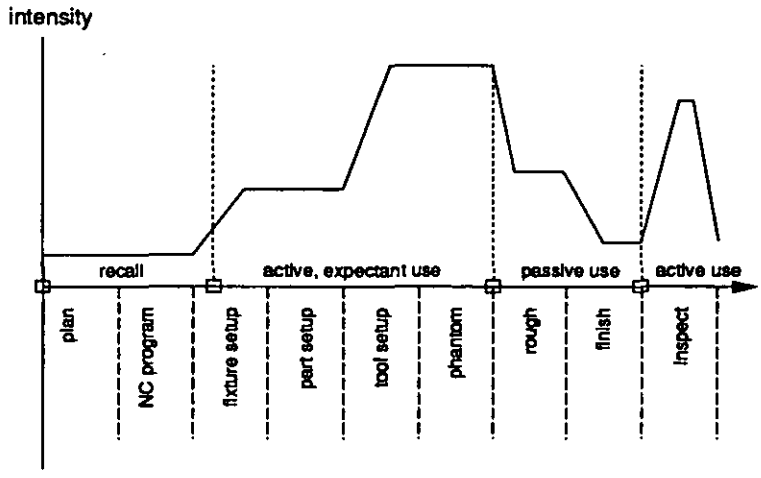


Figure 2.6	THE USE OF VISUAL MONITORING DURING PROTOTYPING	Ref. 60

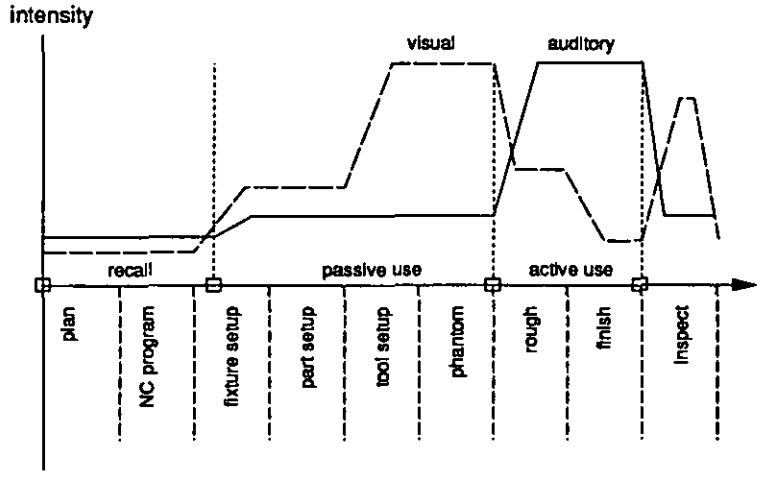


Figure 2.7	THE USE OF AUDITORY MONITORING DURING PROTOTYPING	Ref. 60

TYPE A TASKS	
Normal run of batch	1. swarf removal from piece, tools, etc.
	2. adjusting coolant
TYPE B TASKS	
Normal run of batch	3. loading of pieces (mounting and resetting)
	4. unloading of pieces
	5. workpiece measurement
	6. tool adjustment and tip changing
	7. monitoring for malfunction
	8. deburring of pieces
Machine setup	9. tools
	10. jigs, clamps, chucks
	11. first workpiece
Jig, tool and workpiece availability	12. grinding, presetting, delivery of tools
	13. making and delivery of jigs
	14. preparing & delivery of clamping tools, chucks
	15. delivery of workpieces
Determination of cutting programs	16. cutting sequences
	17. geometry of contours
	18. tooling arrangement
	19. feed rate/ cutting speed for sequences
Test run	20. observation of machine and workpiece movement
	21. checking compatibility, safety, economy of program
	22. checking quality and precision of cuts
	23. readjustment of cutting conditions
	24. modification of sequences, geometry
	25. change of tools, setup, jigs, etc.
Storage	26. store processed program in memory
Production control	27. estimation of machinery/personnel capacity
	28. setting of production priorities
	29. scheduling
	30. work progress control
Work analysis and planning	31. types of machines
	32. cutting sequences
	33. distribution of cuts
	34. tool and material economy
	35. speed of operation
	36. safety
Type C Task	
Design	40. design of piece

Figure 2.8	OPERATING ACTIVITIES IN PREPARATION AND EXECUTION OF MACHINING TASKS	Ref. 87

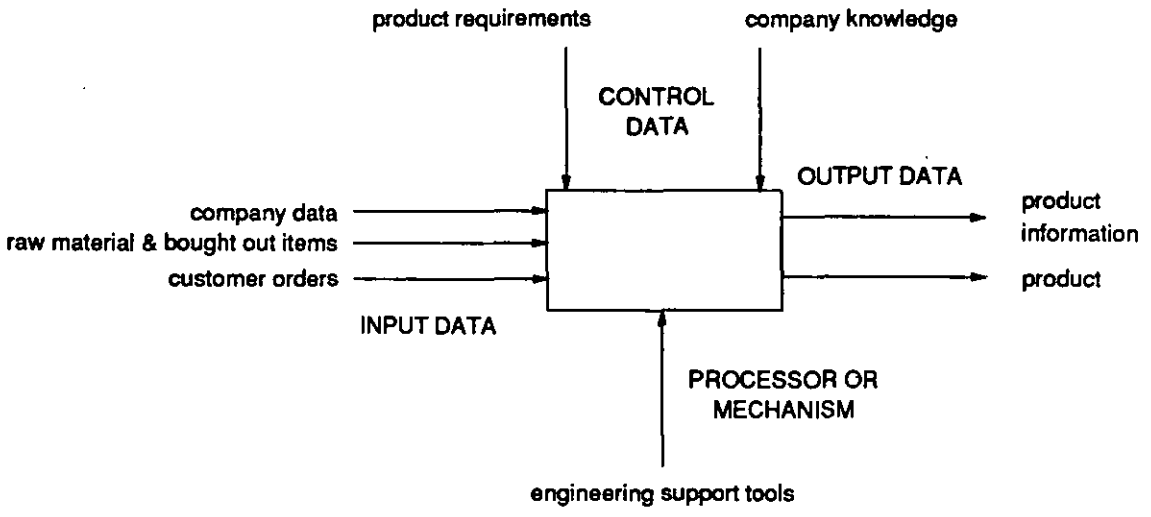


Figure 3.1 IDEF METHODOLOGY - PRODUCE PRODUCT

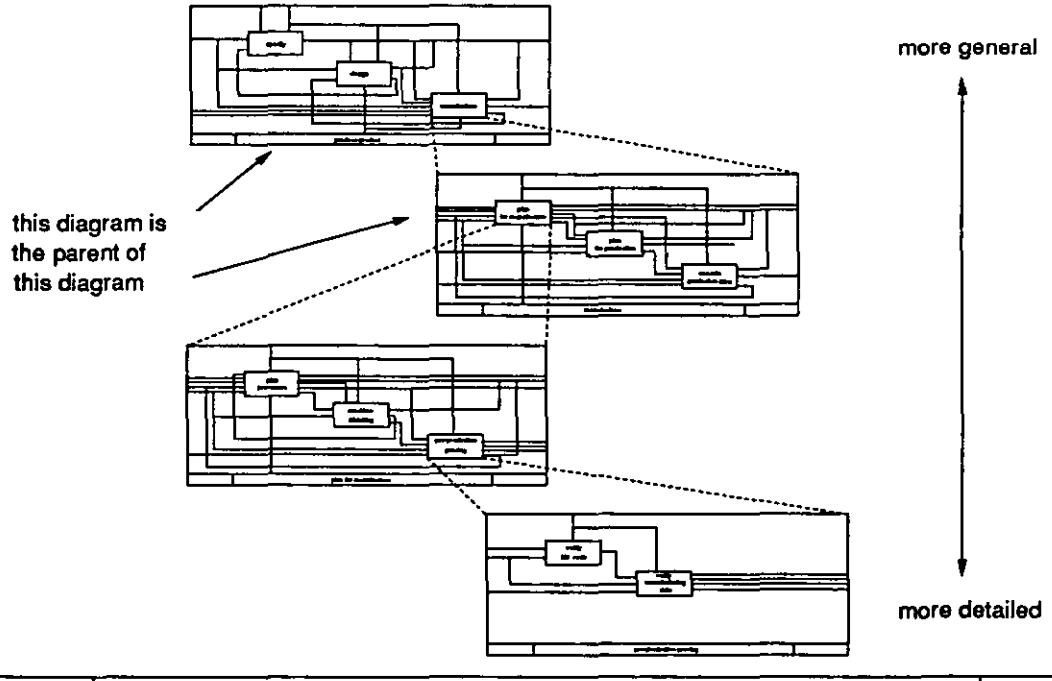


Figure 3.2 VIEW OF THE INFORMATION SUPPORT SYSTEM USING IDEF

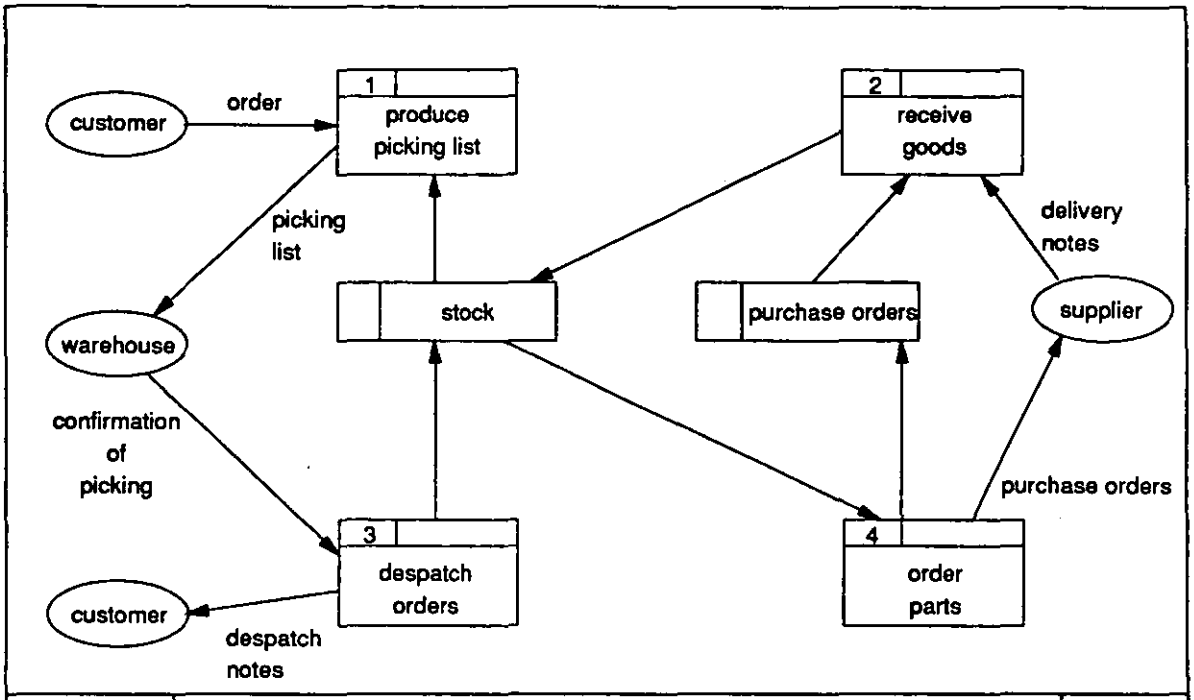


Figure 3.3	AN EXAMPLE OF THE USE OF SSADM (OVERVIEW DFD)	Ref. 189

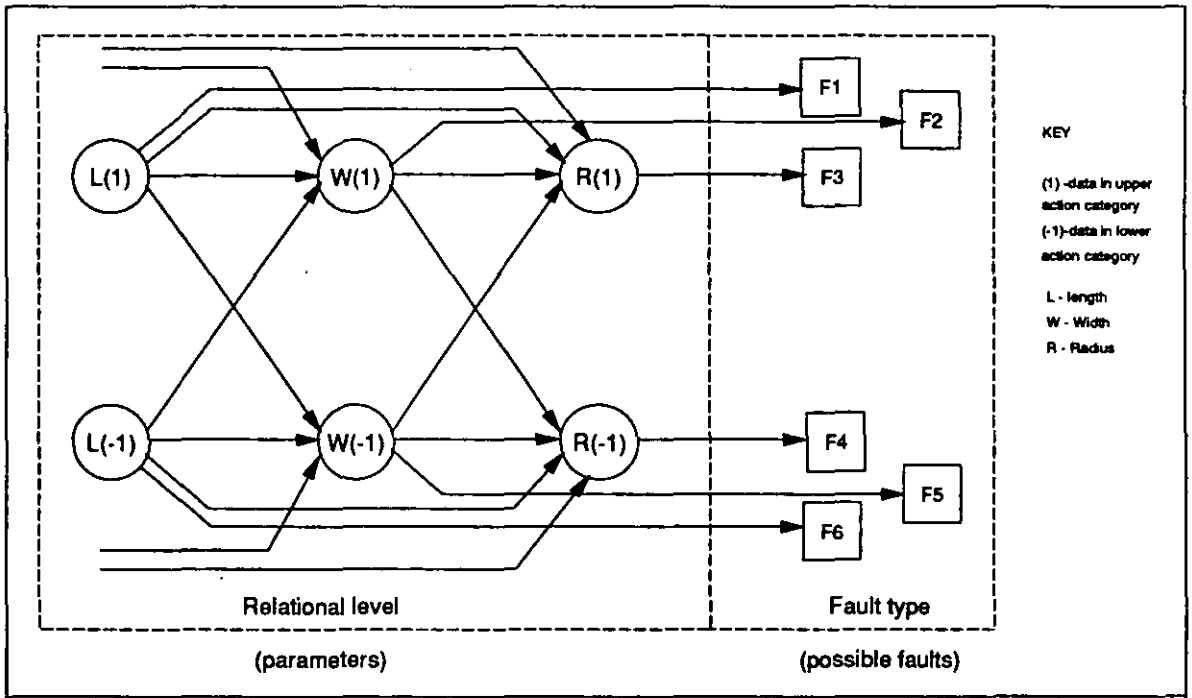


Figure 3.4	THE USE OF AN INFLUENCE DIAGRAM	Ref. 216

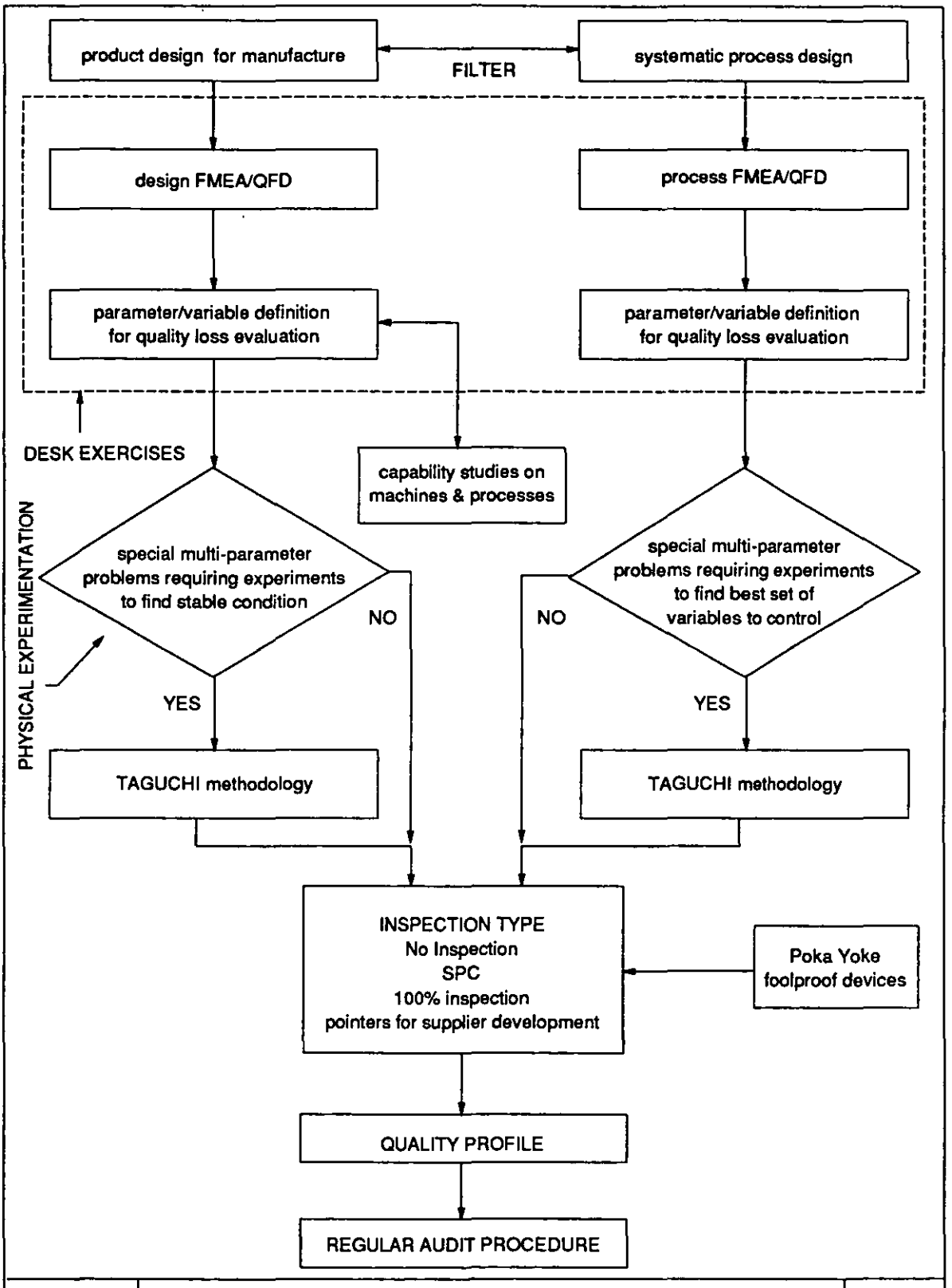


Figure 3.5 SYSTEMATIC APPROACH TO PRODUCT & PROCESS QUALITY Ref. 195

POTENTIAL FAILURE MODE	POTENTIAL EFFECTS OF FAILURE	POTENTIAL CAUSES OF FAILURE	EXISTING CONDITIONS				
			CURRENT CONTROLS	OCCURENCE	SEVERITY	DETECTION	RPN

RECOMMENDED ACTIONS AND STATUS	RESULTING CONDITIONS				
	REVISED CONTROLS	OCCURENCE	SEVERITY	DETECTION	RPN

RATING	OCCURENCE	SEVERITY	DETECTION
1	almost never	hardly noticeable	absolutely obvious
↓	occassionally ↓	dissatisfaction ↓	visible ↓
10	often	serious effects	undetectable

Figure 3.6 FAILURE MODES AND EFFECTS ANALYSIS (FMEA) Ref. 195

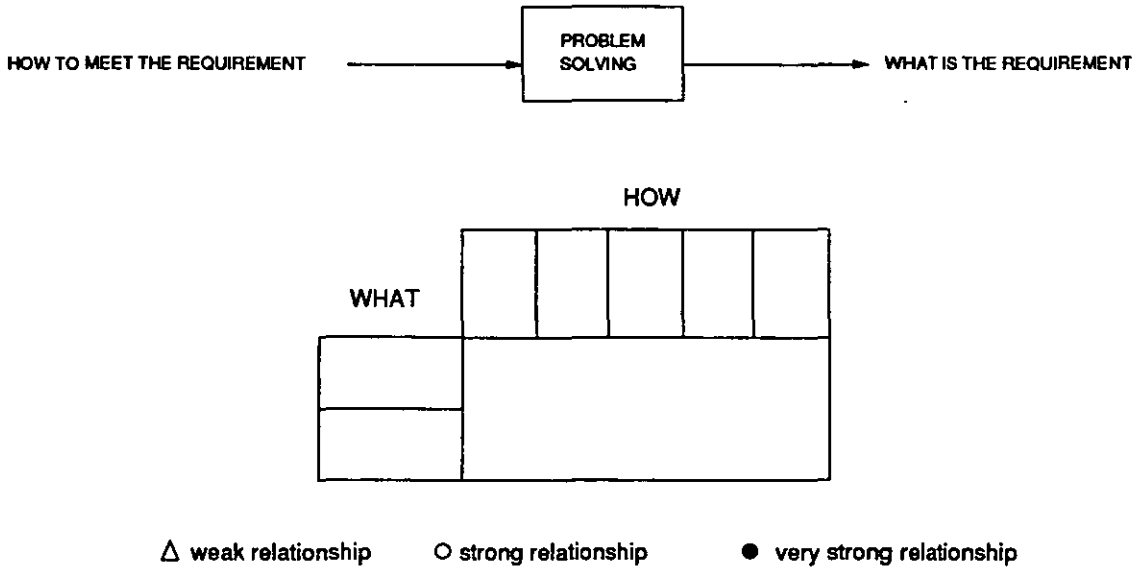


Figure 3.7 QUALITY FUNCTION DEPLOYMENT Ref. 195

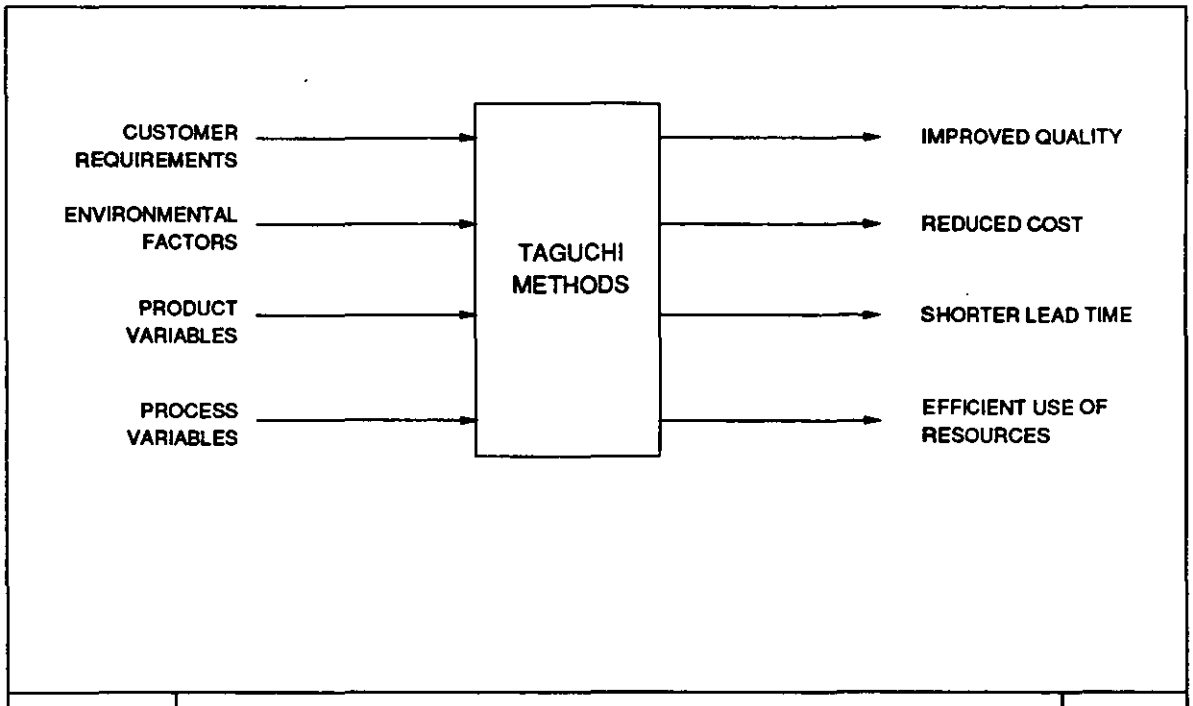


Figure 3.8	TAGUCHI METHODS	Ref. 195

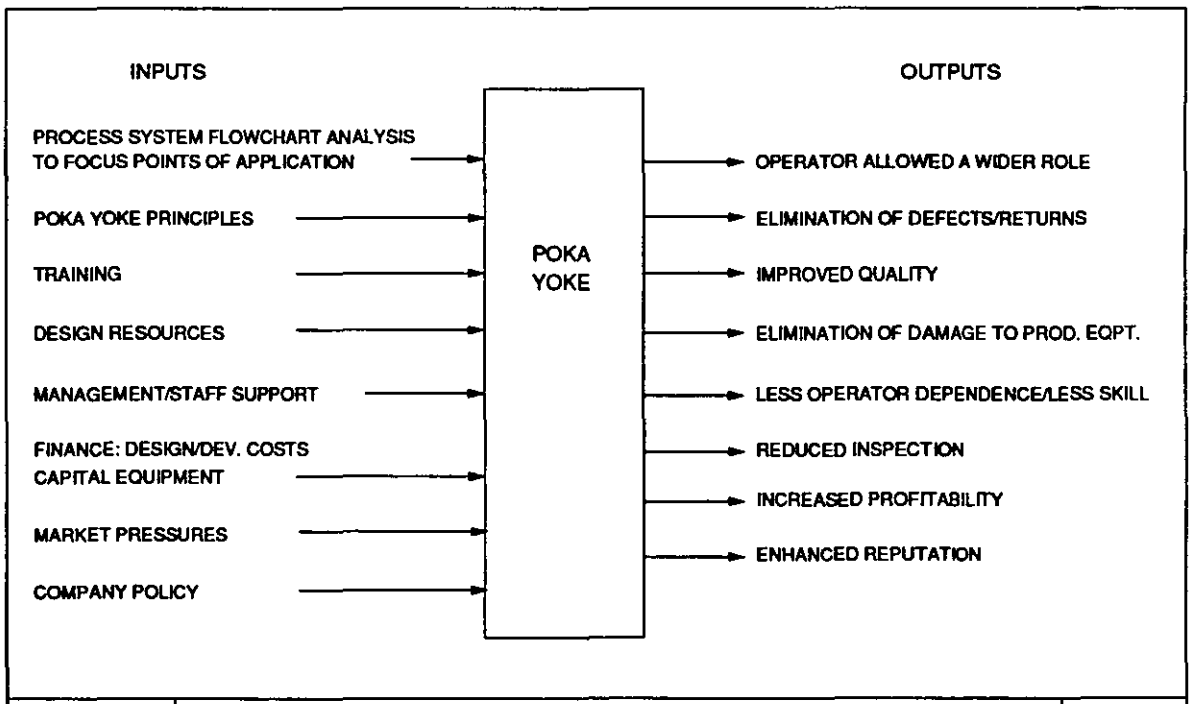
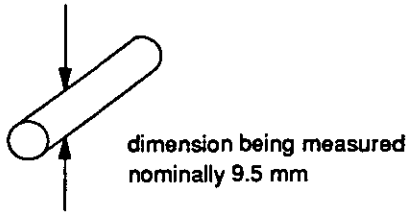


Figure 3.9	POKA YOKE	Ref. 195



(frequency = rate of occurence of a particular dimension)

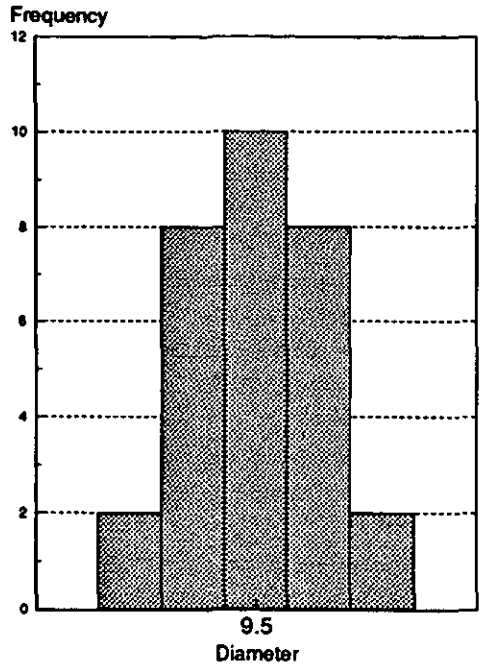
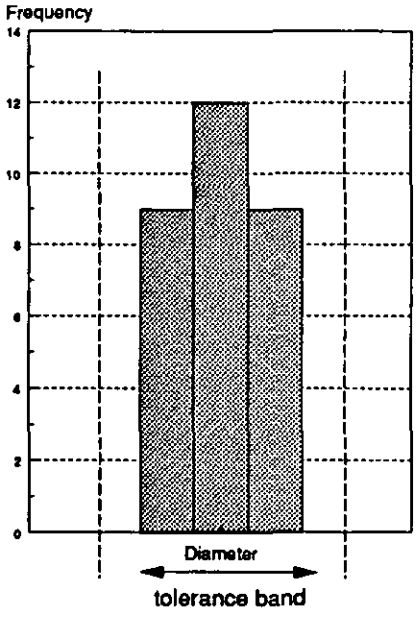
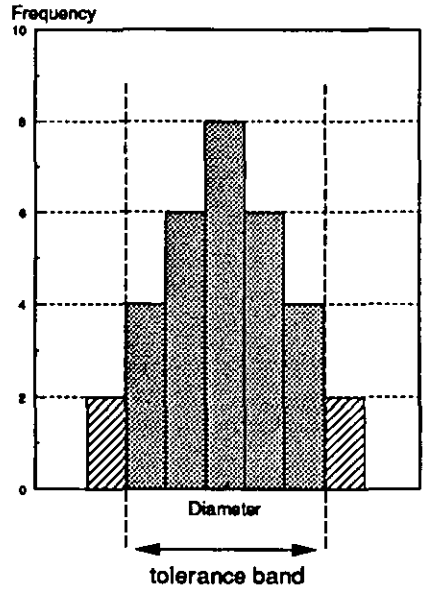


Figure 3.10	STATISTICAL PROCESS CONTROL	Ref. 195



machine capable of achieving accuracy



machine not capable of achieving accuracy

Figure 3.11	PROCESS CAPABILITY	Ref. 195

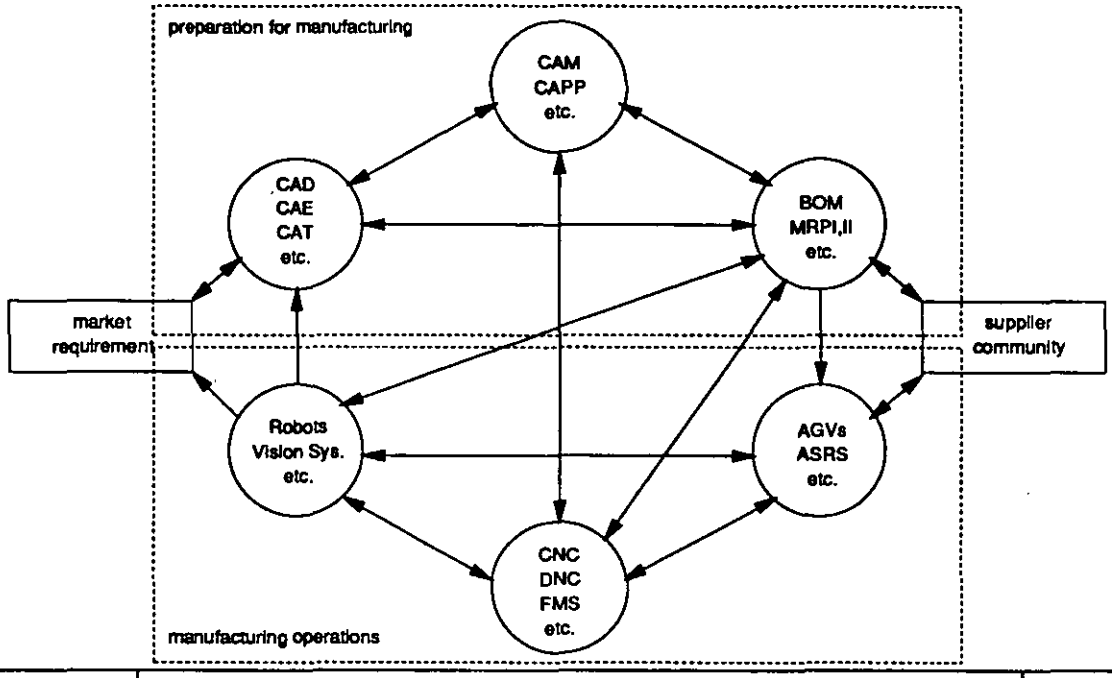


Figure 4.1	THE INTEGRATED MANUFACTURING ENTERPRISE	Ref. 268

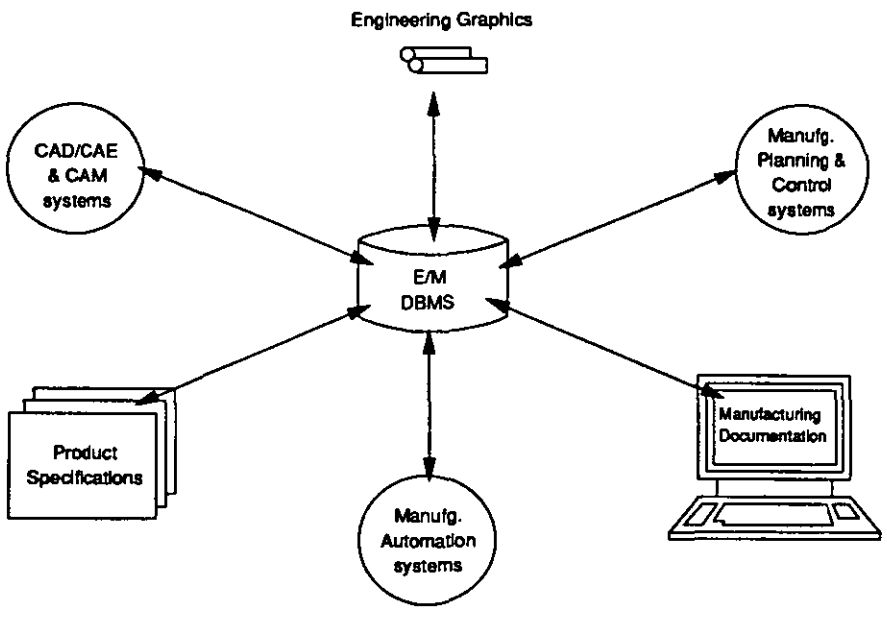


Figure 4.2	CIM USING AN ENGINEERING MANAGEMENT DBMS	Ref. 268

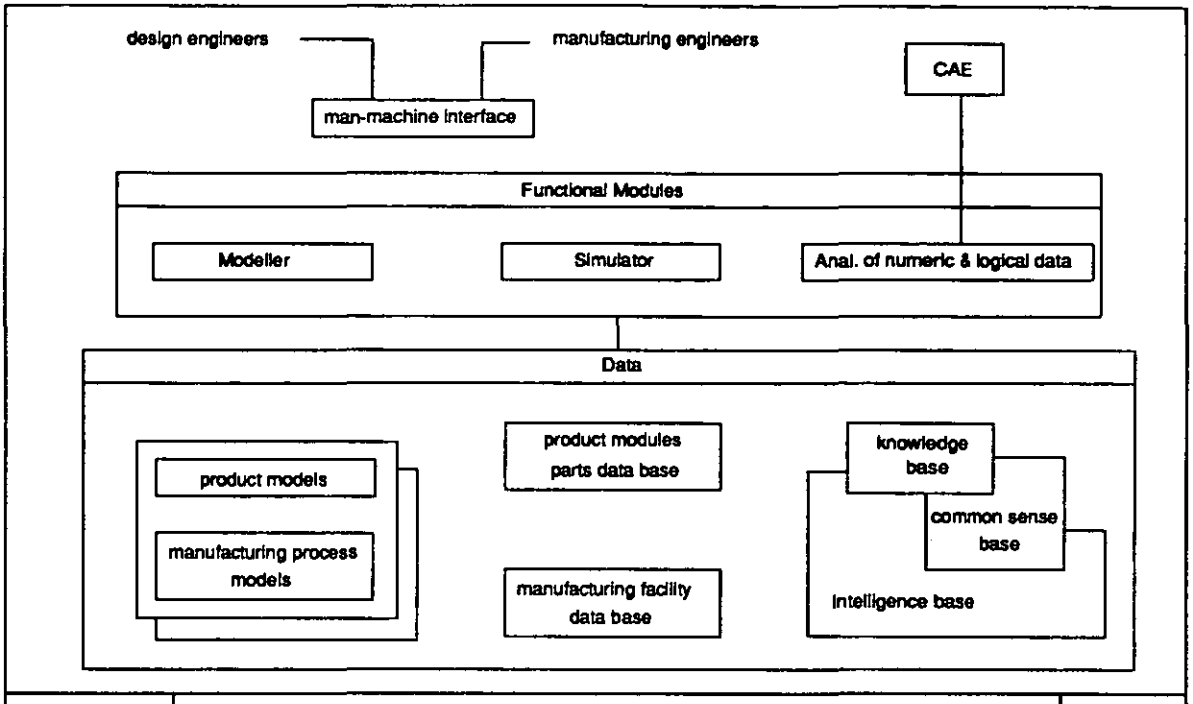


Figure 4.3	ELEMENTS OF INTEGRATED CAD/CAM SYSTEM	Ref. 151

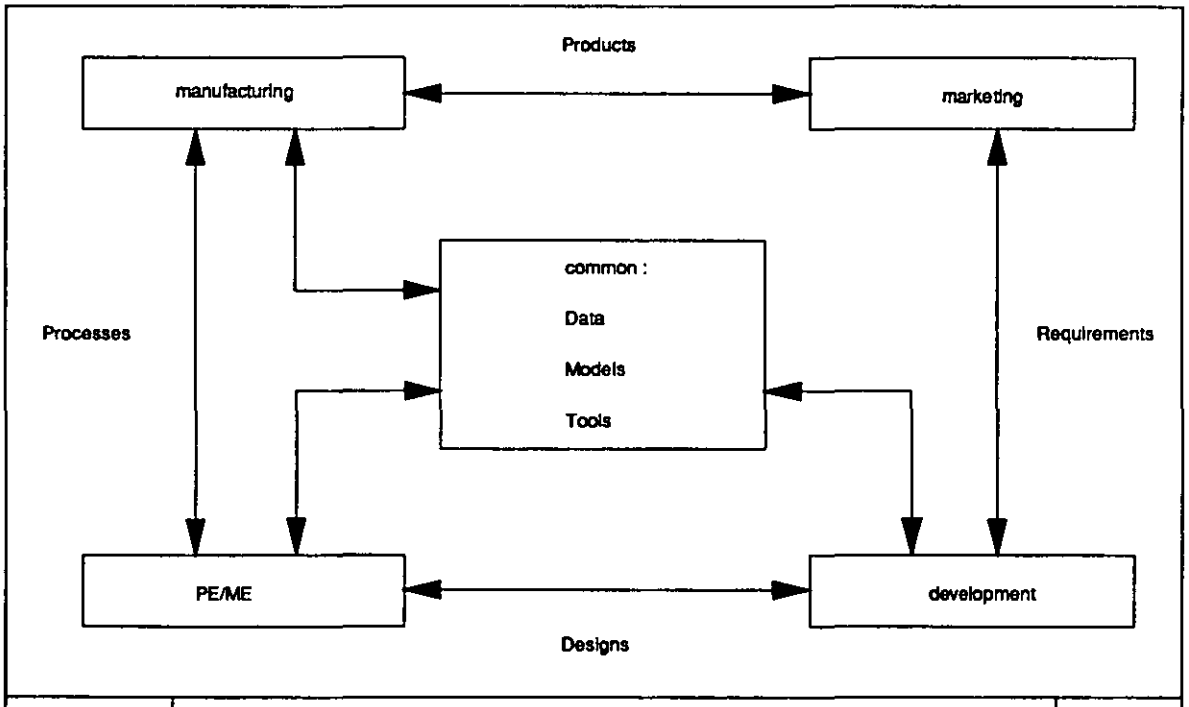


Figure 4.4	IDEALISED PRODUCT CYCLE	Ref. 151

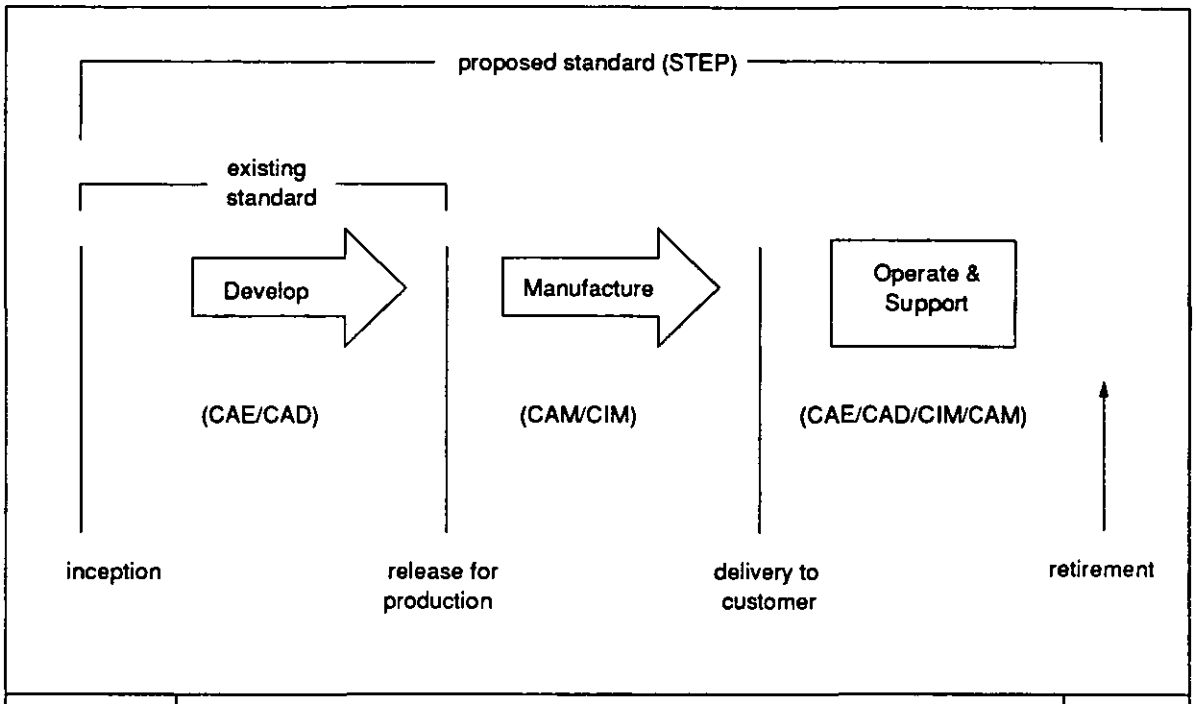


Figure 4.5	A TYPICAL PRODUCT'S LIFE CYCLE	Ref. 98

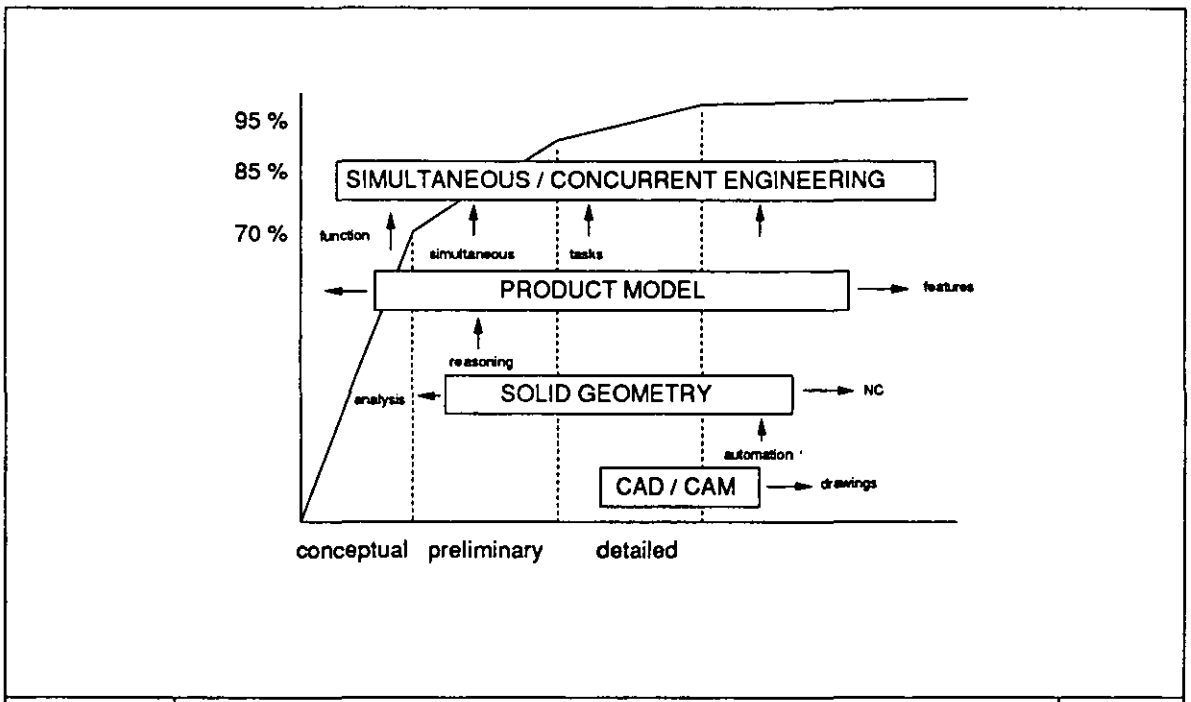


Figure 4.6	% TOTAL COST COMMITTED DURING DESIGN PHASE	Ref. 98

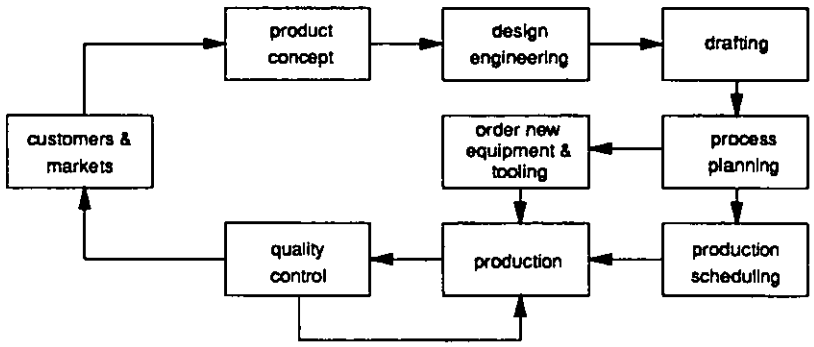


Figure 4.7	THE PRODUCT CYCLE (DESIGN & MANUFACTURING)	Ref. 132

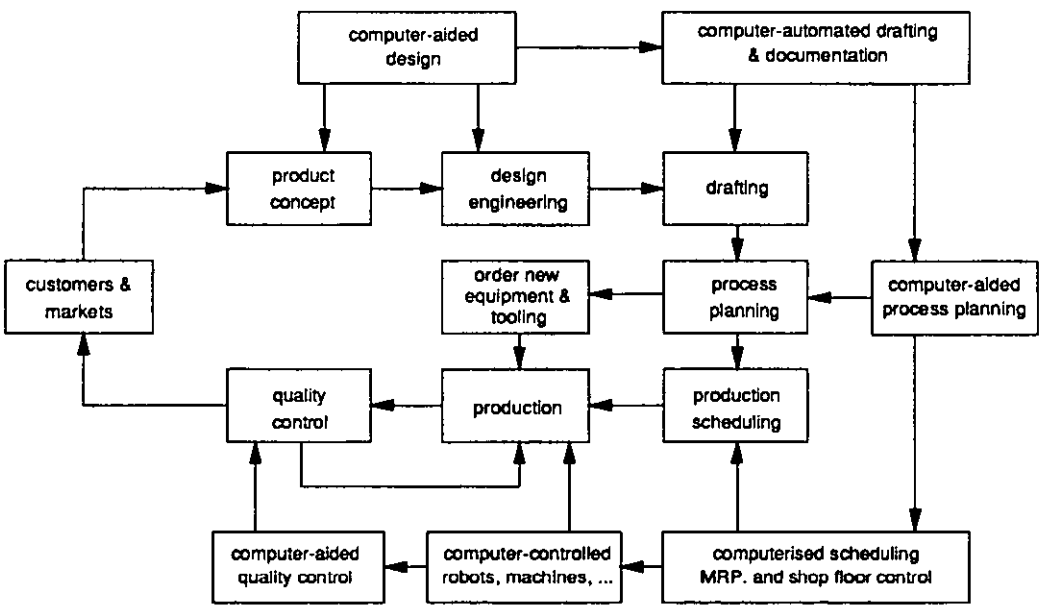


Figure 4.8	THE PRODUCT CYCLE REVISED WITH CAD/CAM OVERLAID	Ref. 132

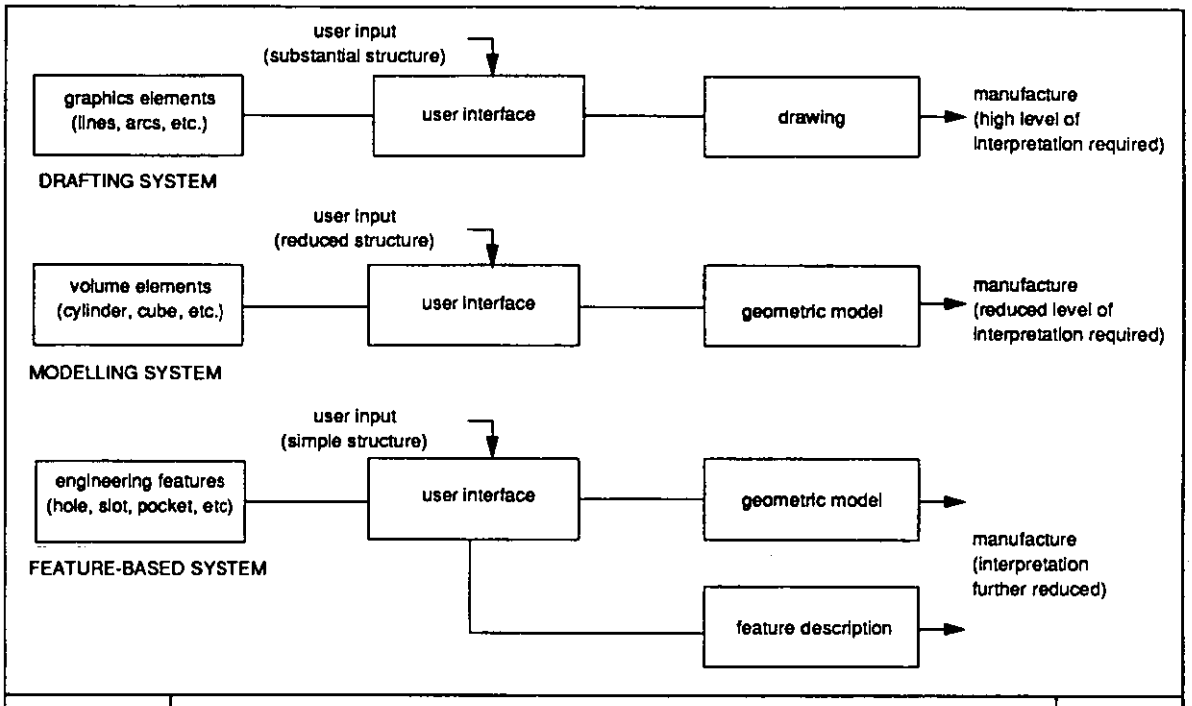


Figure 4.9	CAD SYSTEM STRUCTURES	Ref. 232a

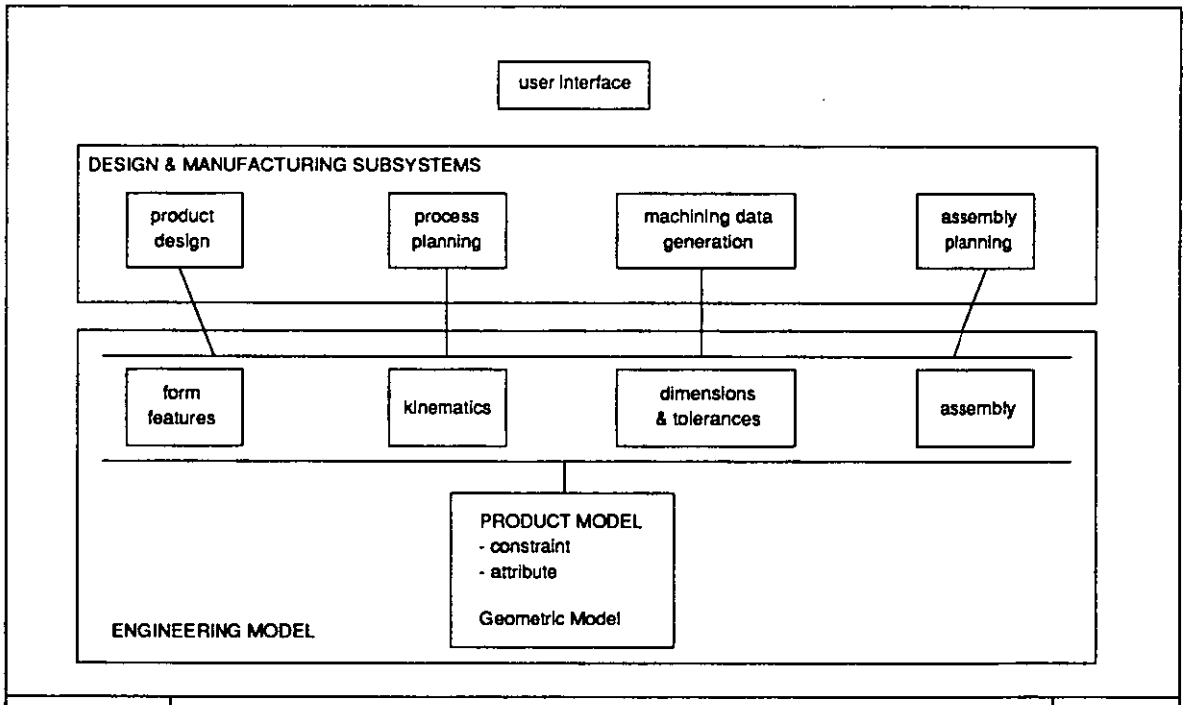


Figure 4.10	CIM SYSTEM ARCHITECTURE BASED ON PRODUCT MODELLING	Ref. 173

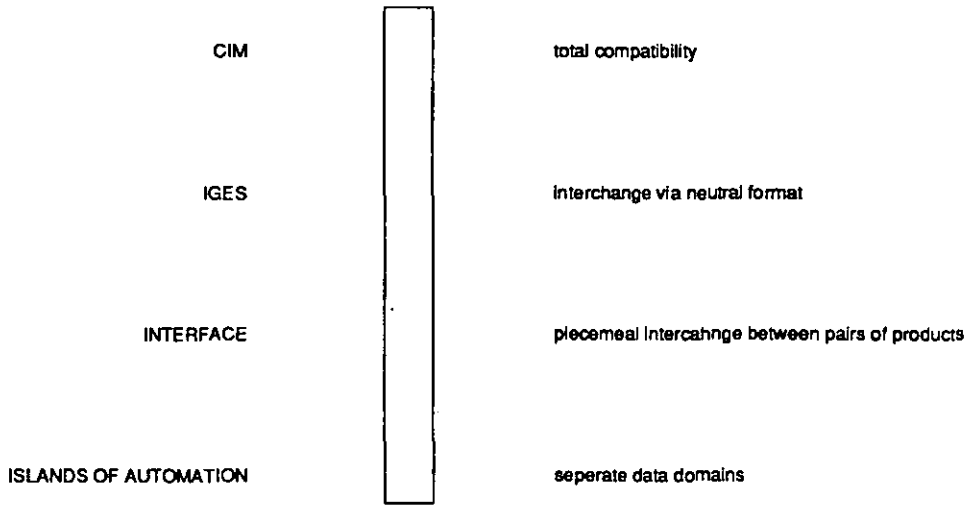


Figure 4.11	DATA COMPATIBILITY	Ref. 98

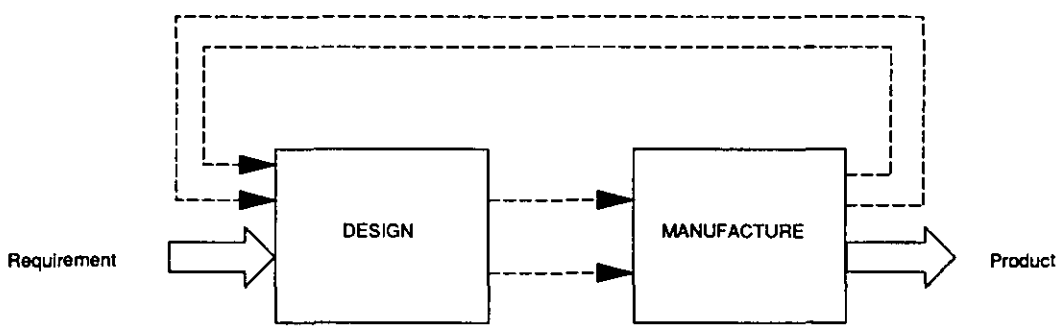


Figure 4.12	IMPRECISE LINKAGES - TODAY'S PRACTICE	Ref. 46

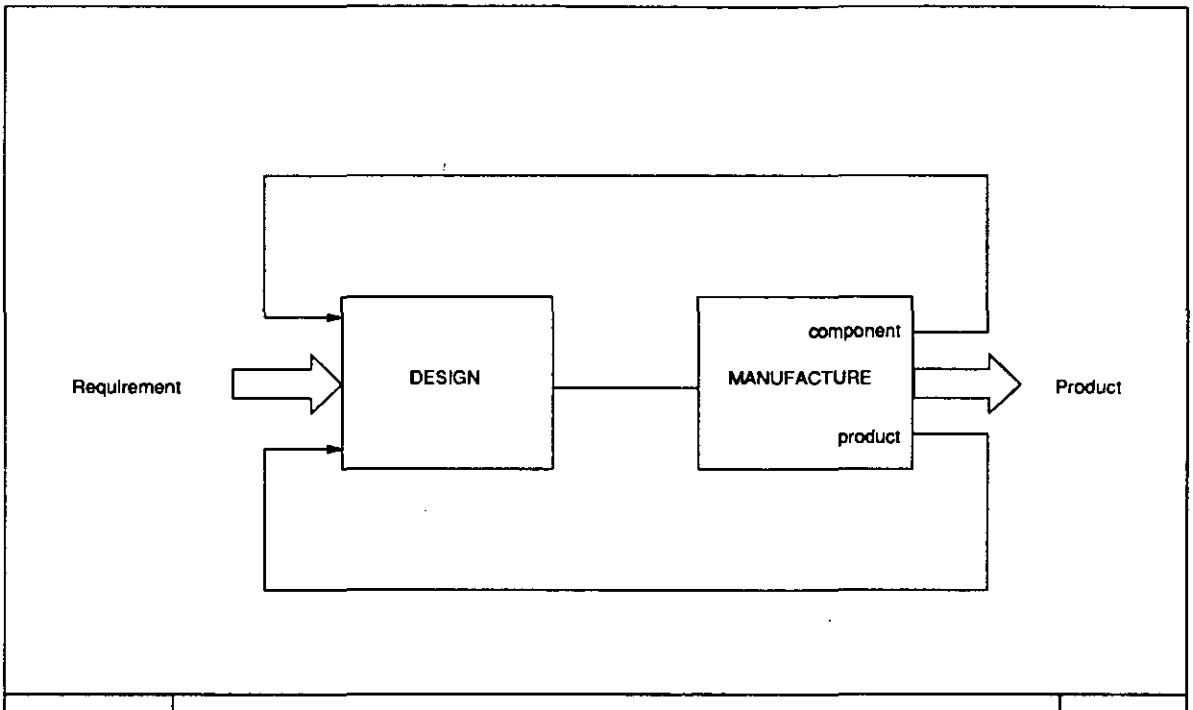


Figure 4.13	HIGHLY AUTOMATED LINKAGES - TOMORROW'S POSSIBILITY	Ref. 46

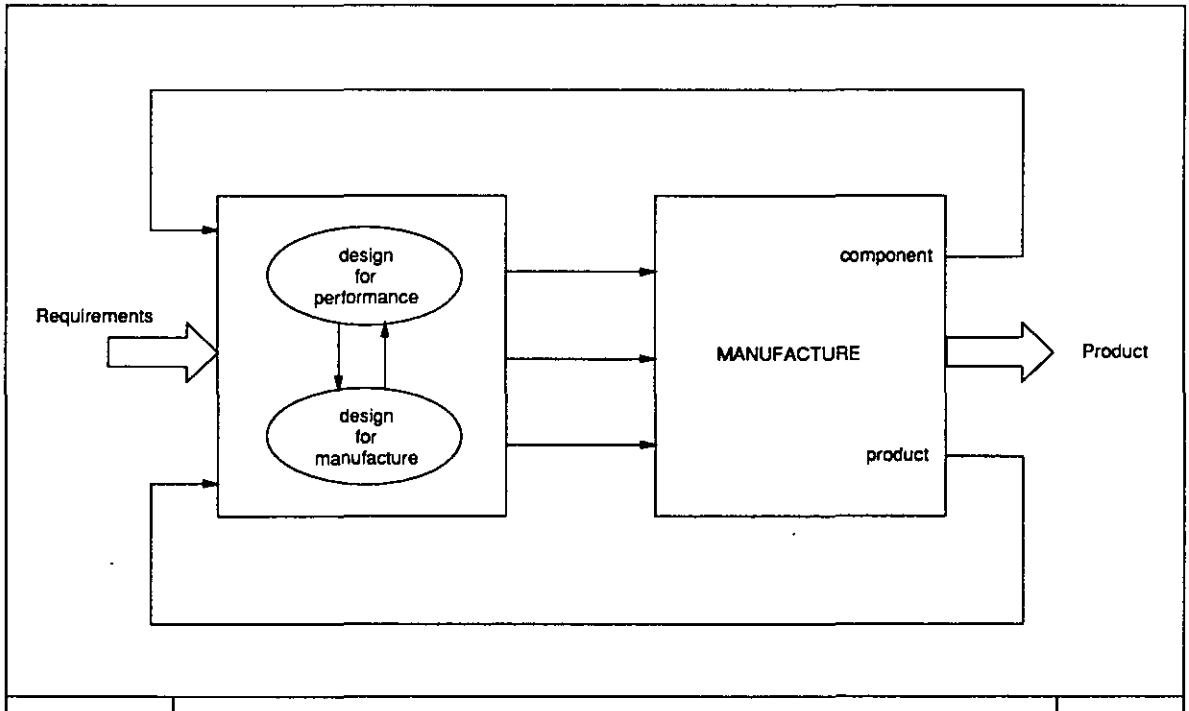


Figure 4.14	FULLY INTEGRATED DESIGN & MANUFACTURE - CIRCA 199?	Ref. 46

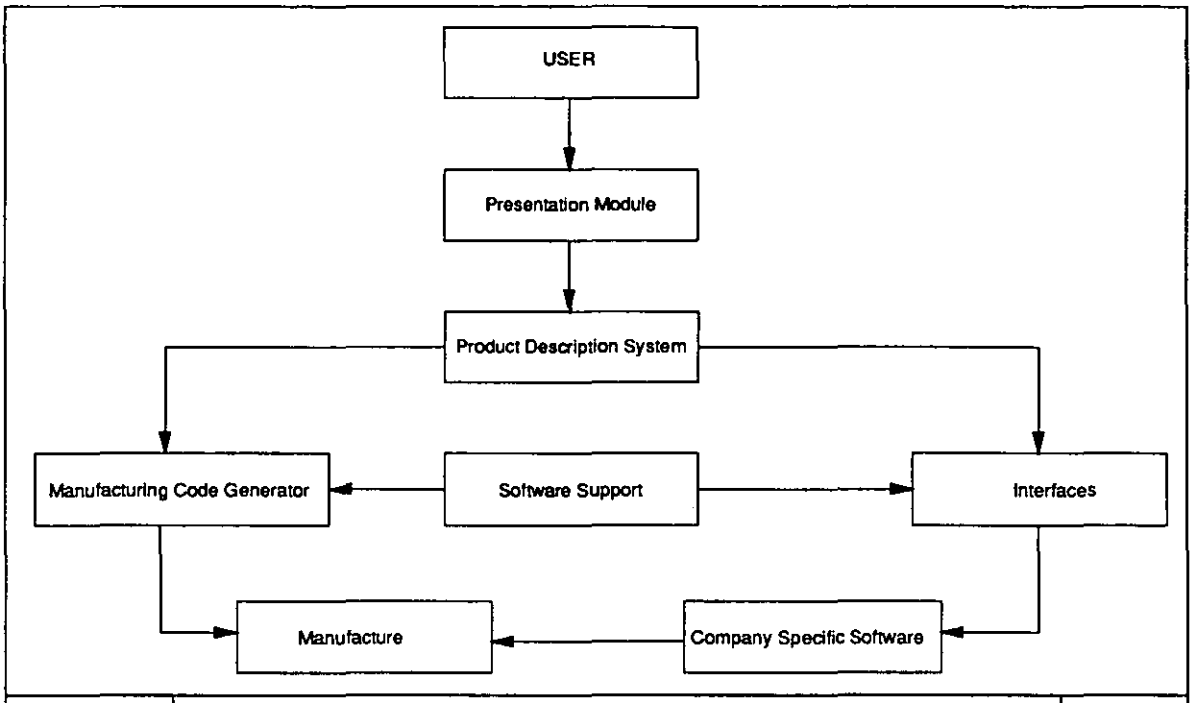


Figure 4.15 PROJECT OVERVIEW

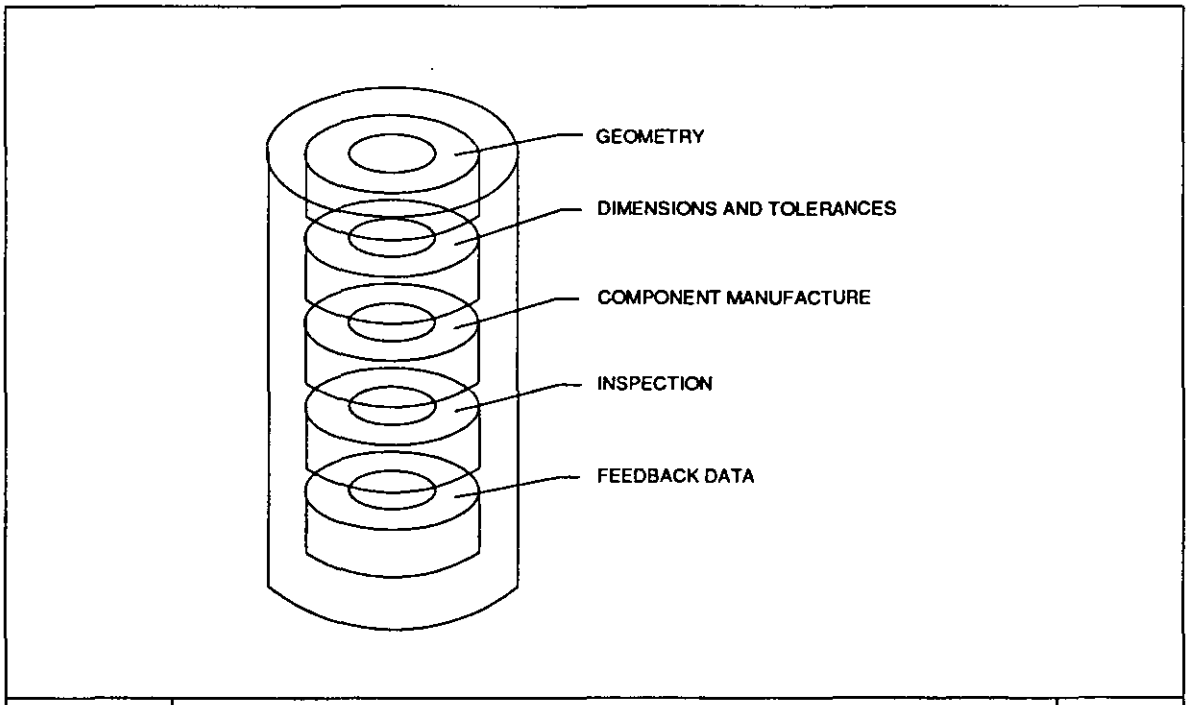


Figure 4.16 PRODUCT DATA MODEL

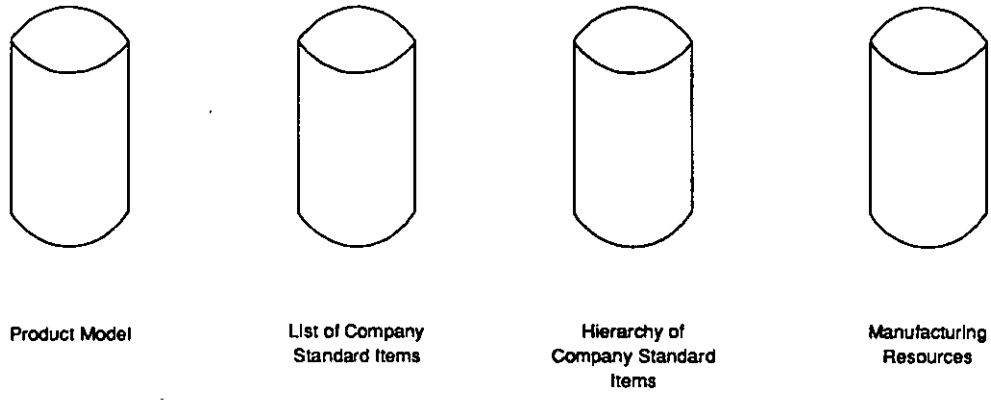


Figure 4.17	THE PROJECT META-STRUCTURE	Ref. 151

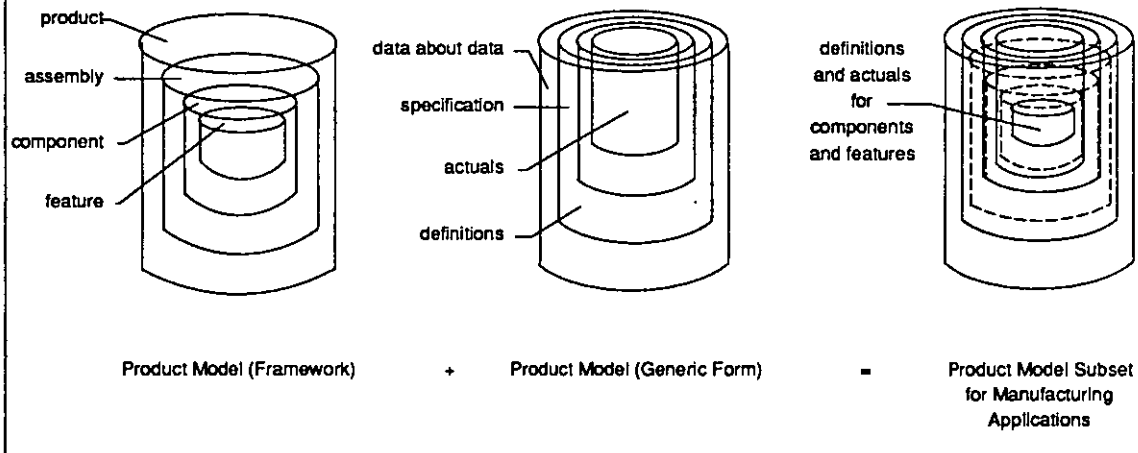


Figure 4.18	PRODUCT MODEL DEFINITIONS	Ref. 151

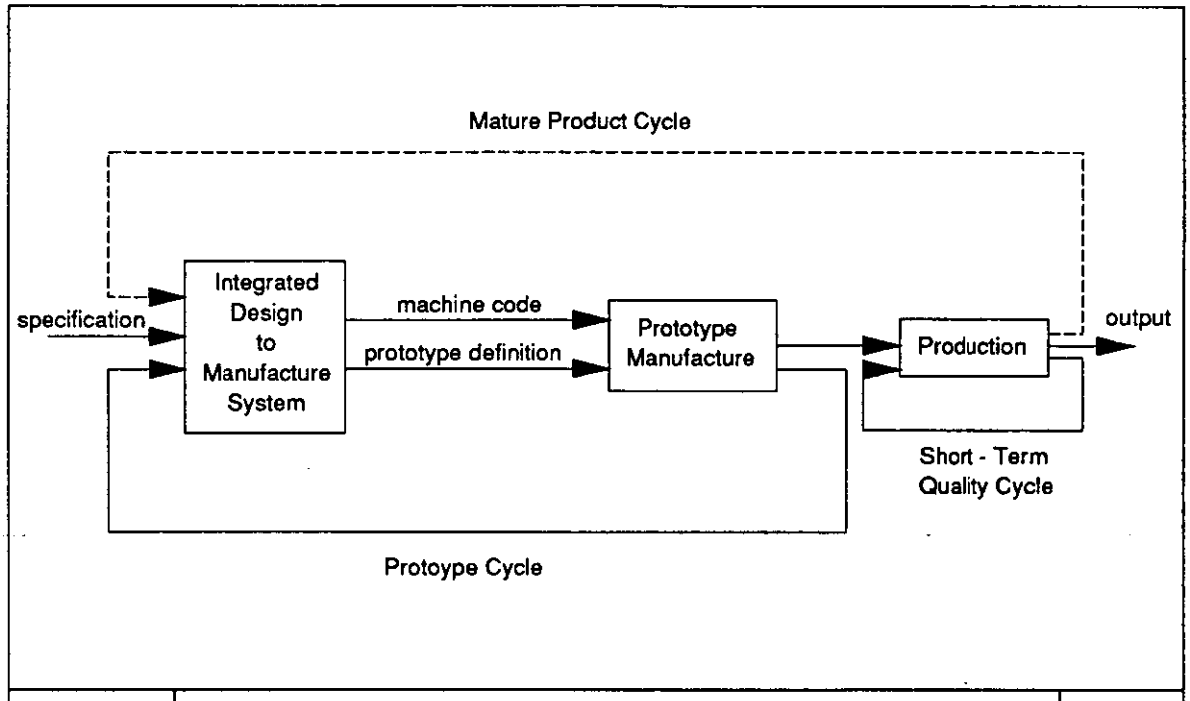


Figure 5.1 THE PRODUCT LIFE CYCLE

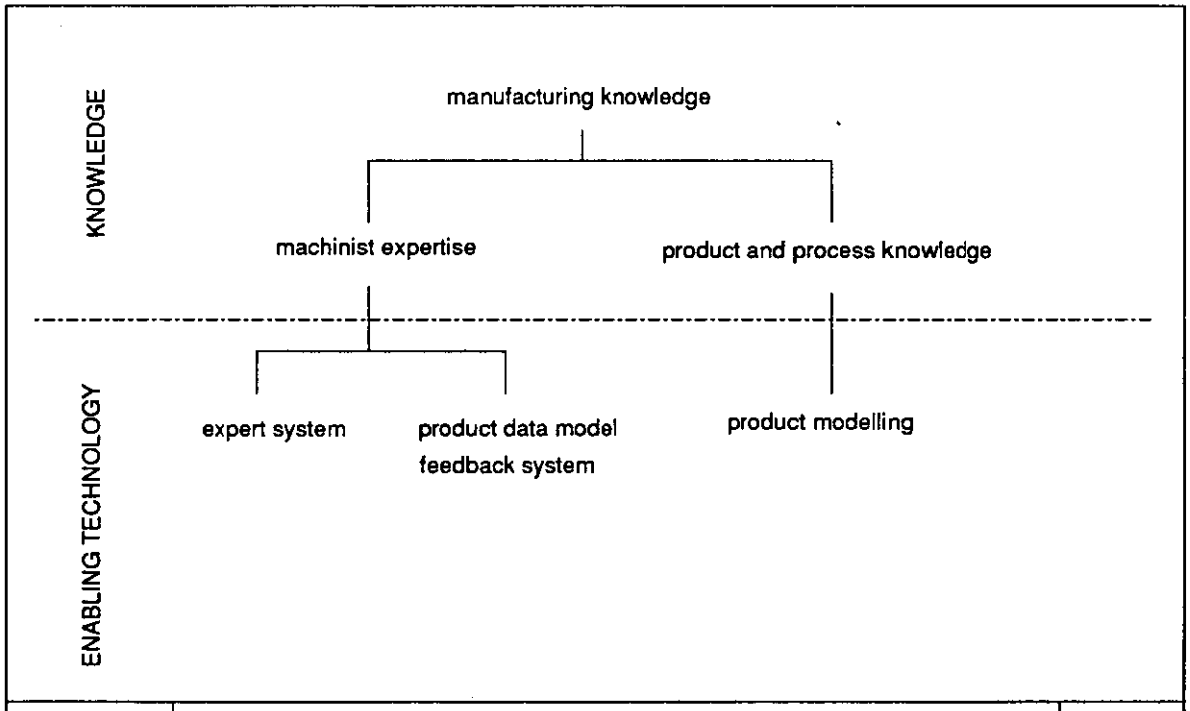


Figure 5.2 CAPTURING MANUFACTURING KNOWLEDGE

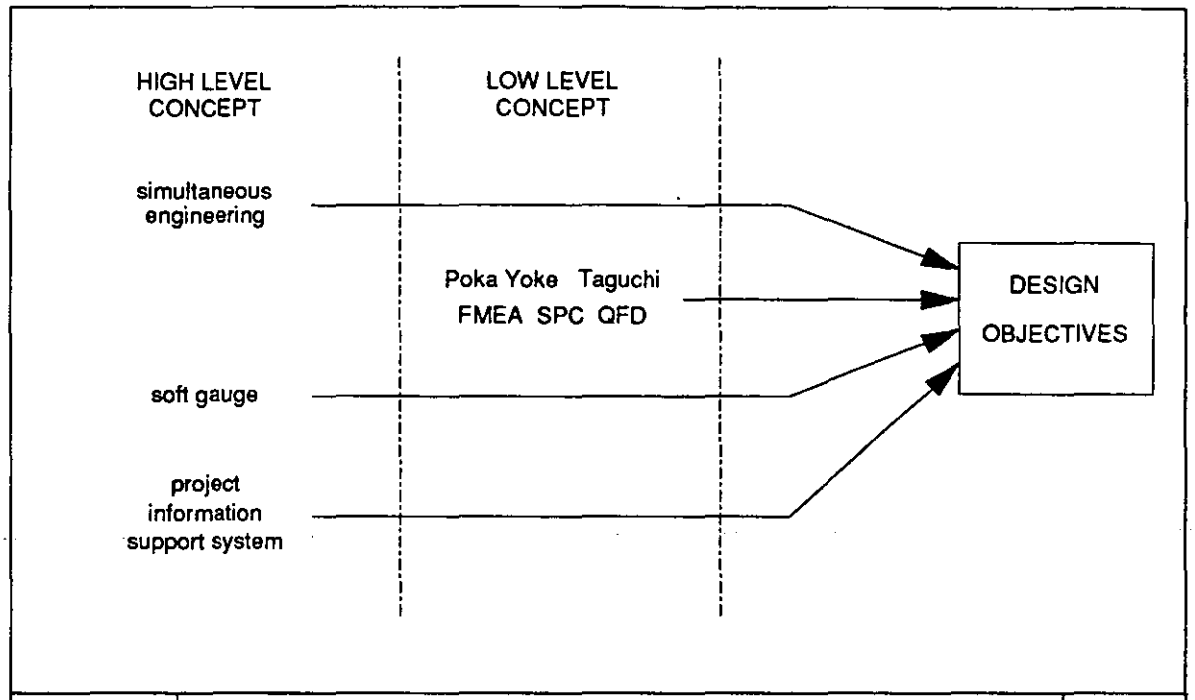


Figure 5.3 ACHIEVING THE PRODUCT DESIGN OBJECTIVES

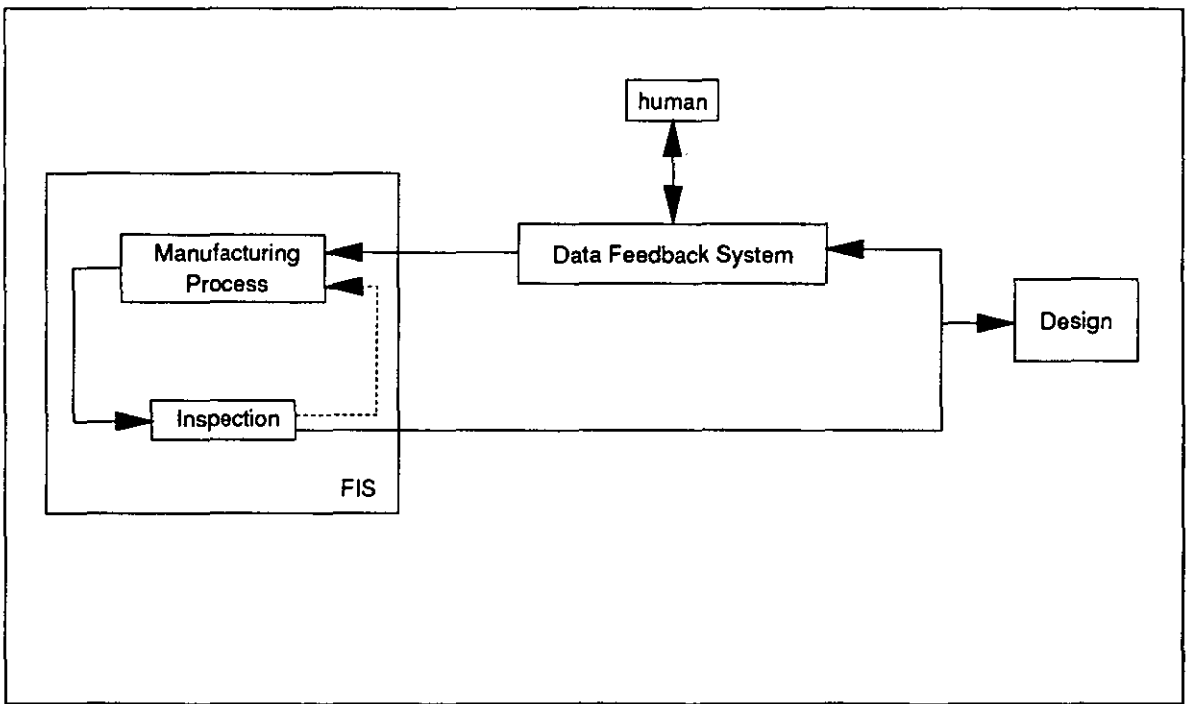


Figure 5.4 'CLOSING THE LOOP'

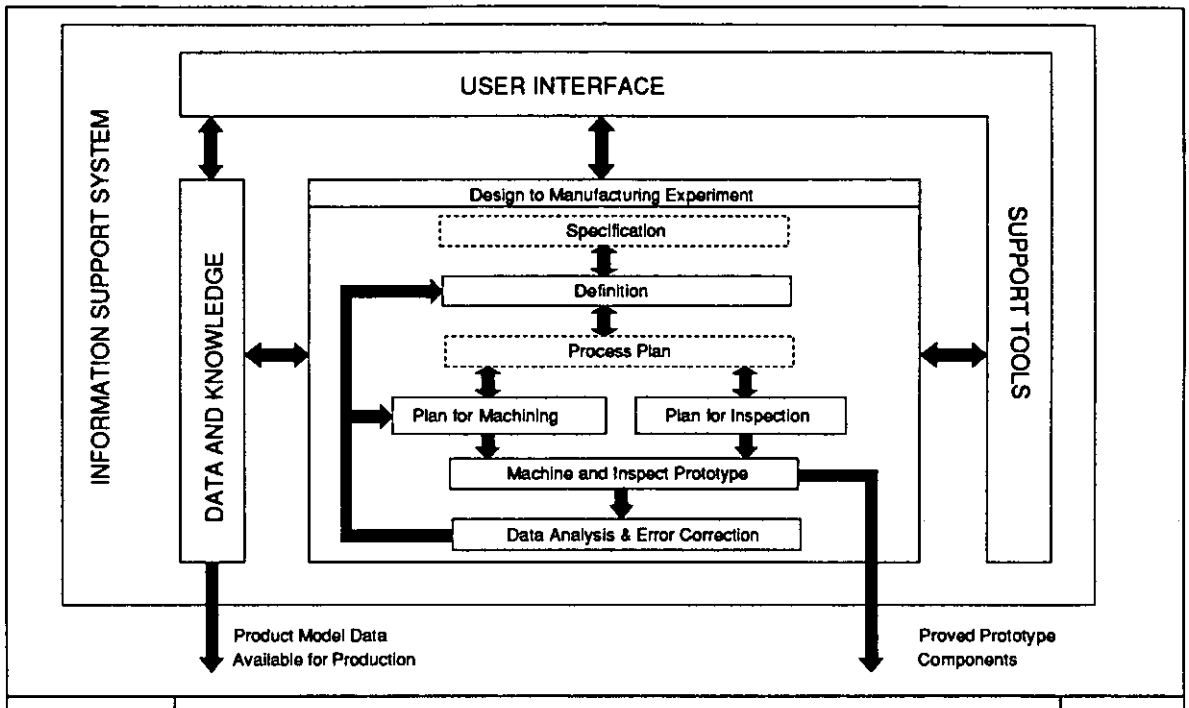


Figure 6.1 THE DESIGN TO MANUFACTURE ENVIRONMENT

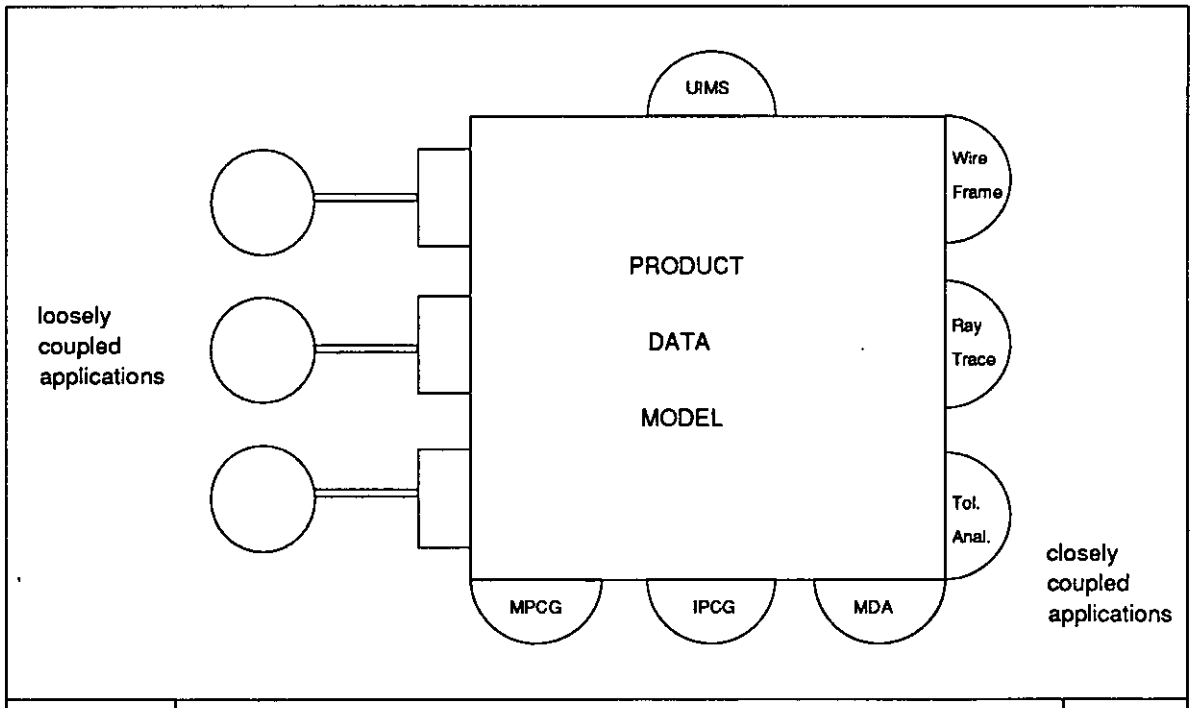


Figure 6.2 THE PRODUCT MODELLING ENVIRONMENT Ref. 57

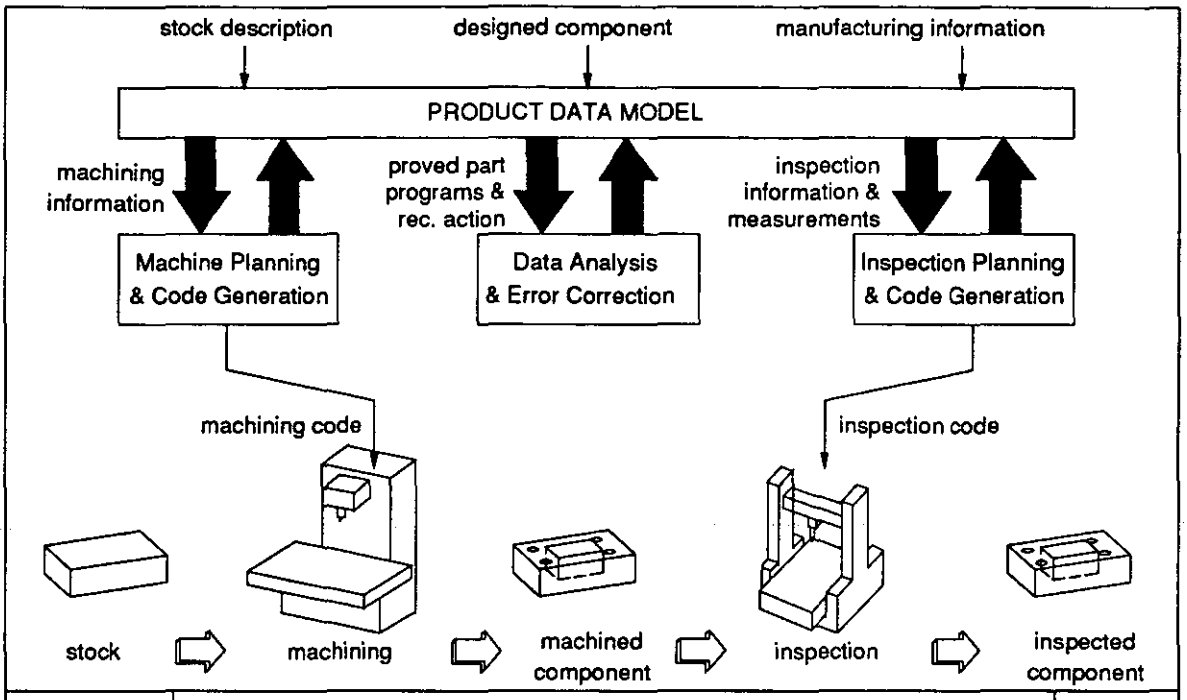


Figure 6.3 GENERATION OF MACHINING CODE MANUFACTURING APPLICATIONS

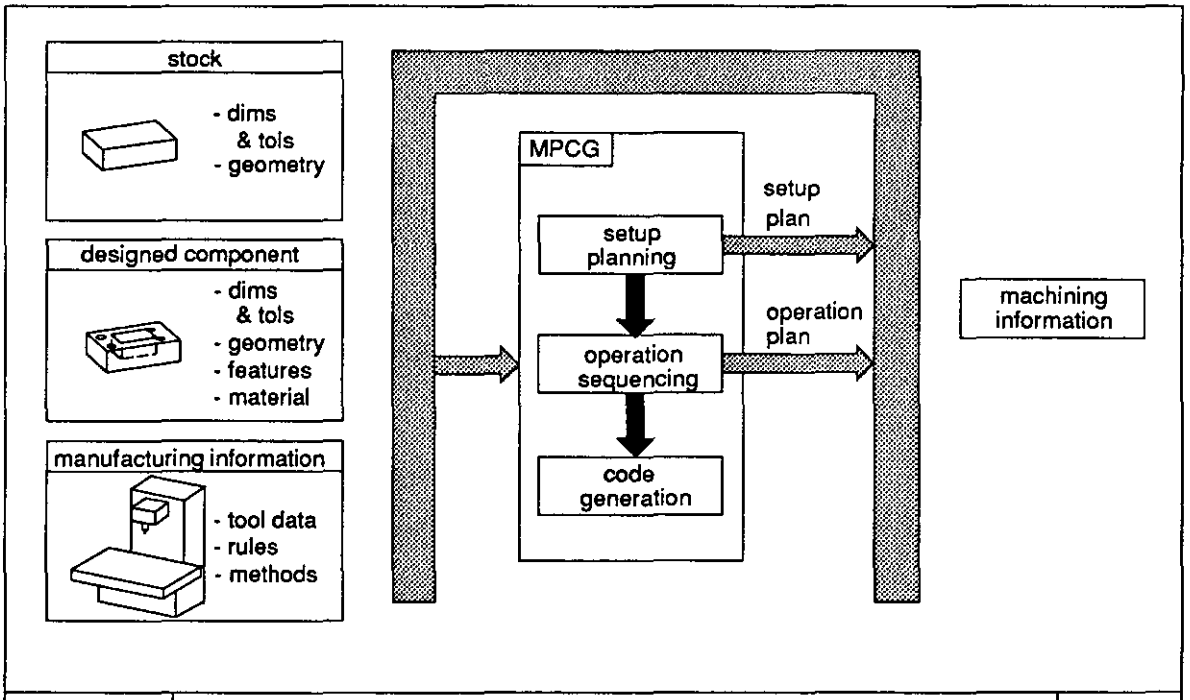


Figure 6.4 INFORMATION AND DATA FLOW IN MACHINE PLAN AND CODE GENERATION

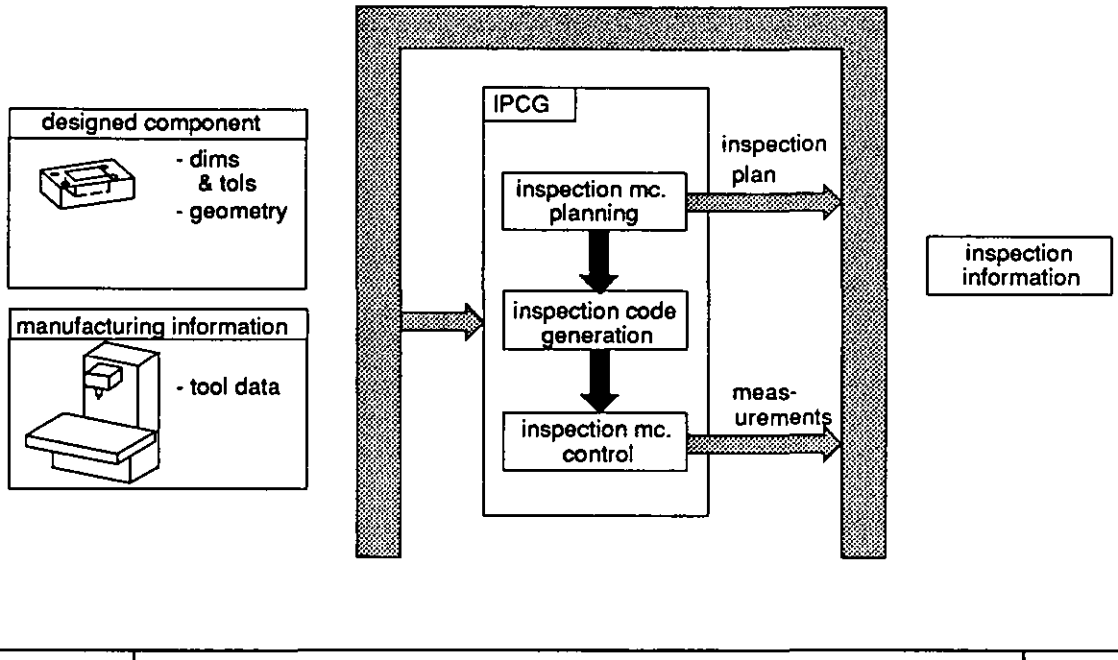


Figure 6.5 INFORMATION AND DATA FLOW IN INSPECTION PLAN AND CODE GENERATION

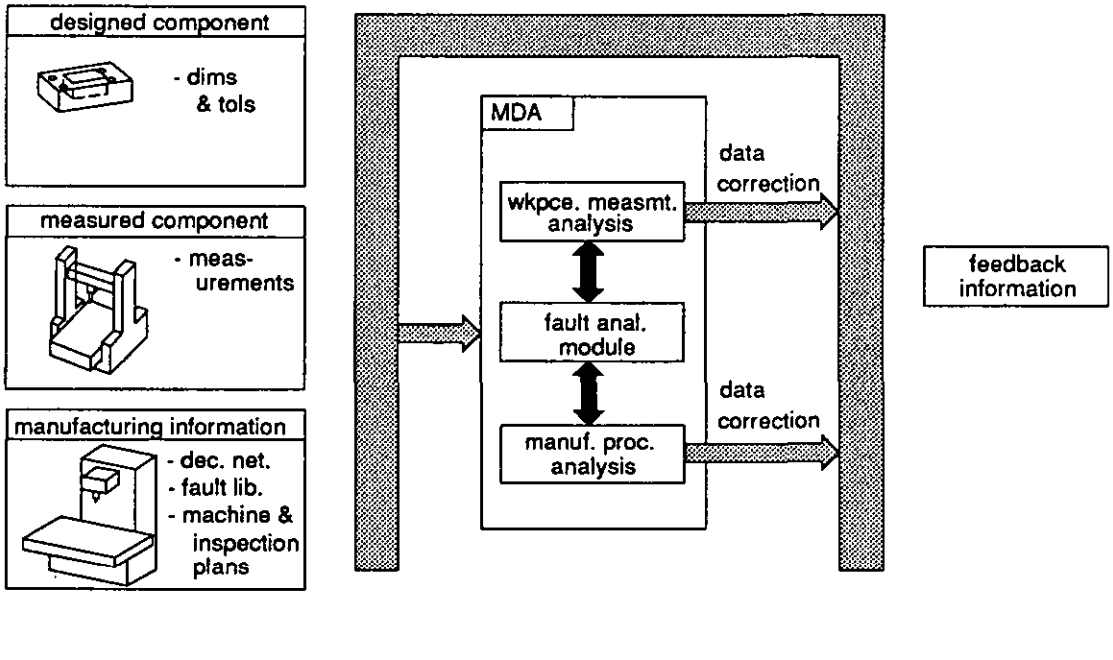


Figure 6.6 INFORMATION AND DATA FLOW IN MANUFACTURING DATA ANALYSIS

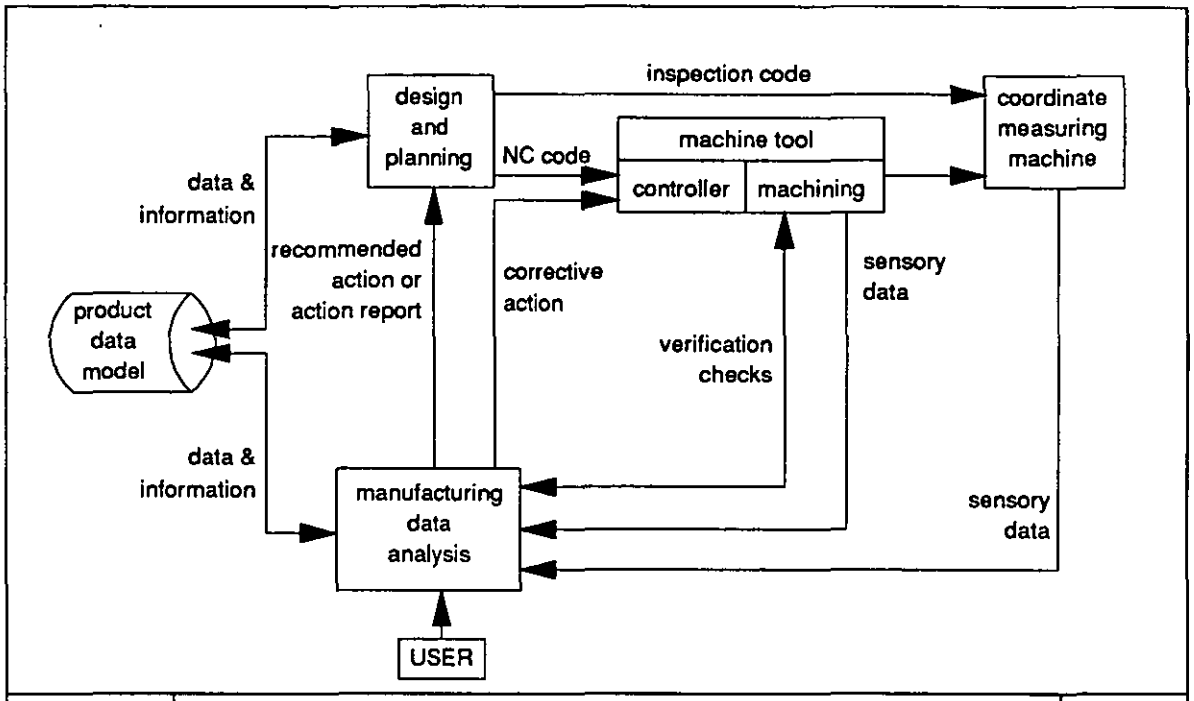


Figure 6.7 THE DATA FEEDBACK SYSTEM

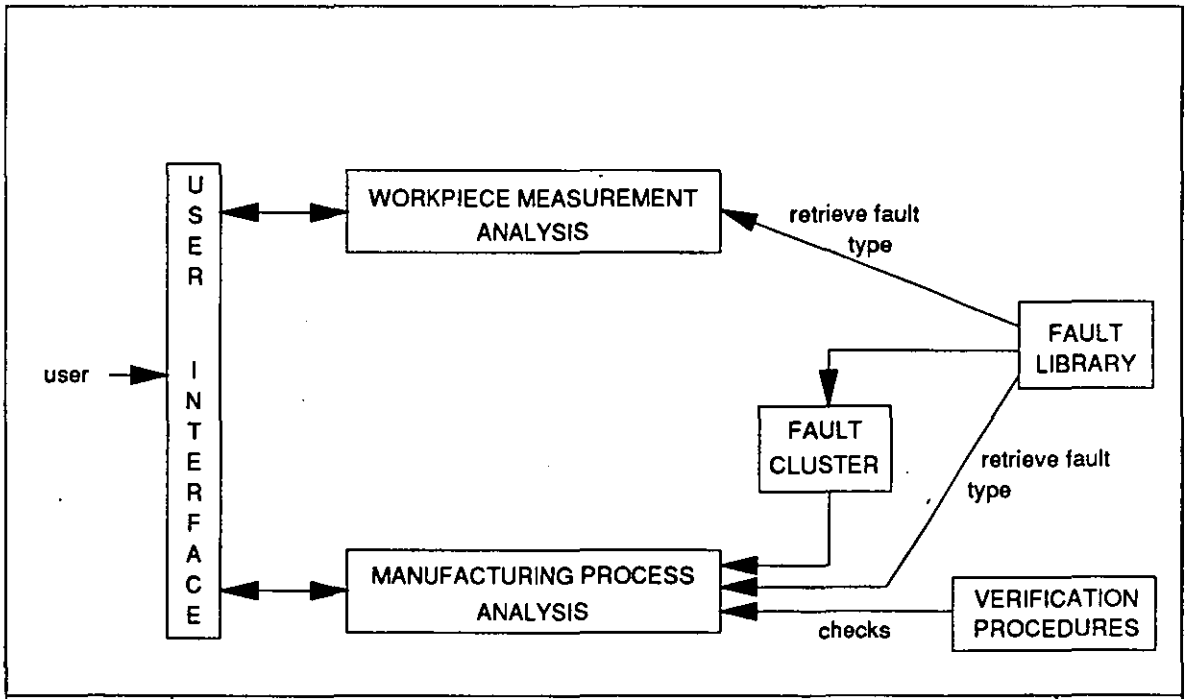


Figure 6.8 THE DATA FEEDBACK SYSTEM CONFIGURATION

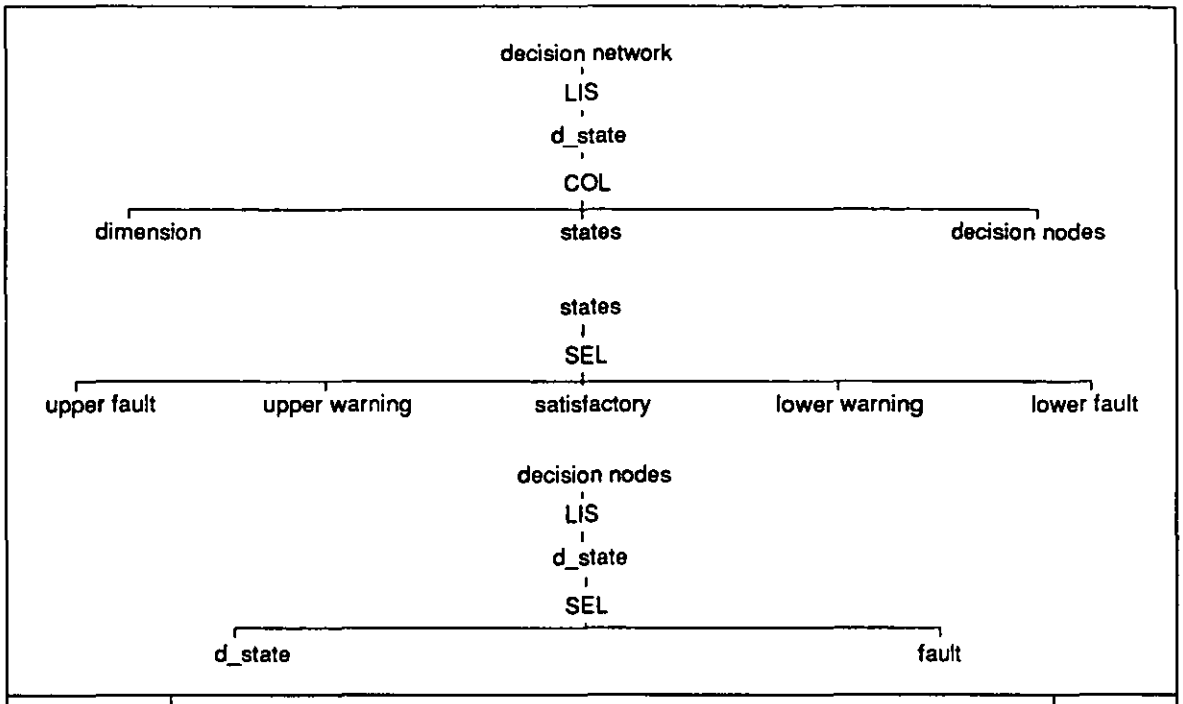


Figure 6.9 DECISION NETWORK

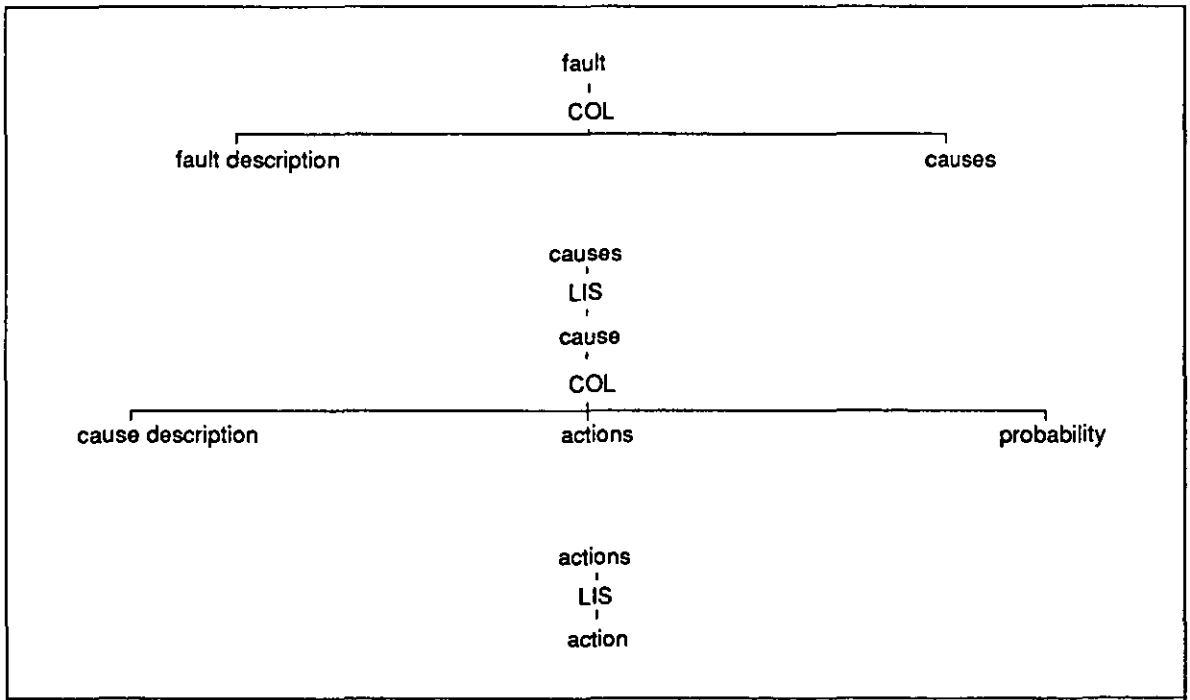


Figure 6.10 THE FAULT STRUCTURE

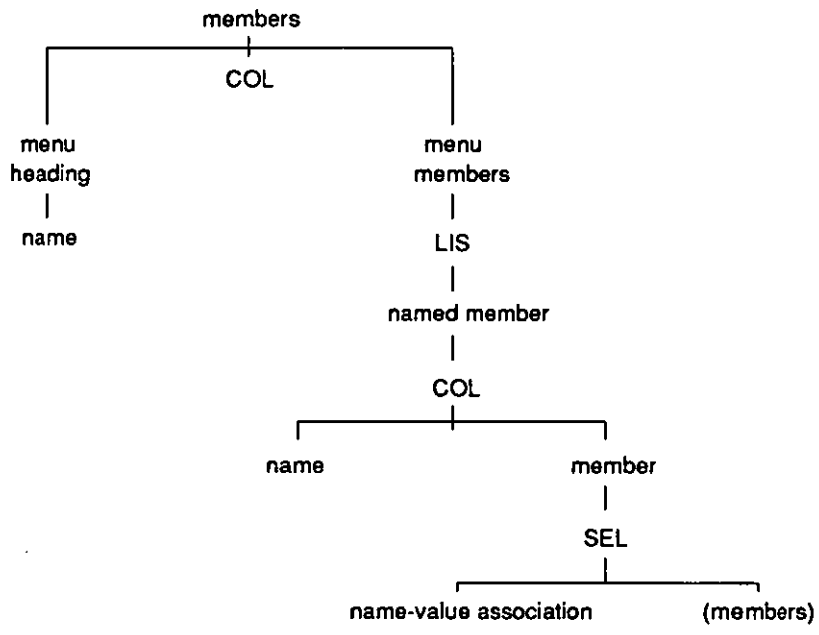


Figure 6.11 TAXONOMIC STRUCTURE

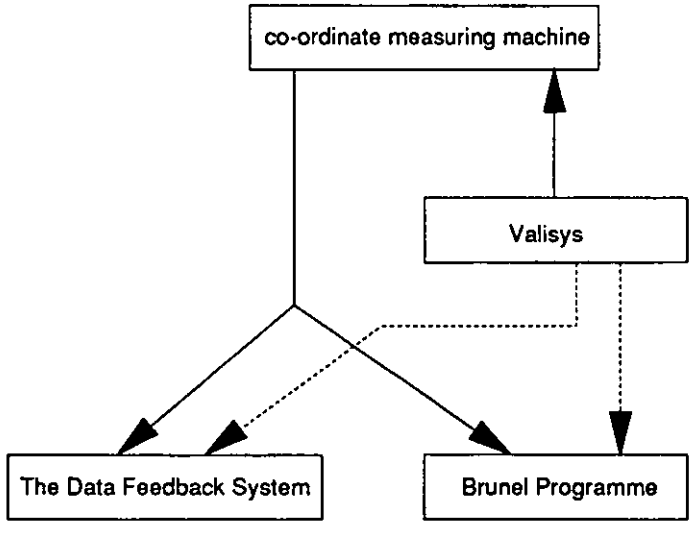


Figure 6.12 THE RESEARCH VIEW IN CONTEXT OF RELATED WORK

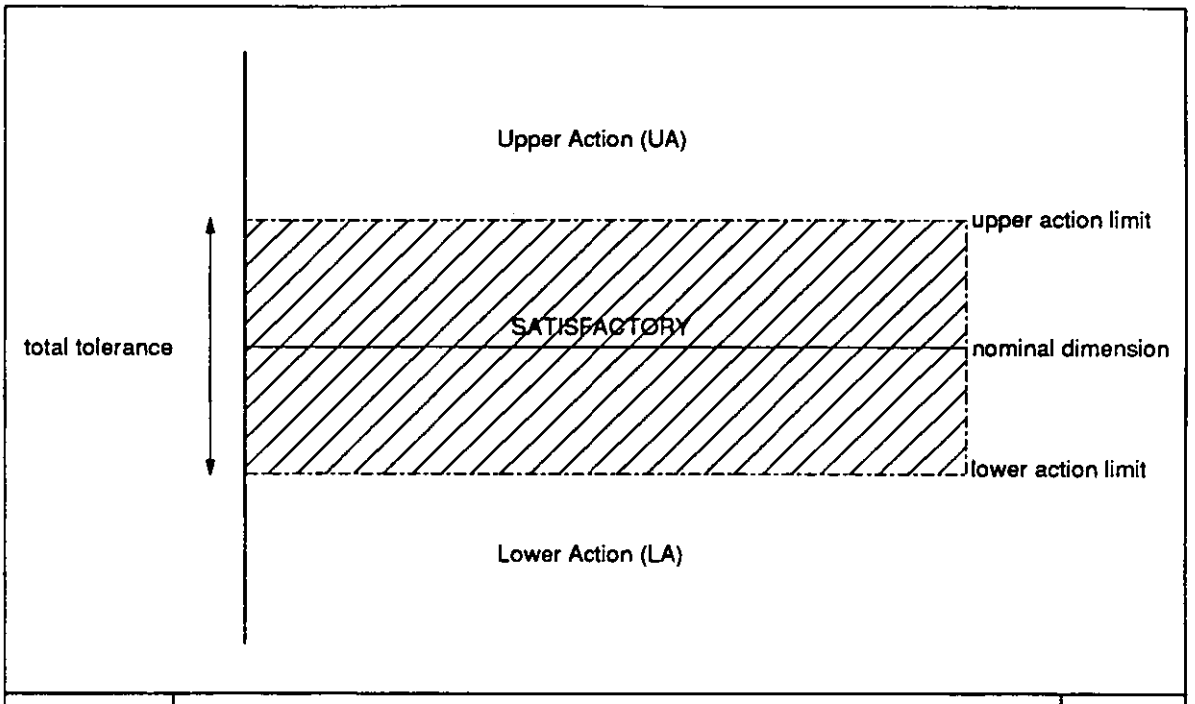


Figure 7.1 MODIFIED CONTROL CHART

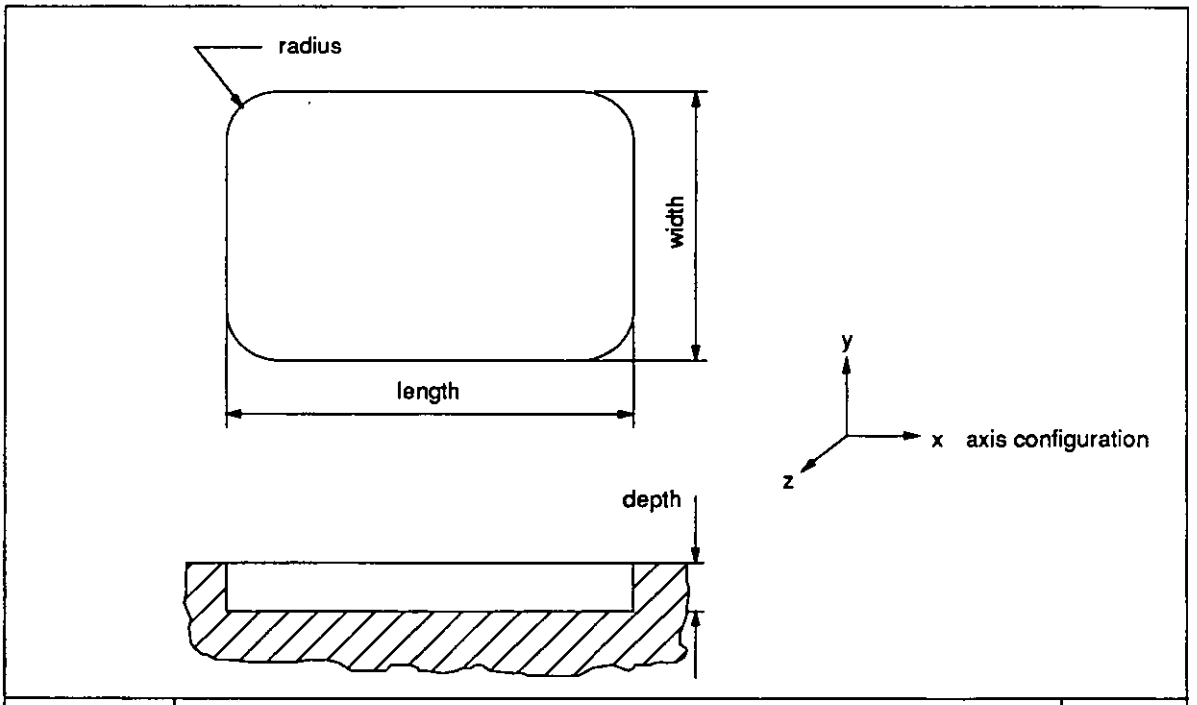


Figure 7.2 POCKET

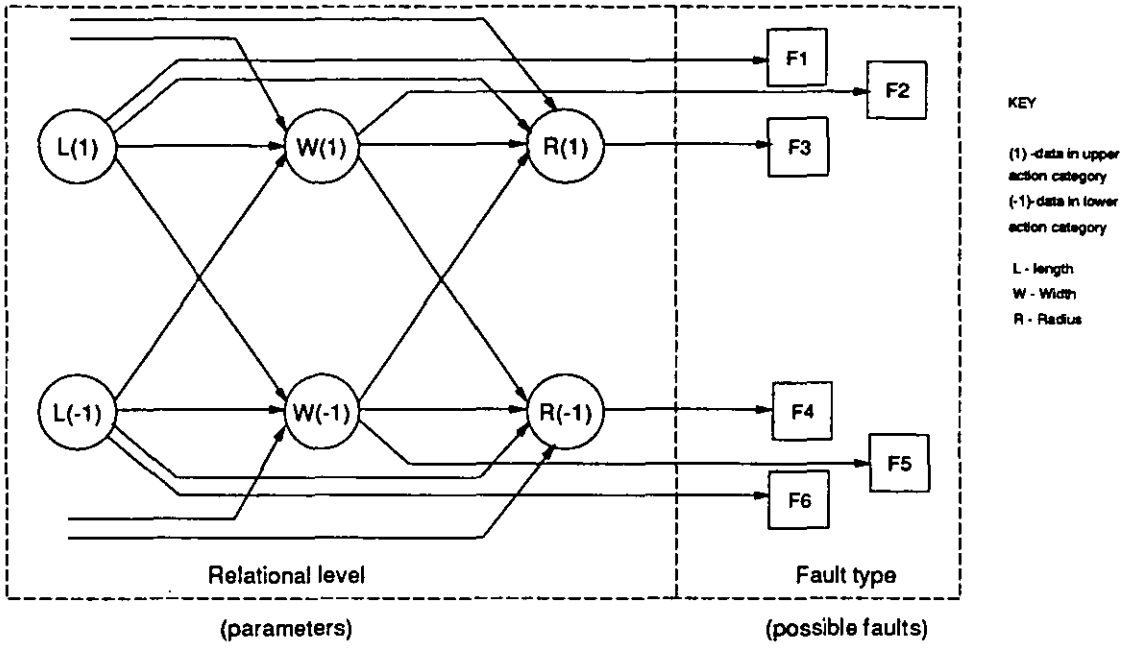


Figure 7.3	AN INFLUENCE DIAGRAM REPRESENTING A POCKET	Ref. 216

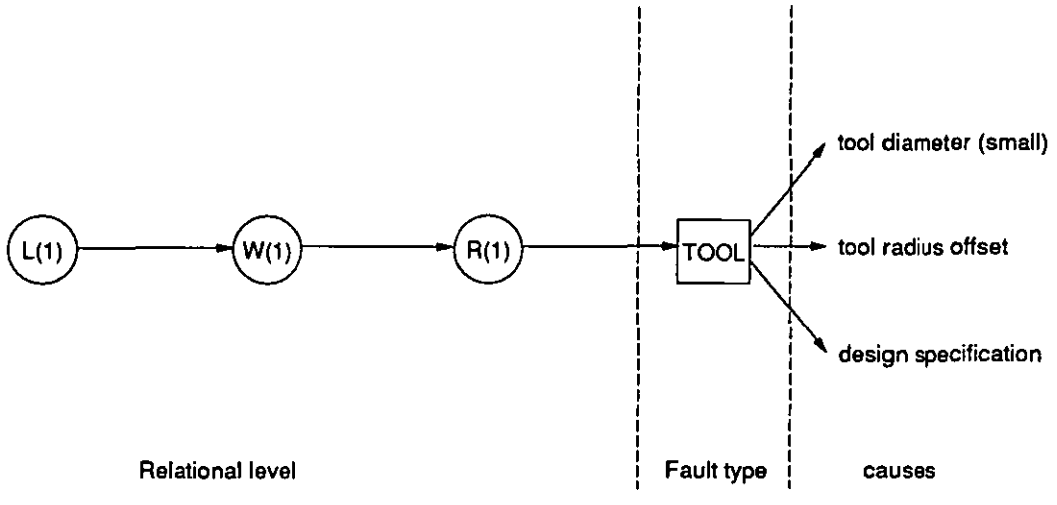


Figure 7.4	A SELECTED BRANCH OF THE INFLUENCE DIAGRAM	

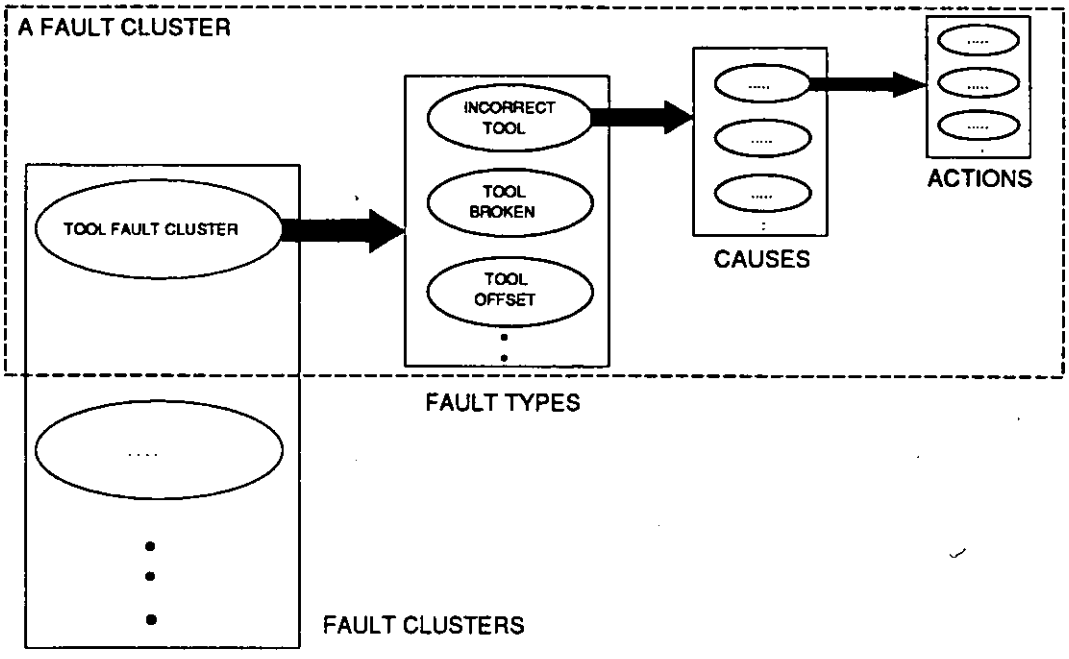
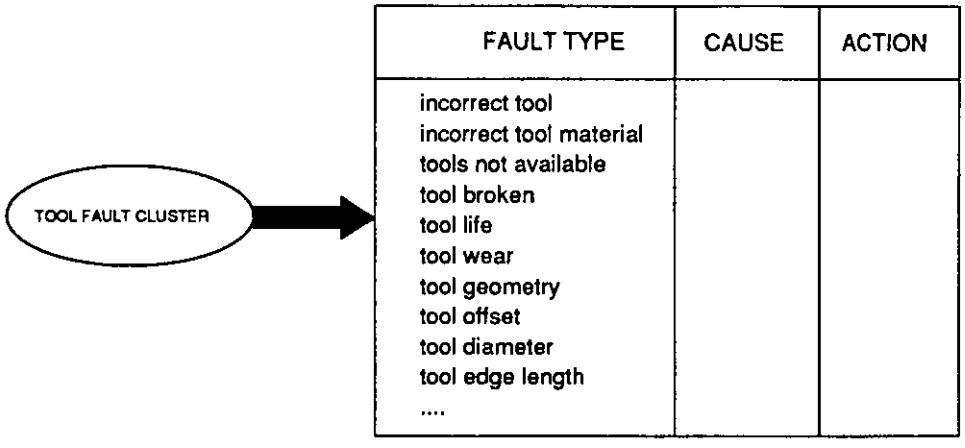


Figure 7.5 USER-MODIFIABLE FAULT CLUSTERS



FAULT TYPE	CAUSE	ACTION
incorrect tool incorrect tool material tools not available tool broken tool life tool wear tool geometry tool offset tool diameter tool edge length		

Figure 7.6 THE TOOL FAULT CLUSTER

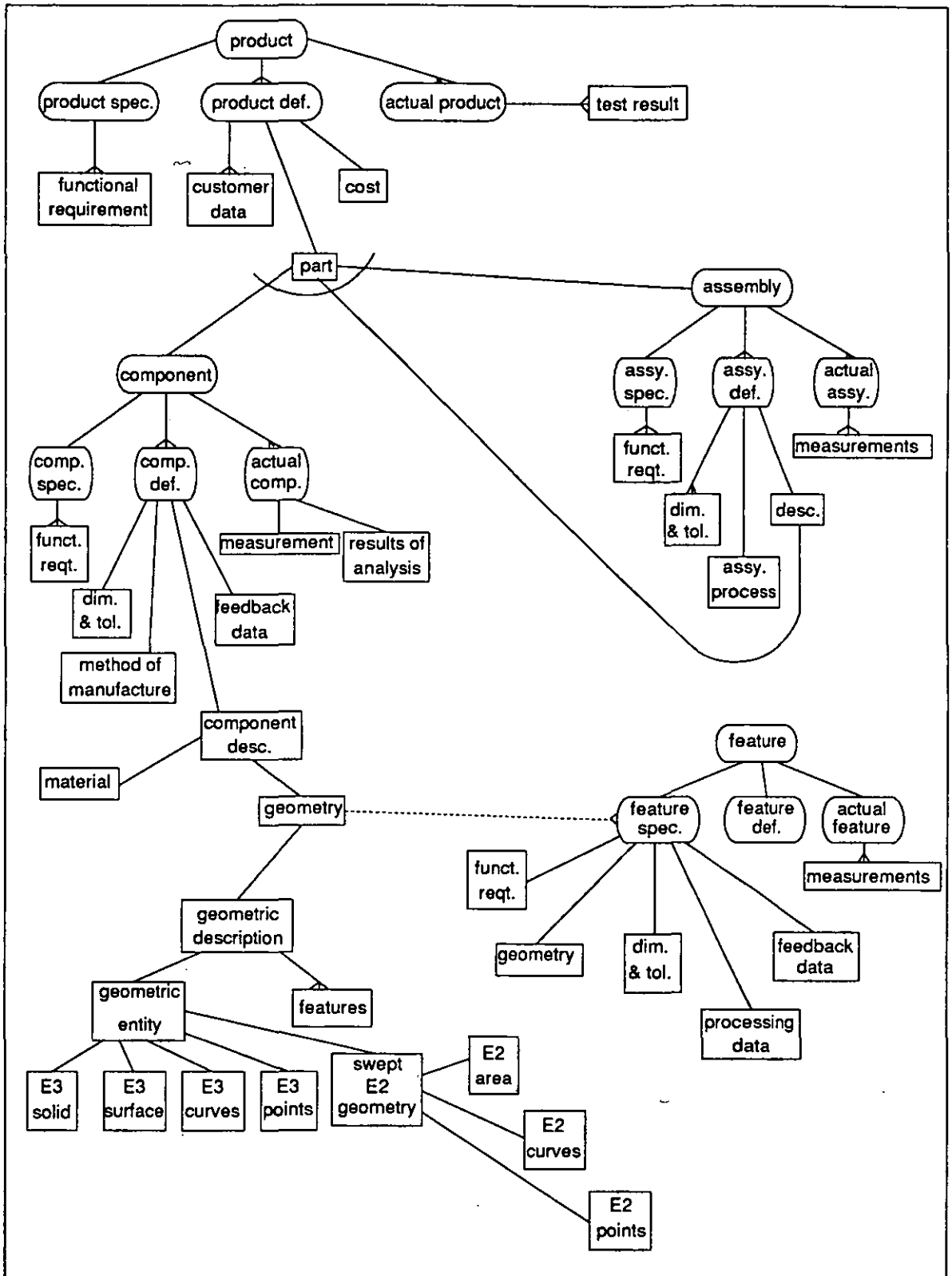


Figure 8.1	THE FRAMEWORK OF THE PRODUCT DATA MODEL	Ref. 206

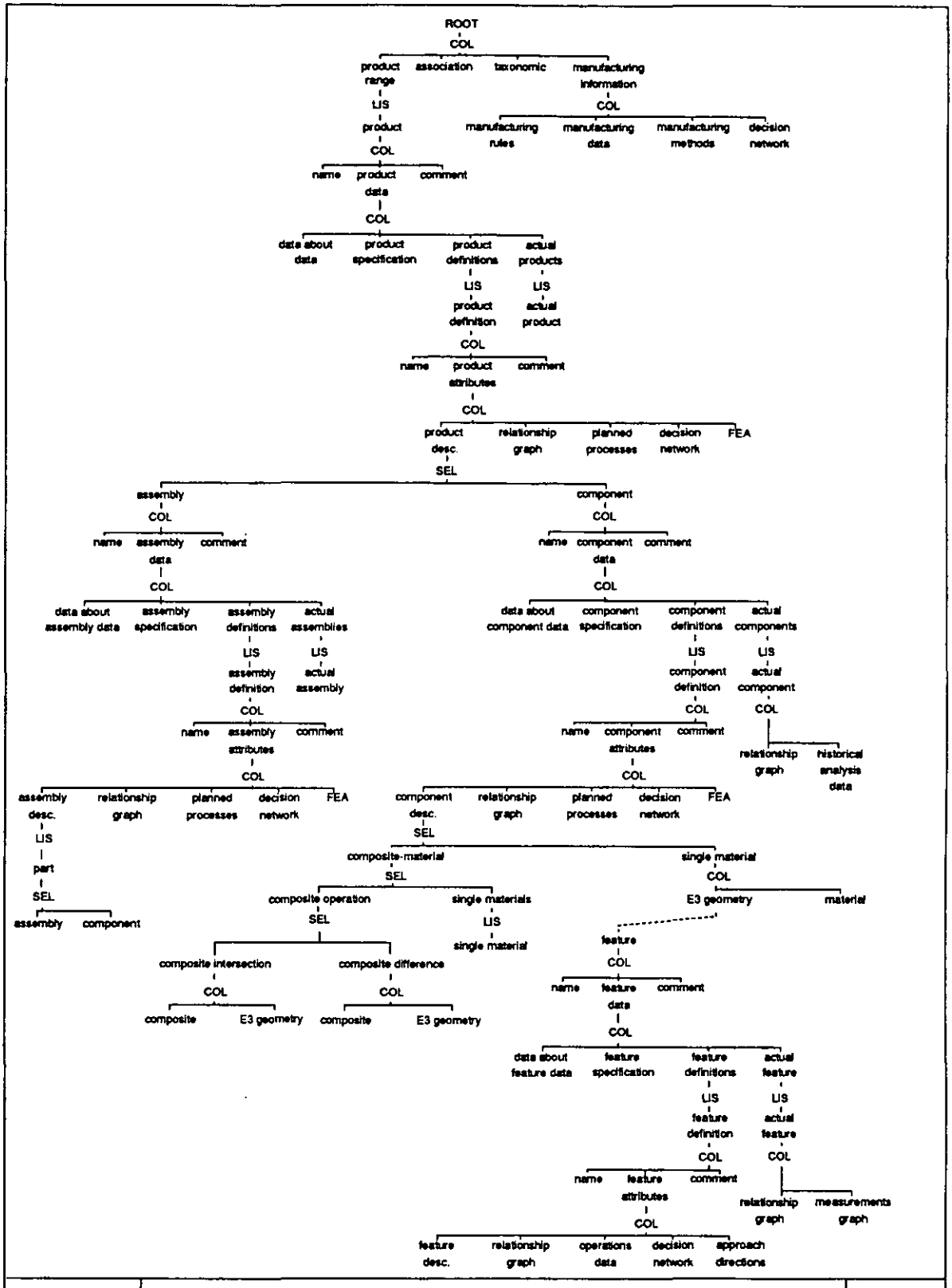


Figure 8.2	THE DATA STRUCTURE OF THE PRODUCT DATA MODEL	Ref. 206

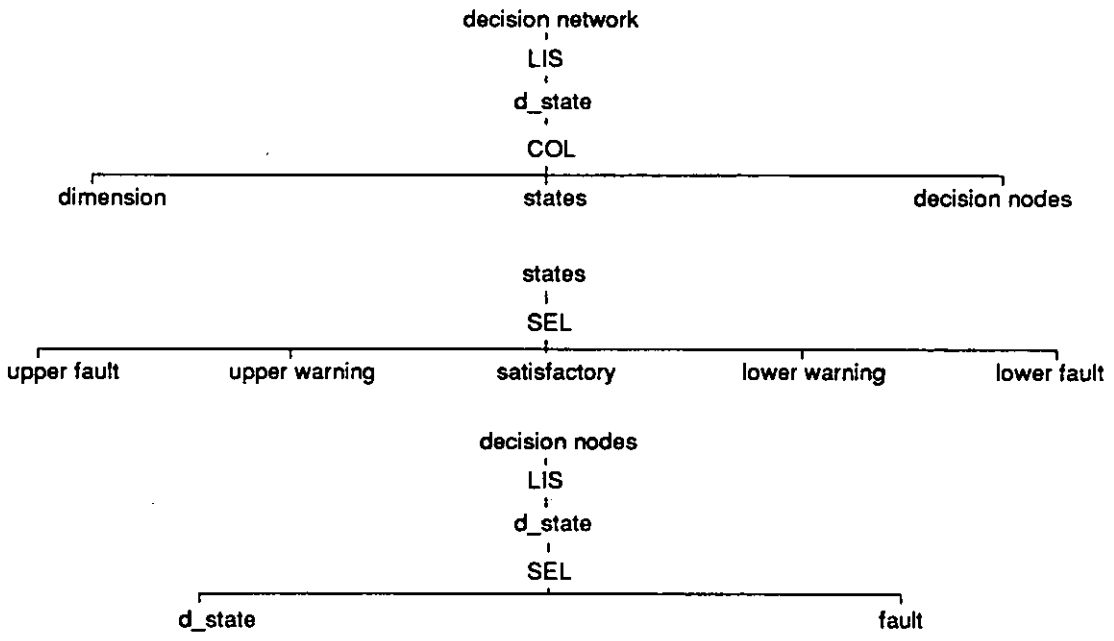


Figure 8.3 DECISION NETWORK

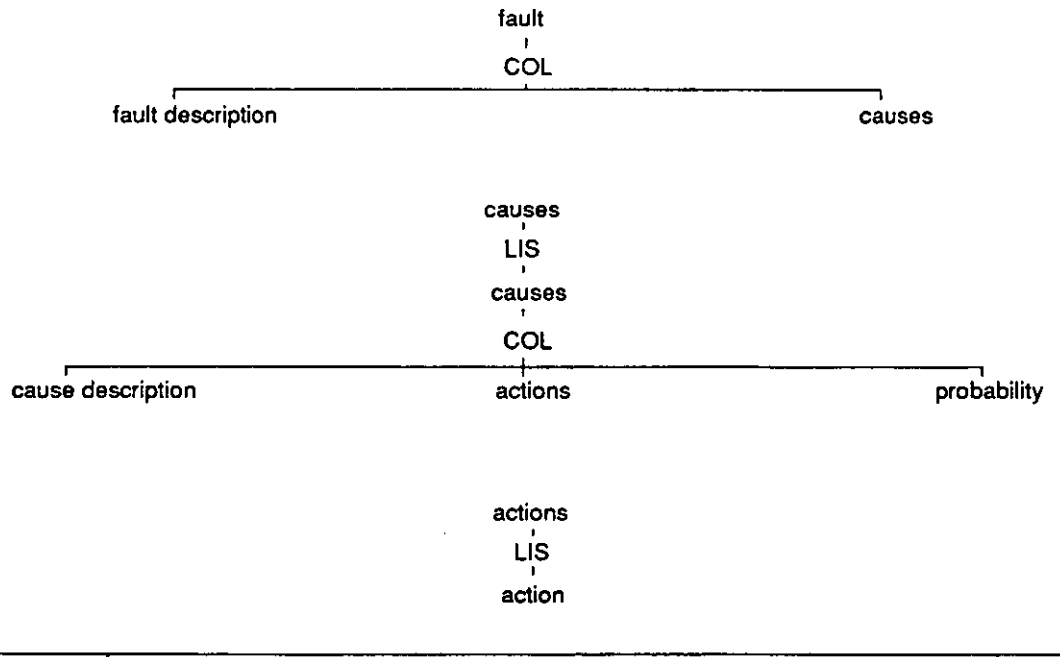


Figure 8.4 THE FAULT STRUCTURE

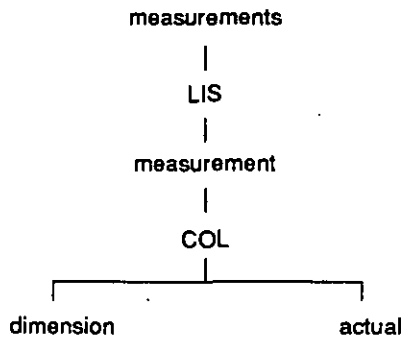


Figure 8.5 THE MEASUREMENT GRAPH

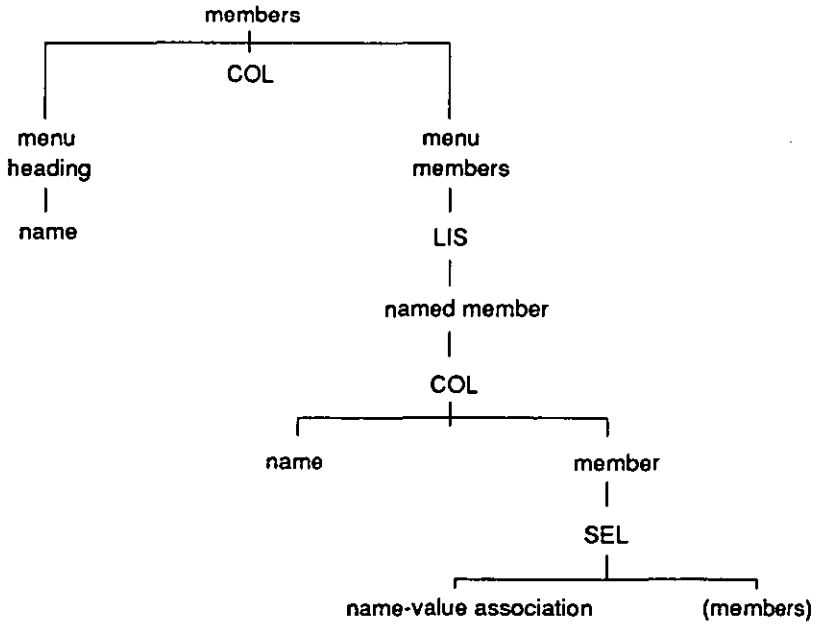


Figure 8.6 THE TAXONOMIC STRUCTURE

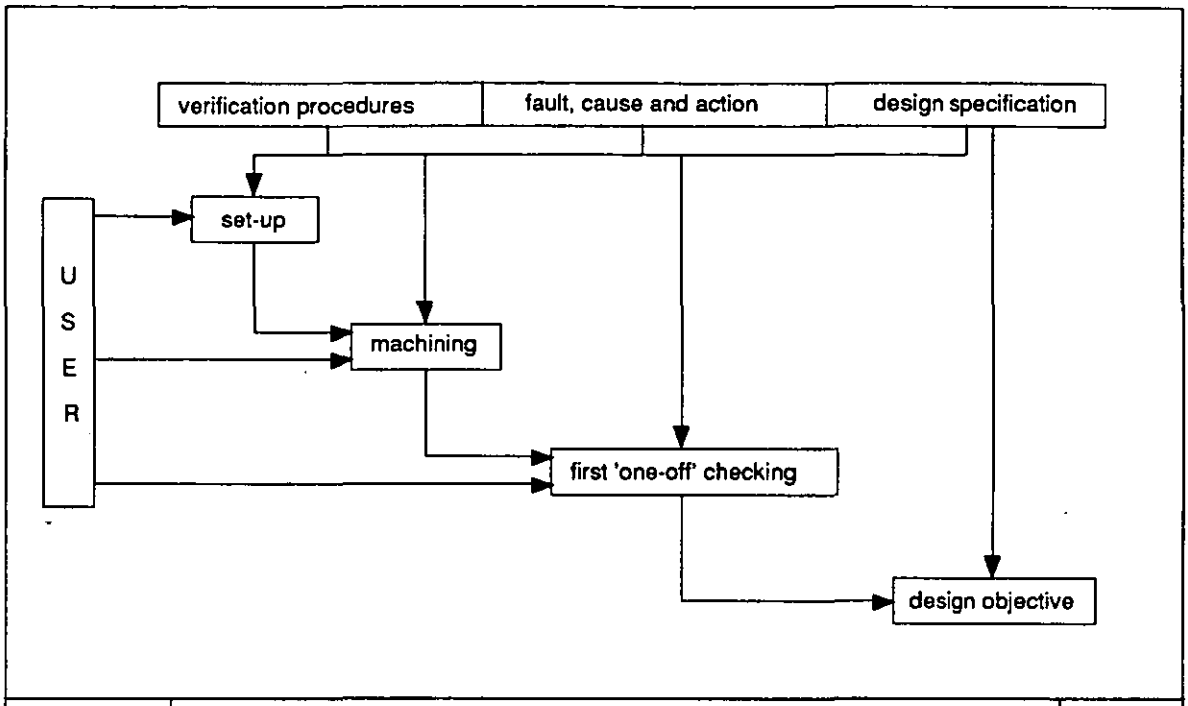


Figure 9.1 DATA ORGANIZATION AND APPLICATION

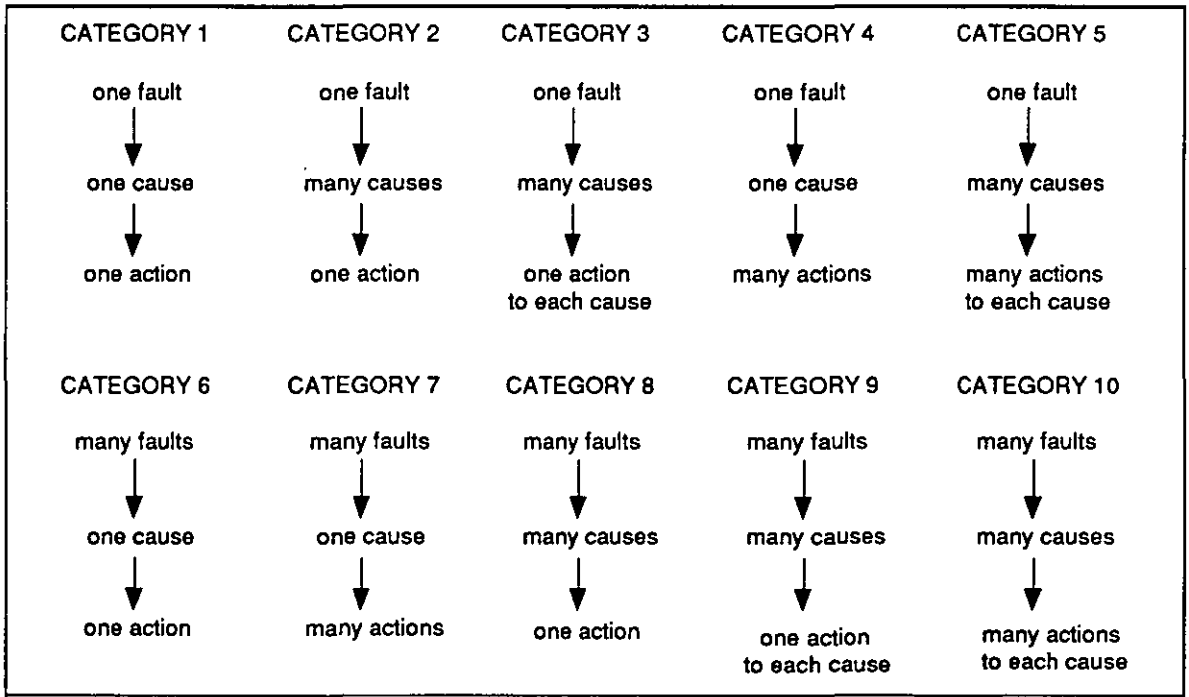


Figure 9.2 CATEGORIES OF FAULT-CAUSE-ACTION RELATIONSHIPS

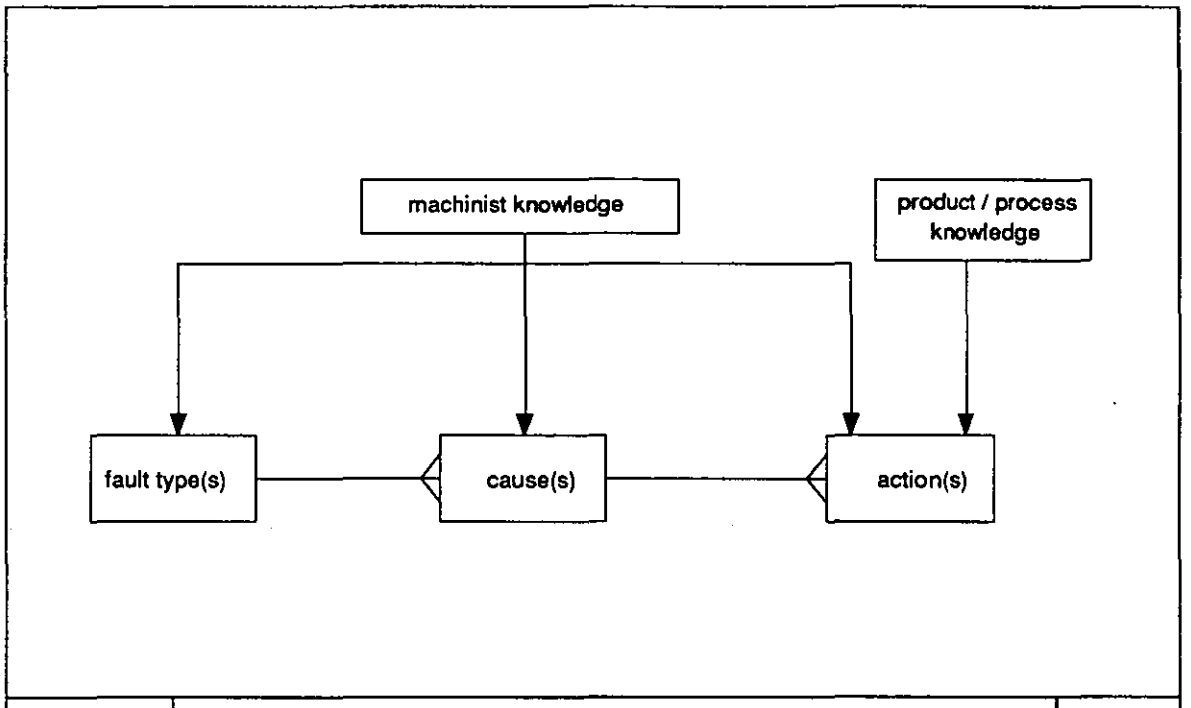


Figure 9.3 THE FAULT LIBRARY

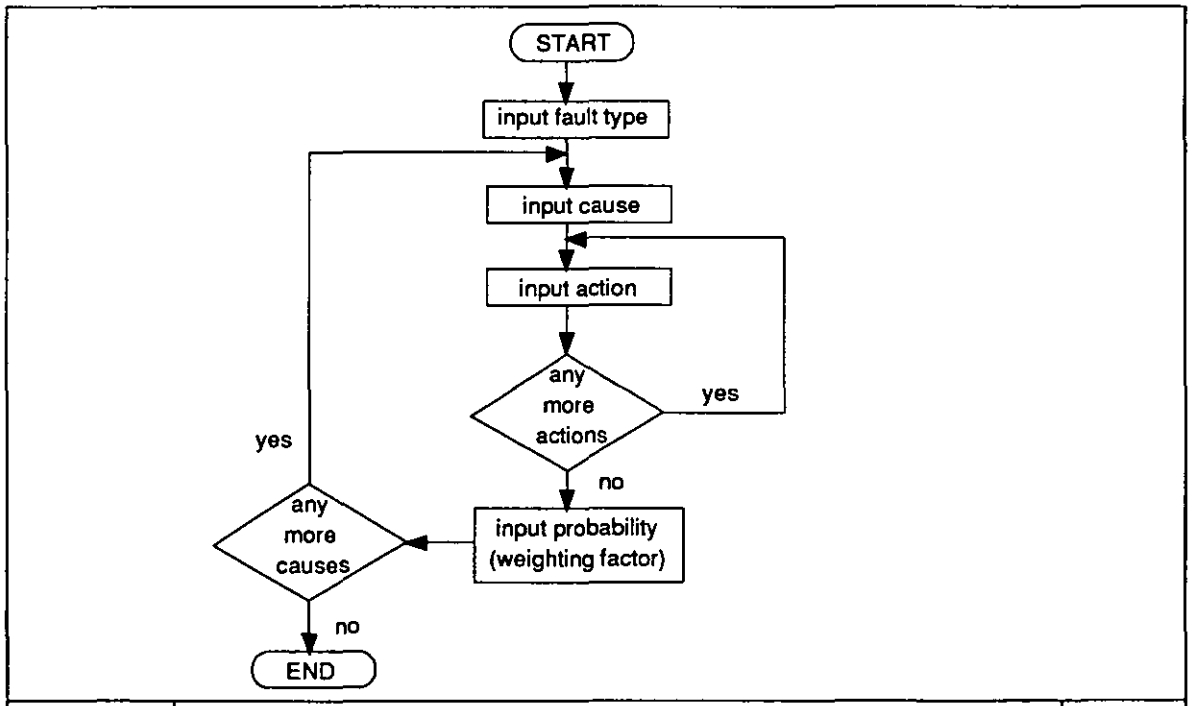


Figure 9.4 BUILDING THE FAULT LIBRARY

CAUSE	position of spot drill with repect to program in XY direction
PROBABILITY	100 %
ACTION	1. if position is not tied up, move spot drill in program - check actual position against drawing 2. if position tied up, move both spot drill and position in program - check actual position against drawing
FAULT TYPE	wrong positioning of the drill

Figure 9.5 AN ENTRY IN THE FAULT LIBRARY

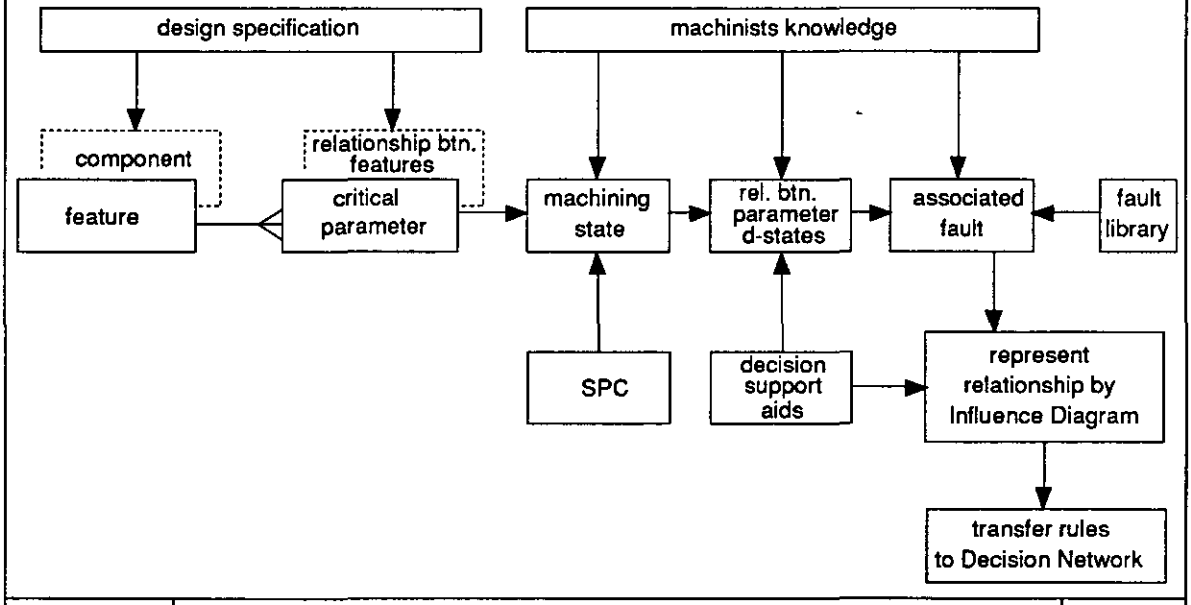


Figure 9.6 A DECISION NETWORK'S REQUIREMENT

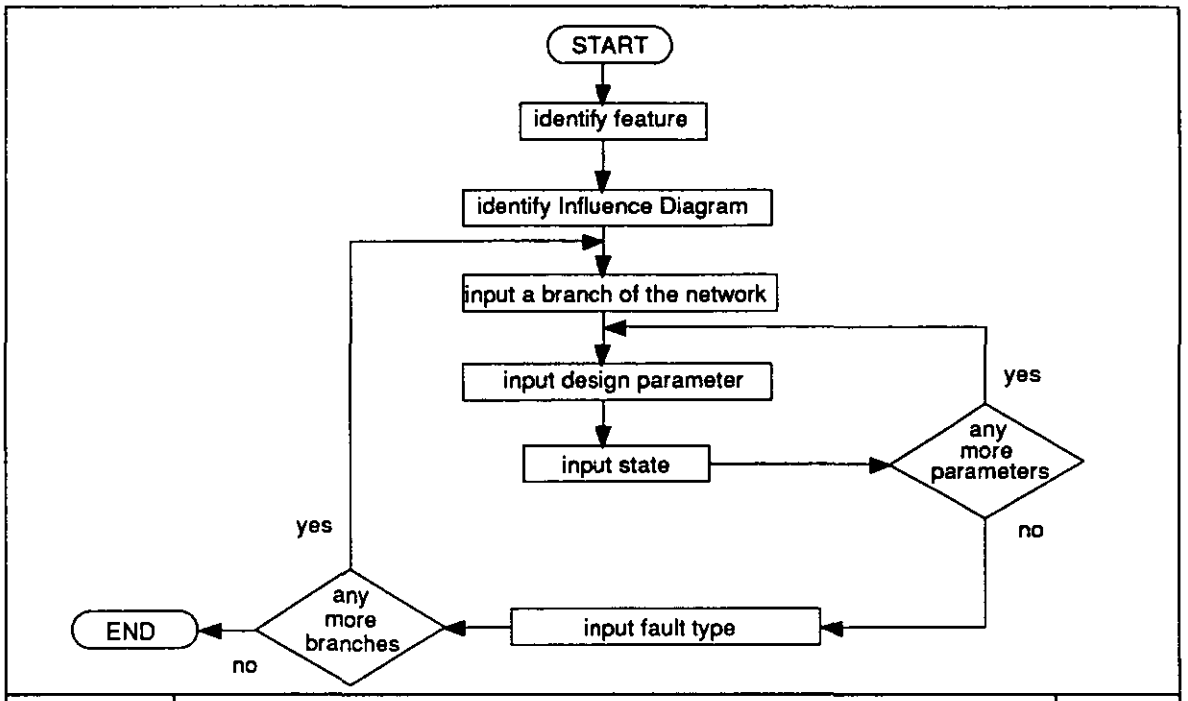


Figure 9.7 BUILDING A DECISION NETWORK FOR A FEATURE

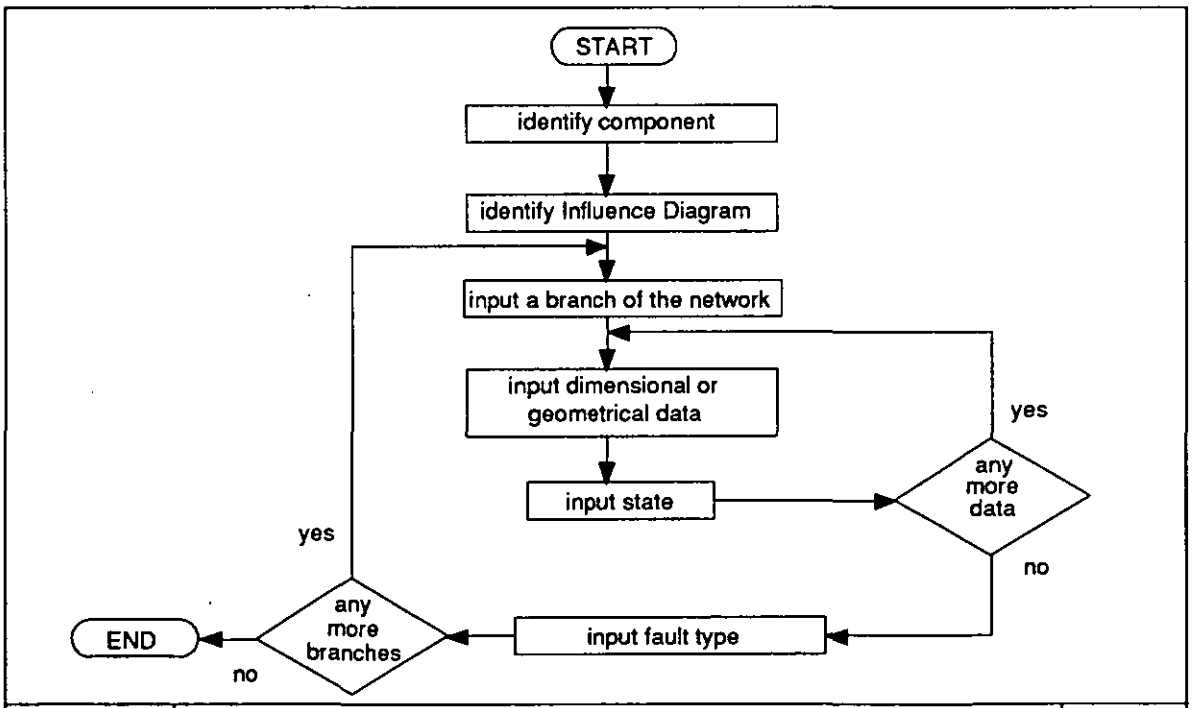


Figure 9.8 BUILDING A DECISION NETWORK FOR THE RELATIONSHIP BETWEEN FEATURES

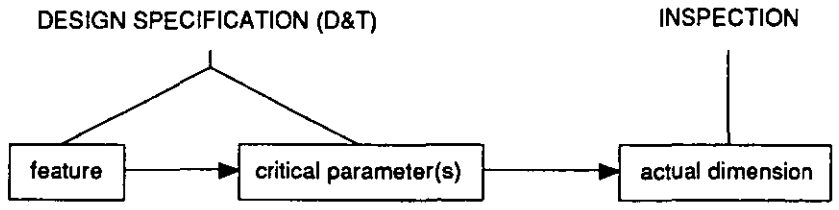


Figure 9.9 REQUIREMENTS FOR BUILDING A MEASUREMENT GRAPH

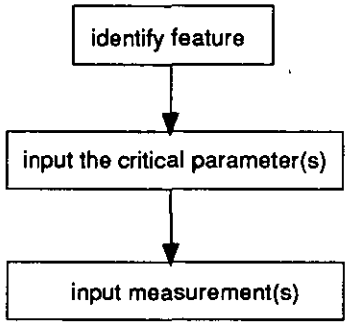


Figure 9.10 BUILDING THE MEASUREMENT GRAPH

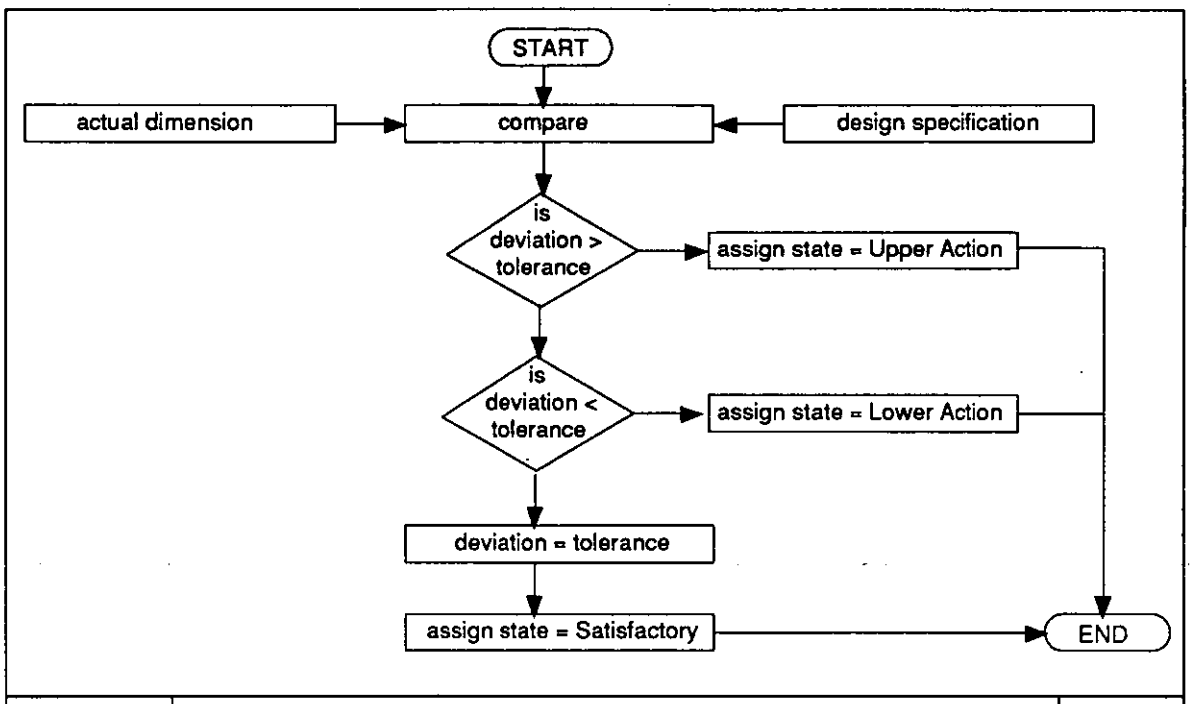


Figure 9.11 AN ALGORITHM FOR ANALYSING INSPECTION DATA

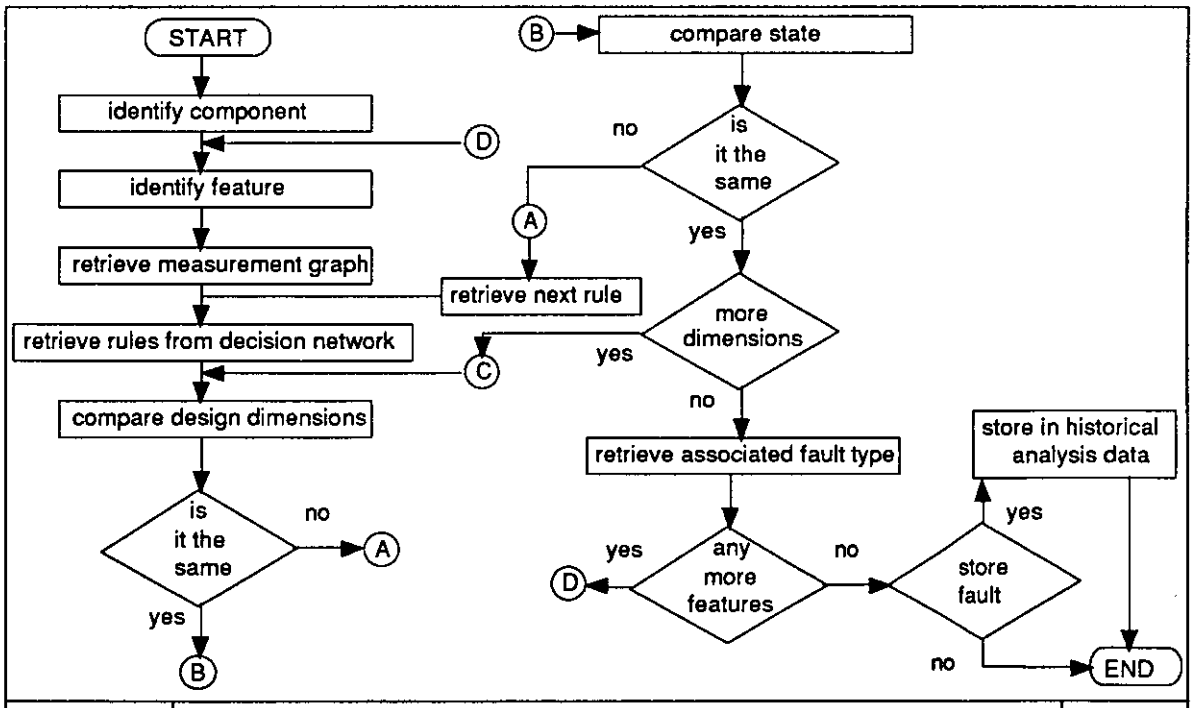


Figure 9.12 AN ALGORITHM FOR DIMENSIONAL ANALYSIS

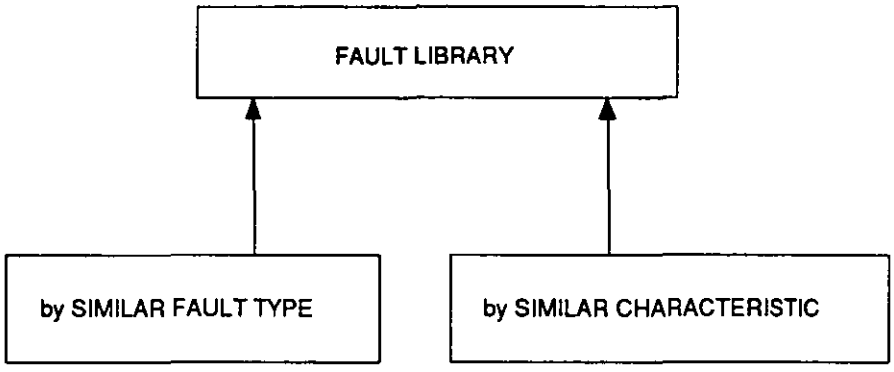


Figure 9.13 KNOWLEDGE FOR GROUPING FAULTS

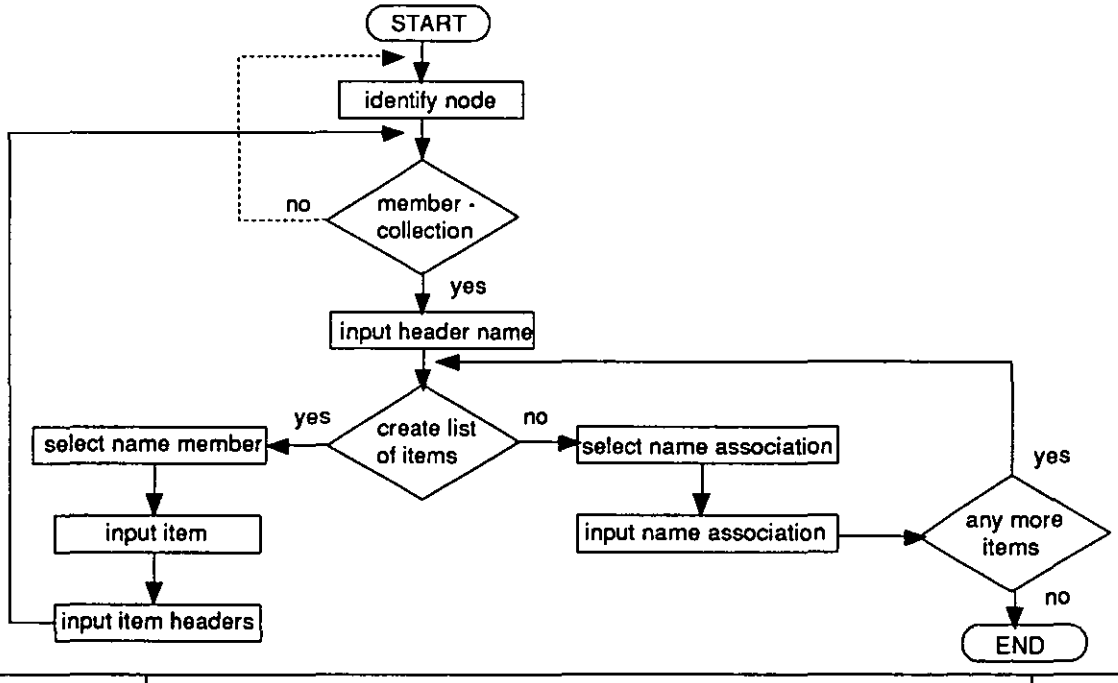


Figure 9.14 A GENERIC USE OF THE TAXONOMIC STRUCTURE

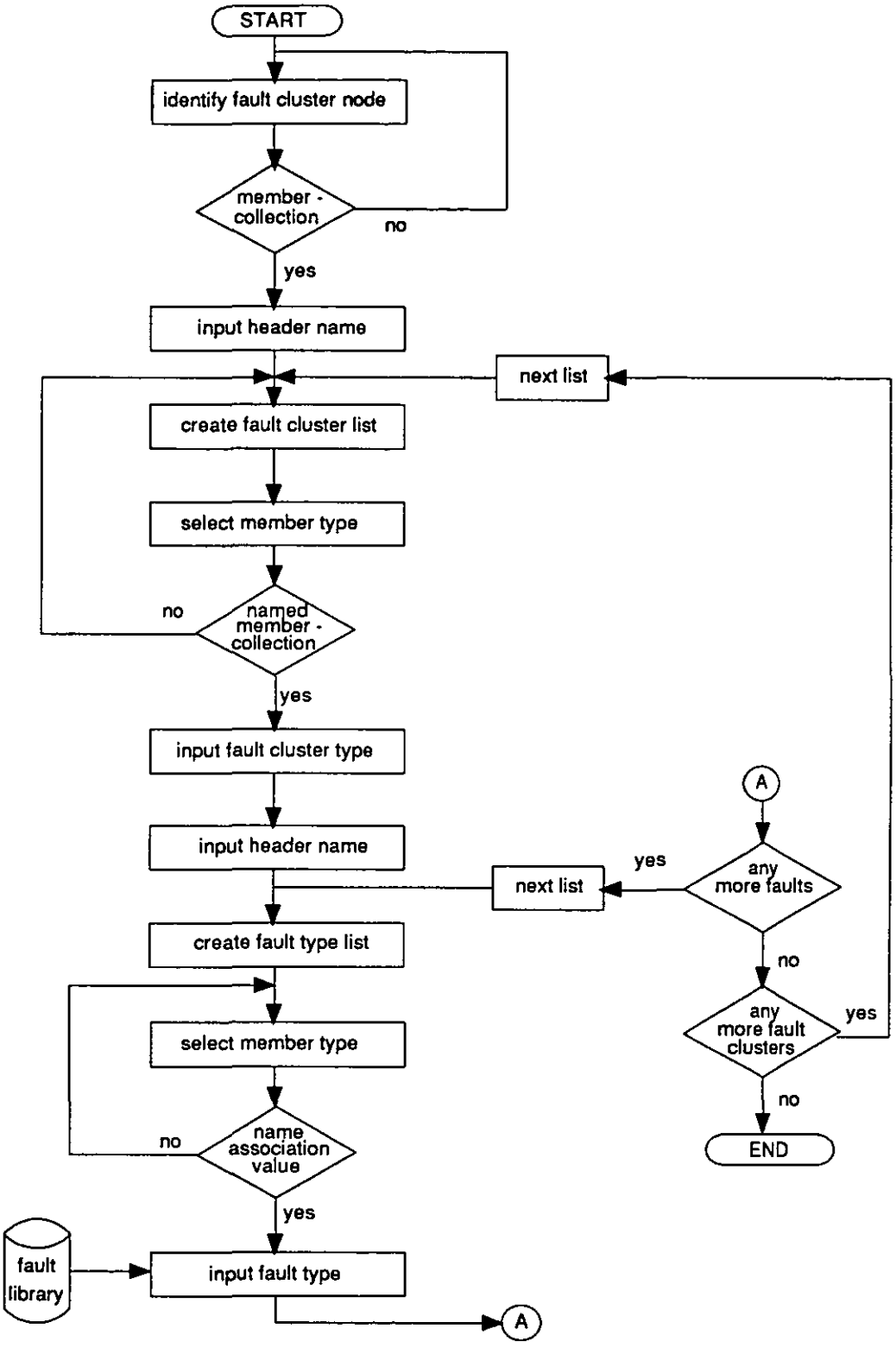


Figure 9.15 BUILDING OF FAULT CLUSTERS

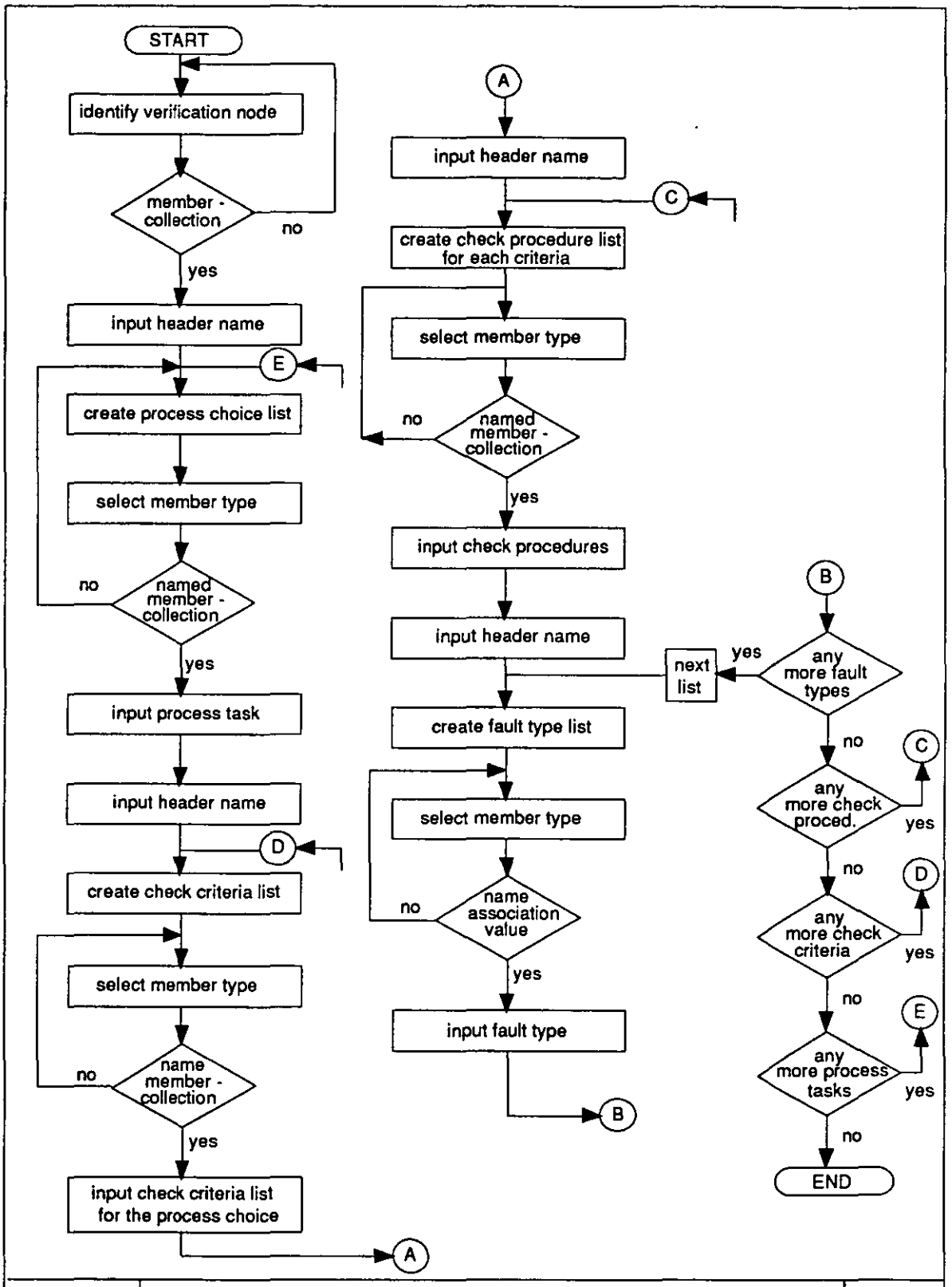


Figure 9.16 THE PROCESS TASK

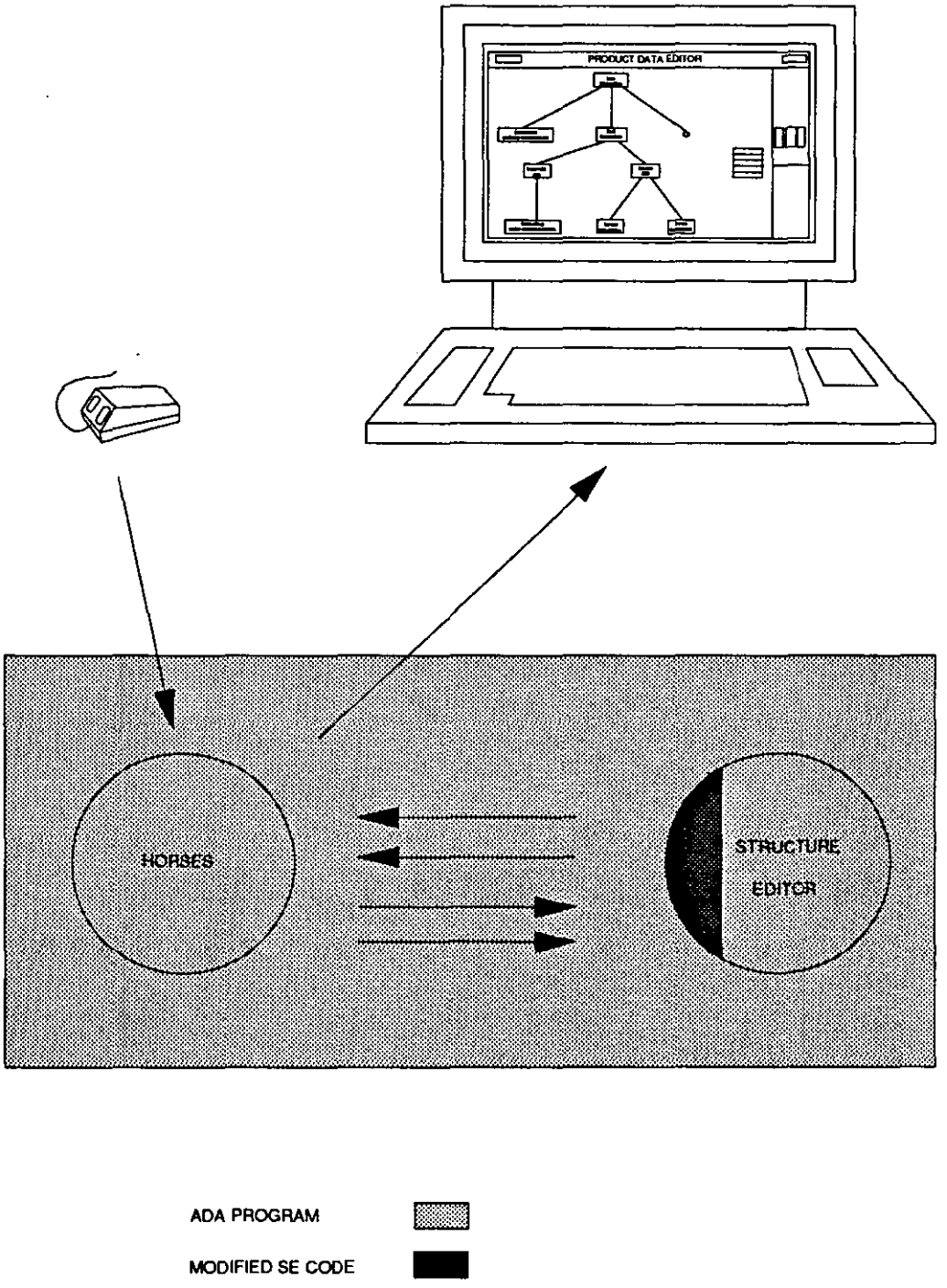
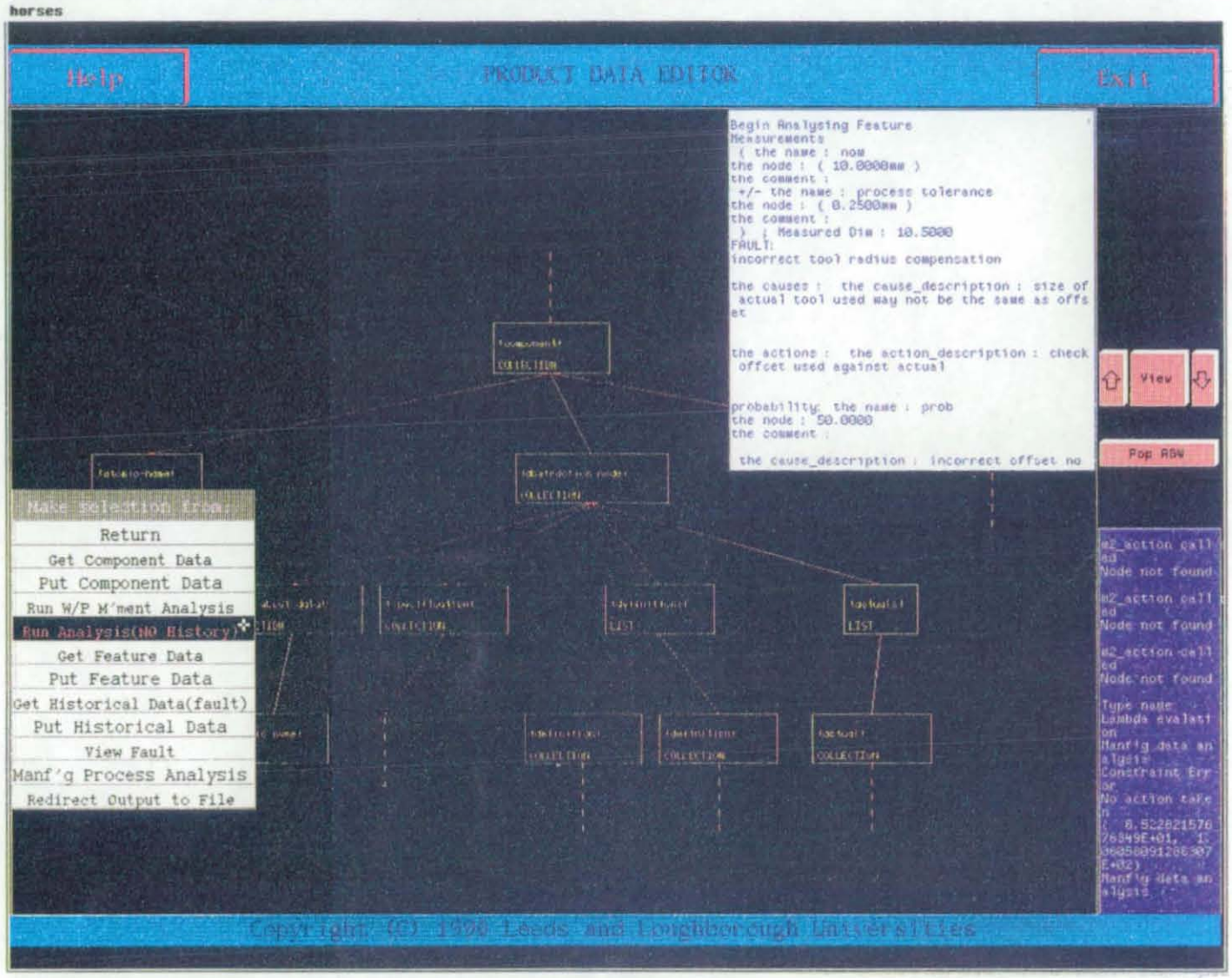


Figure 10.1	THE SYSTEM USING HORSES	Ref. 97

Figure 10.2

VISUALISATION



Ref.97

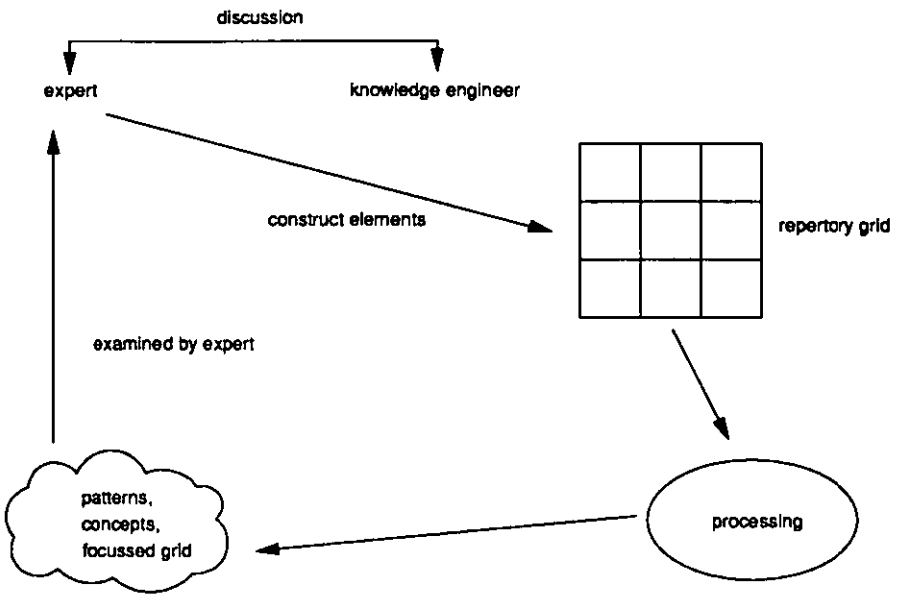


Figure 11.1	THE REPERTORY GRID	Ref. 135

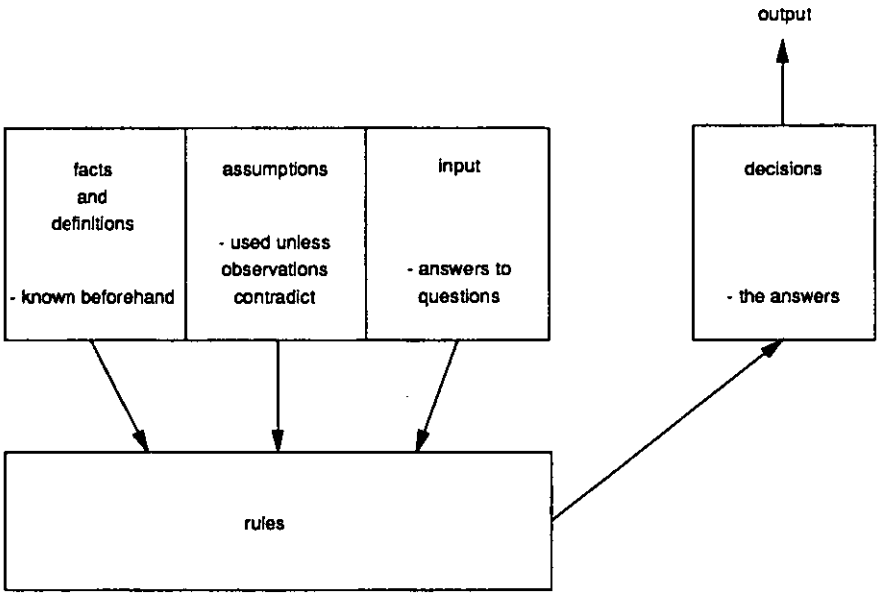


Figure 11.2	FACT-FINDING BY INTERVIEWS	Ref. 135

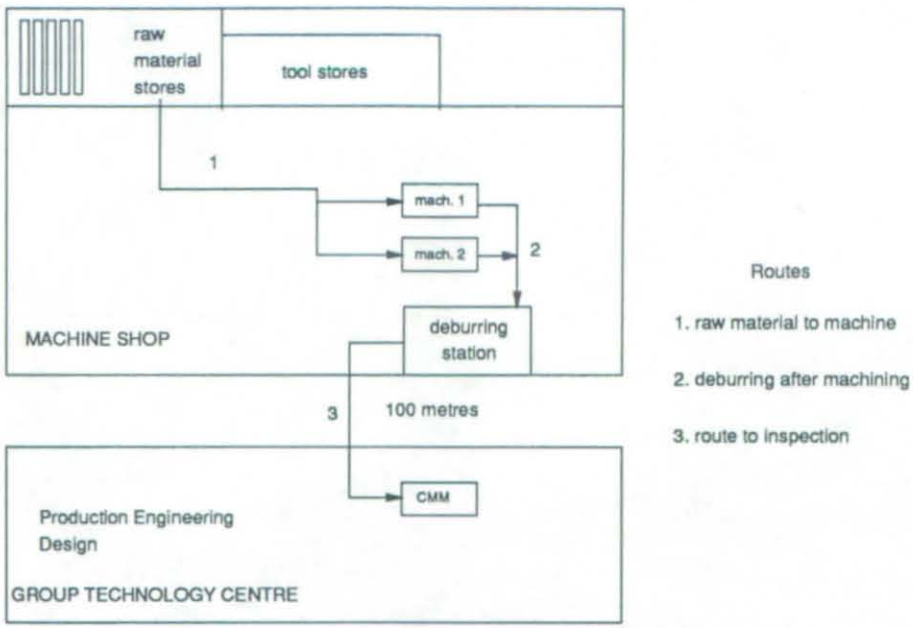


Figure 12.1	SCHEMATIC LAYOUT - RENISHAW PROTOTYPING CELL	

Figure 12.2	A TYPICAL COMPONENT	Renishaw

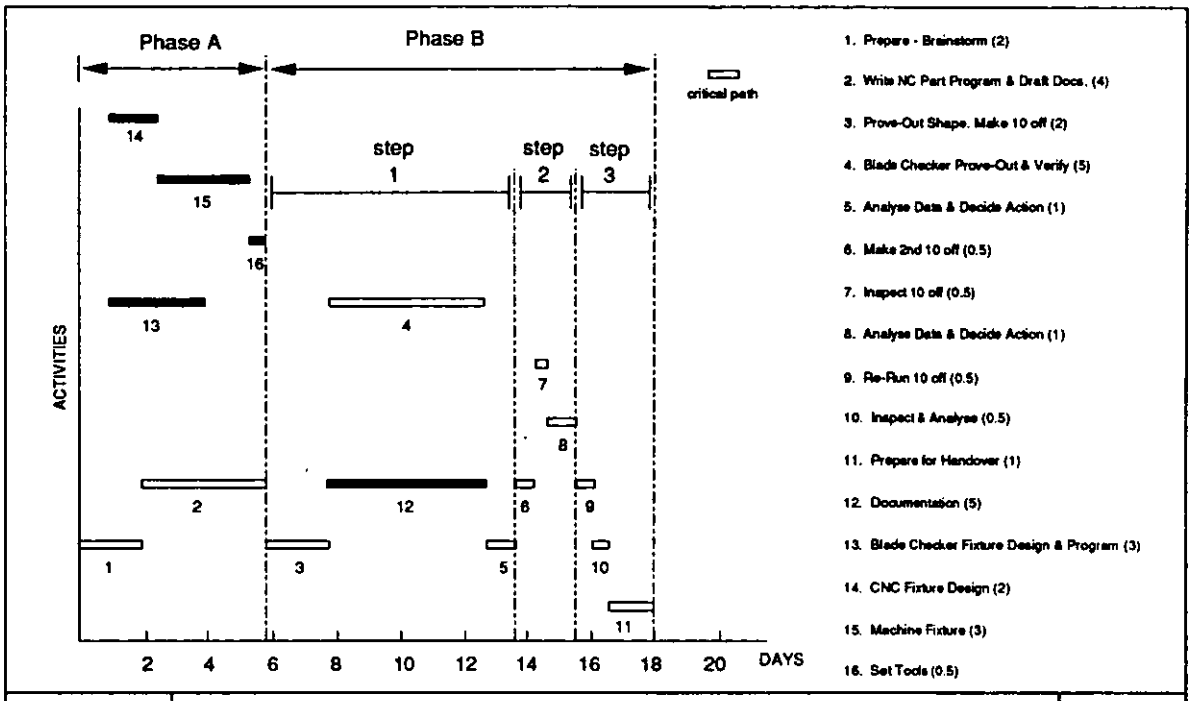


Figure 12.3 THE PROTOTYPE LIFE CYCLE Renishaw

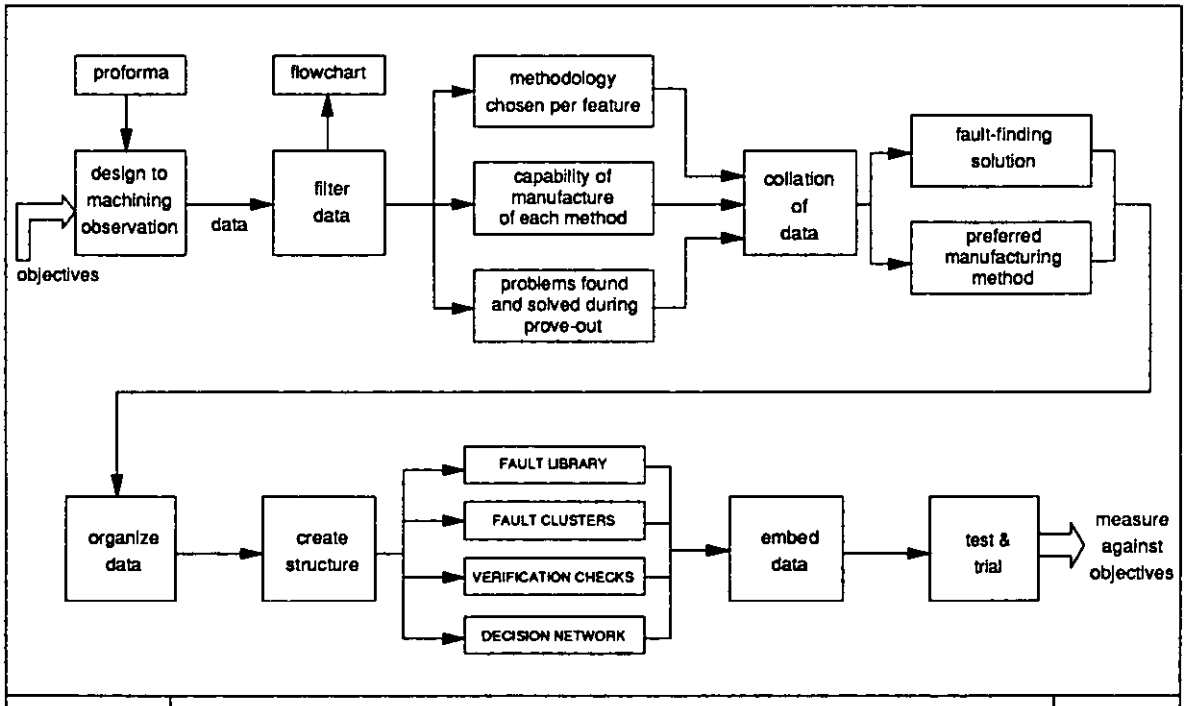


Figure 12.4 THE CASE STUDY ACTIVITIES

RENISHAW METROLOGY LTD. PROBLEM SOLVING SHEET 1

Sheet of

Problem Number :

Cross Reference Number :

Part Number : M - - -

Machine Description :

Part Description :

Operation Number : _ _

Tape Number : T

PROBLEM IDENTIFIED wrong positioning of drill

Suggest likely cause(s) : spotcentre drill position might not be in line with the drill position

ACTIONS TAKEN	WHY ?
1. move spotcentre drills in program	position of the two drills did not match
2. move spotcentre drills in actual xy position	position of the two drills are in the wrong positions respectively

Consequence of Actions ? :

Figure 13.1 CASE STUDY - PROBLEM SOLVING SHEET 1

RENISHAW METROLOGY LTD. PROBLEM SOLVING SHEET 2

Sheet of

Problem Number :

MACHINING INFORMATION			DESIGN INFORMATION		
Parameters	Before	After	Features	Before	After
Raw Material Type					
Raw Material Size					
Raw Material Form					
Tool Assembly					
Tool Projection					
Tool Condition					
Tool Offset (length)					
Tool Offset (radius)					
Tool Runout					
Cutting Speed					
Cutting Feed					
Depth of Cut					
Surface Texture Achieved					
Tool Sequence					
Tool Paths					
'G' Codes					
'M' Codes					
Machine Condition					
Bladechecker Repeatability			Datum Setting		
Machine Repeatability			Design Changes		
Index. Machine Repeatability			Fixture Changes		

Figure 13.2 CASE STUDY - PROBLEM SOLVING SHEET 2

RENISHAW METROLOGY LTD. PROBLEM SOLVING SHEET 3

Sheet of

Problem Number :

MACHINING INFORMATION	DESIGN INFORMATION
SKETCHES OF PROBLEM	SKETCHES OF PROBLEM
incorrect	
correct	

Figure 13.3 CASE STUDY - PROBLEM SOLVING SHEET 3

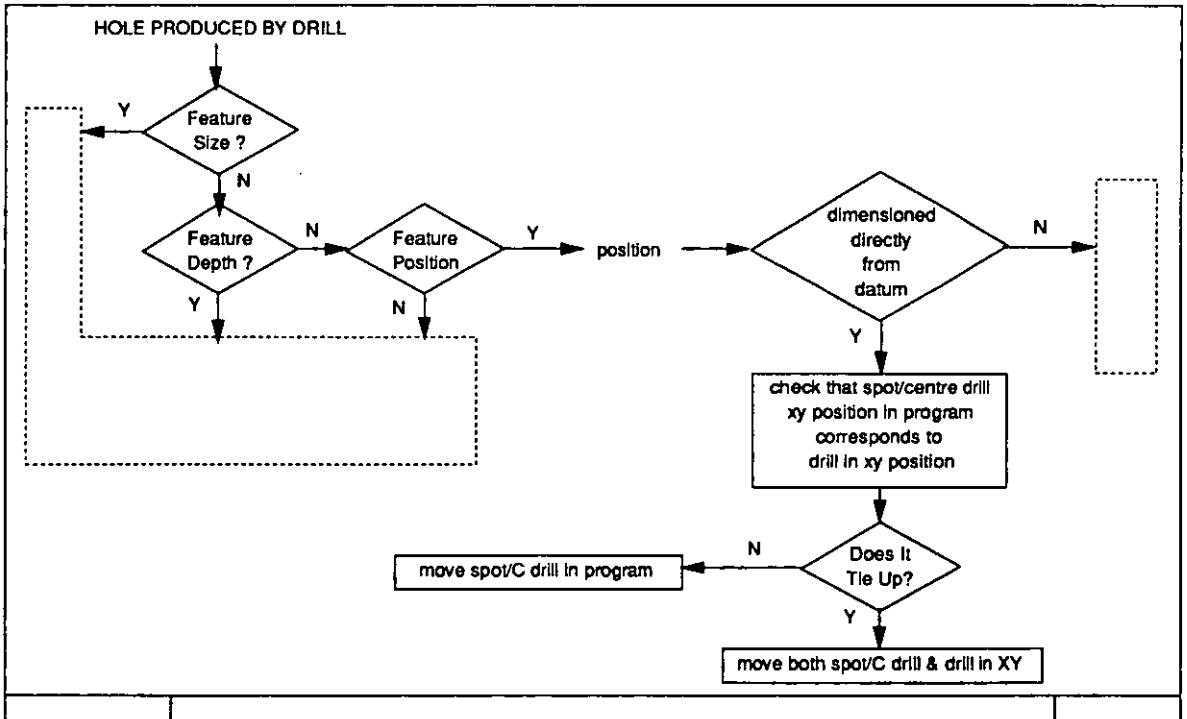


Figure 13.4 FLOWCHART - HOLE PRODUCED BY DRILL (POSITION) Renishaw

CAUSE	spot/c drill position might not be in line with the centre drill position
PROBABILITY	100 %
ACTION	1. move spot/centre drills in program if the position of the two drills do not match 2. move both spot/centre drills and drill in actual XY position if the position of the two drills match
FAULT TYPE	positioning of the drill

Figure 13.5 THE ENTRY IN THE FAULT LIBRARY

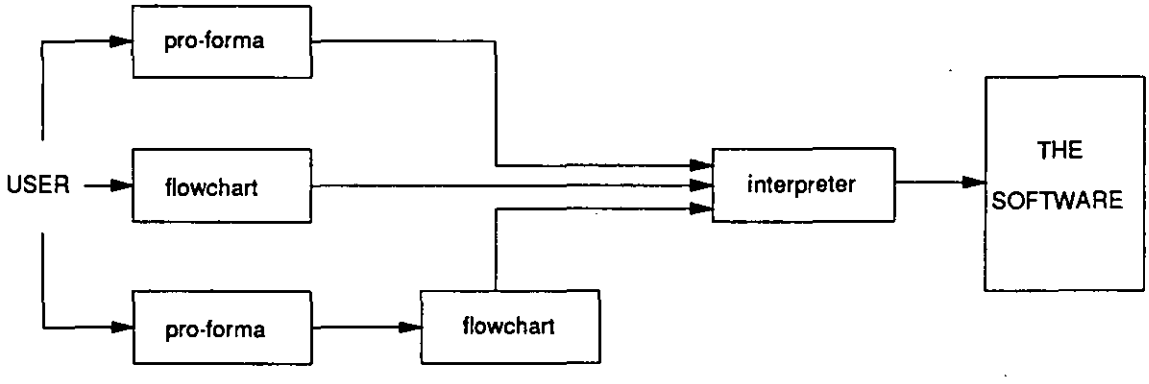


Figure 13.6 TRANSFERING EXPERT KNOWLEDGE TO SOFTWARE

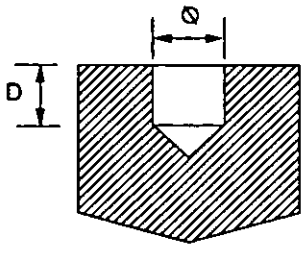
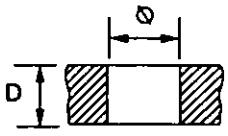
HOLES / BORES (TO A DRILL POINT OR THROUGH HOLES)		
TO A DRILL POINT	THROUGH HOLE	CRITERIA
		1. Depth, D <= Twice The Hole Diameter Ø 2. Diameter Tolerance >= +/- 0.25um 3. Positional Tolerance >= 0.4 4. Surface Finish >= 6.4 ? 5. Depth Tolerance >= +/- 0.25um 6. Diameter Hole, Ø
THE DEPTH, D <= TWICE THE HOLE DIAMETER ( ) Ø		

Figure 13.7	'GRADE A' TOLERANCE	Renishaw

TITLE	PART NO.	TITLE	PART NO.
1. Ball Plate	M-1041-7566	11. MIH Swivel	M-1070-0063
2. MIH Roller Plate	M-1070-0065	12. PH9 Top Hsg	M-1023--2537
3. MIH Lid	M-1070-0021	13. PH10 Top Hsg	M-1025-0016
4. PH9 Roller Pit	M-1023-7515	14. MIH Half Body	M-1070-0068
5. OMM Body	M-2031-0006	15. MIH Half Body	M-1070-0069
6. MP11 Body	M-2045-0020	16. PH9 LcK Lev	M-1023-2542
7. PH10 Swivel	M-1025-0101	17. MIH Lck Cam Blk	M-1070-0027
8. PH10 LCR Cam Blk	M-1025-0015	18. PH10 Half Body	M-1025-0263
9. MP7 Body	M-2033-1031	19. PH10 Half Body	M-1025-0264
10. MIH B Axis Hsg	M-1070-0020	20. PH10 G/Box	M-1025-0240

Figure 13.8	20 PARTS COLLECTED FOR DIMENSIONAL ANALYSIS	Renishaw

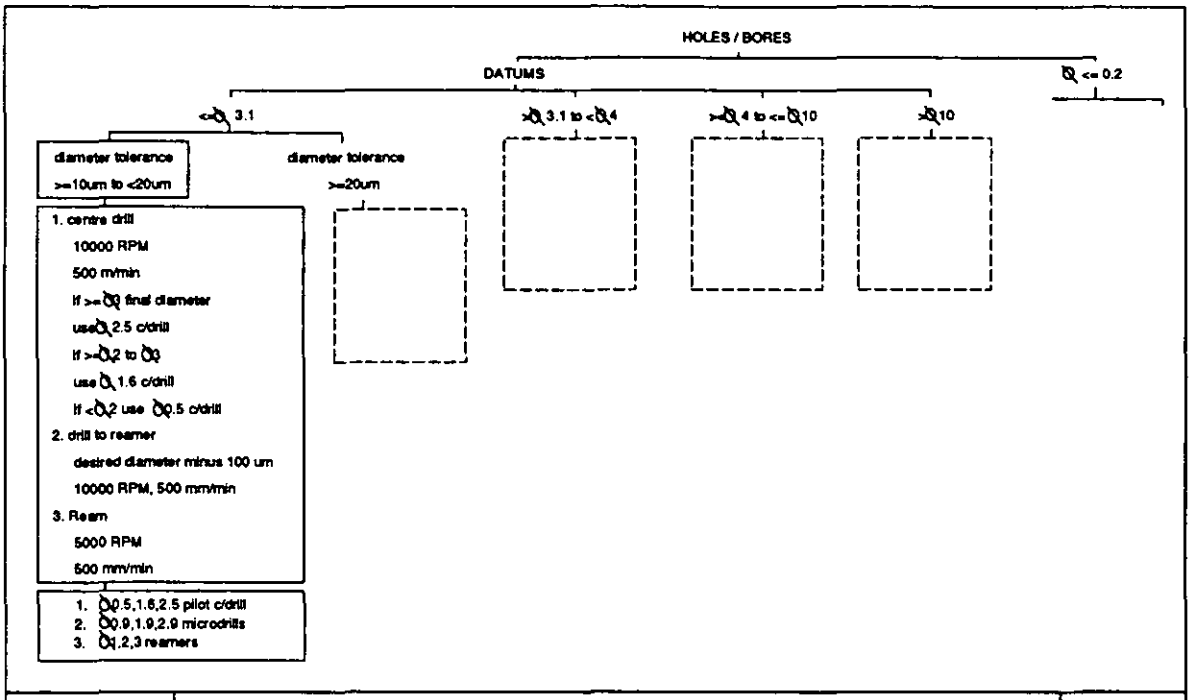
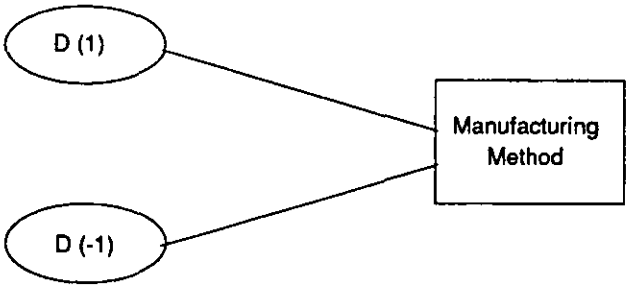


Figure 13.9	RECOMMENDED MANUFACTURING METHODS (DIM. ANAL.)	Renishaw



D : ϕ 3.1

1 : Upper Action

-1 : Lower Action

Figure 13.10	THE INFLUENCE DIAGRAM FOR DIMENSIONAL ANALYSIS	

dimension	diameter 3.1
state	UA
fault type	B />10um to <20um/ <= diameter 3.1 manufacturing method
cause	centre drill, 10000 rpm, 500 mm/min
action	1. if >= diameter 3, use diameter 2.5 c/drill 2. if >= diameter 2 to diameter 3, use diameter 1.6 c/drill 3. if < diameter 2, use diameter 0.5 c/drill
cause	drill to reamer, desired diameter minus 100um, 10000 rpm, 500 mm/min
action	1. if >= diameter 3, use diameter 2.9 m/drill 2. if >= diameter 2 to diameter 3, use diameter 1.9 m/drill 3. if < diameter 2, use diameter 0.9 m/drill
cause	ream, 5000 rpm, 500 mm/min
action	1. if >= diameter 3, use diameter 3 reamer 2. if >= diameter 2 to diameter 3, use diameter 2 reamer 3. if < diameter 2, use diameter 1 reamer

Figure 13.11 DATA FOR THE DECISION NETWORK

```
menu header: what is the diameter range for hole used as datum
  menu elements:
    diameter is le 3.1mm:
      menu header: what is the tolerance range for diameter le 3.1mm
        menu elements:
          tolerance is ge 10 micrometer to lt 20 micrometer:
            menu header: the manufacturing method recommende for ge 0.01mm tol. is
              menu elements:
                B/dia le 3.1/tol ge 0.010 to lt 0.020 == ...
          tolerance is ge 20 micrometer:
            menu header: the manufacturing method recommended for ge 0.020mm tol. is
              menu elements:
                B/dia le 3.1/tol ge 0.020 == ...
    diameter is gt 3.1mm to lt 4.0mm:
      ....
      ....
    diameter is ge 4.0mm to le 10.0 mm:
      ....
      ....
```

Figure 13.12 DATA FOR THE TAXONOMIC STRUCTURE

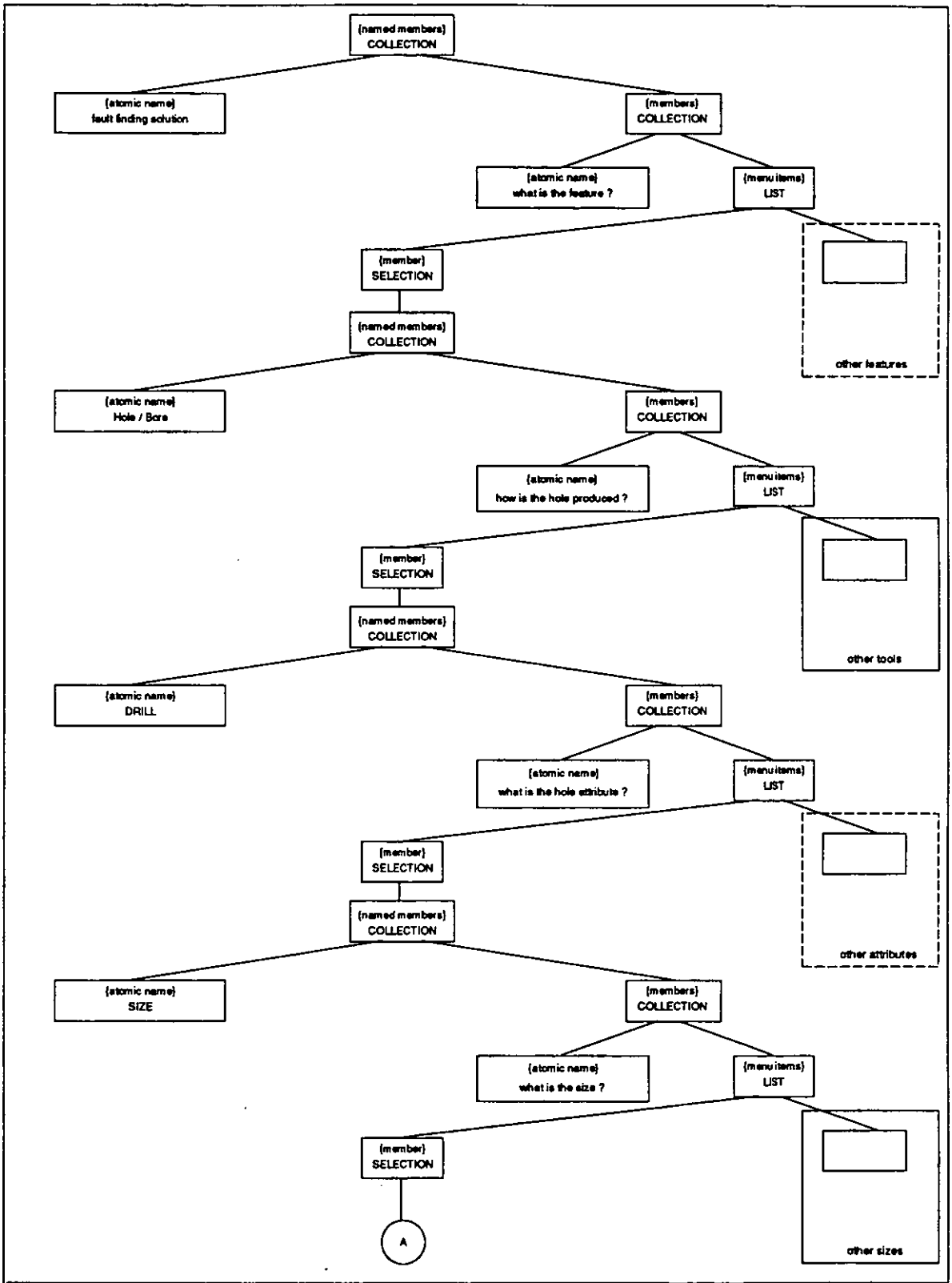


Figure 13.13 THE FAULT-FINDING SOLUTION - 1

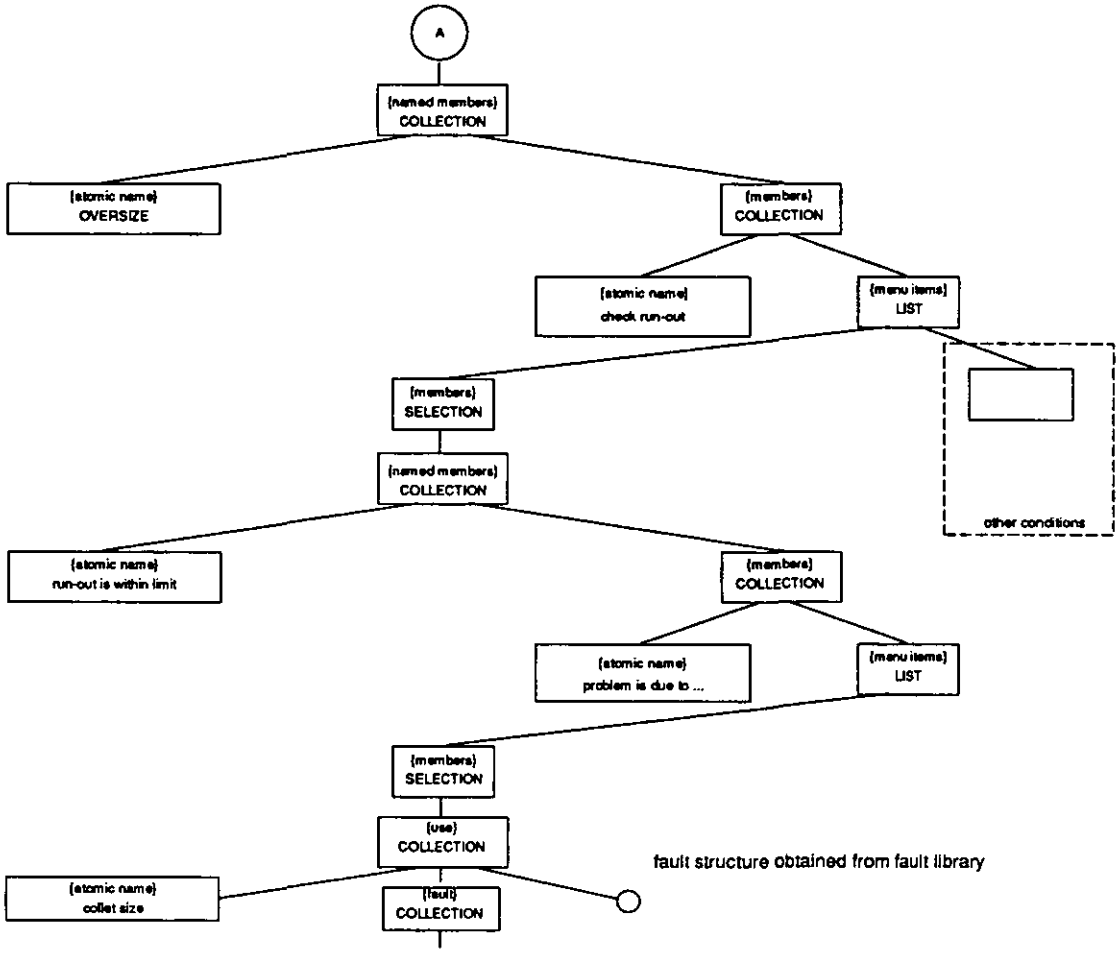


Figure 13.14 THE FAULT-FINDING SOLUTION - 2

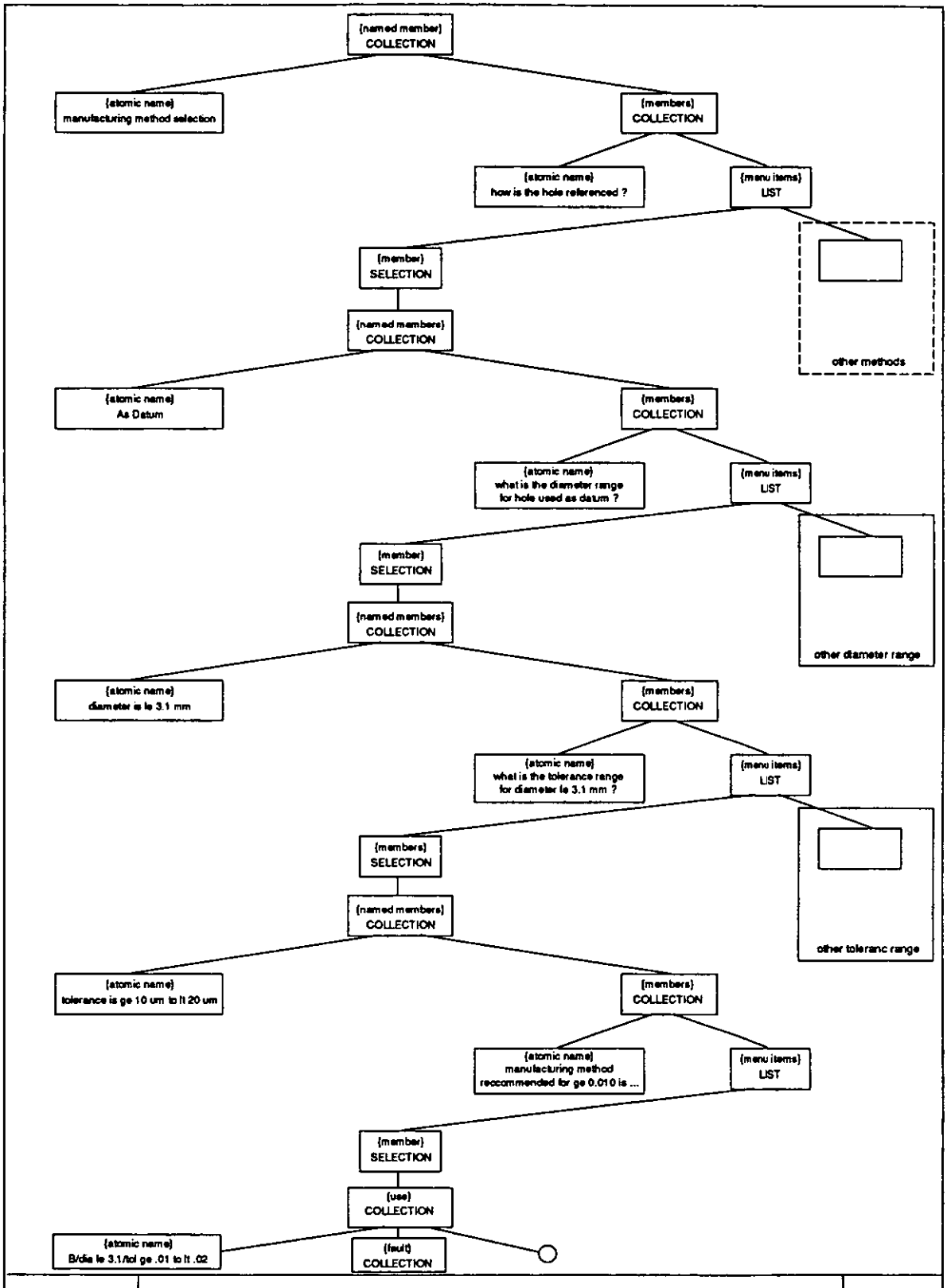


Figure 13.15 THE MANUFACTURING METHOD SOLUTION

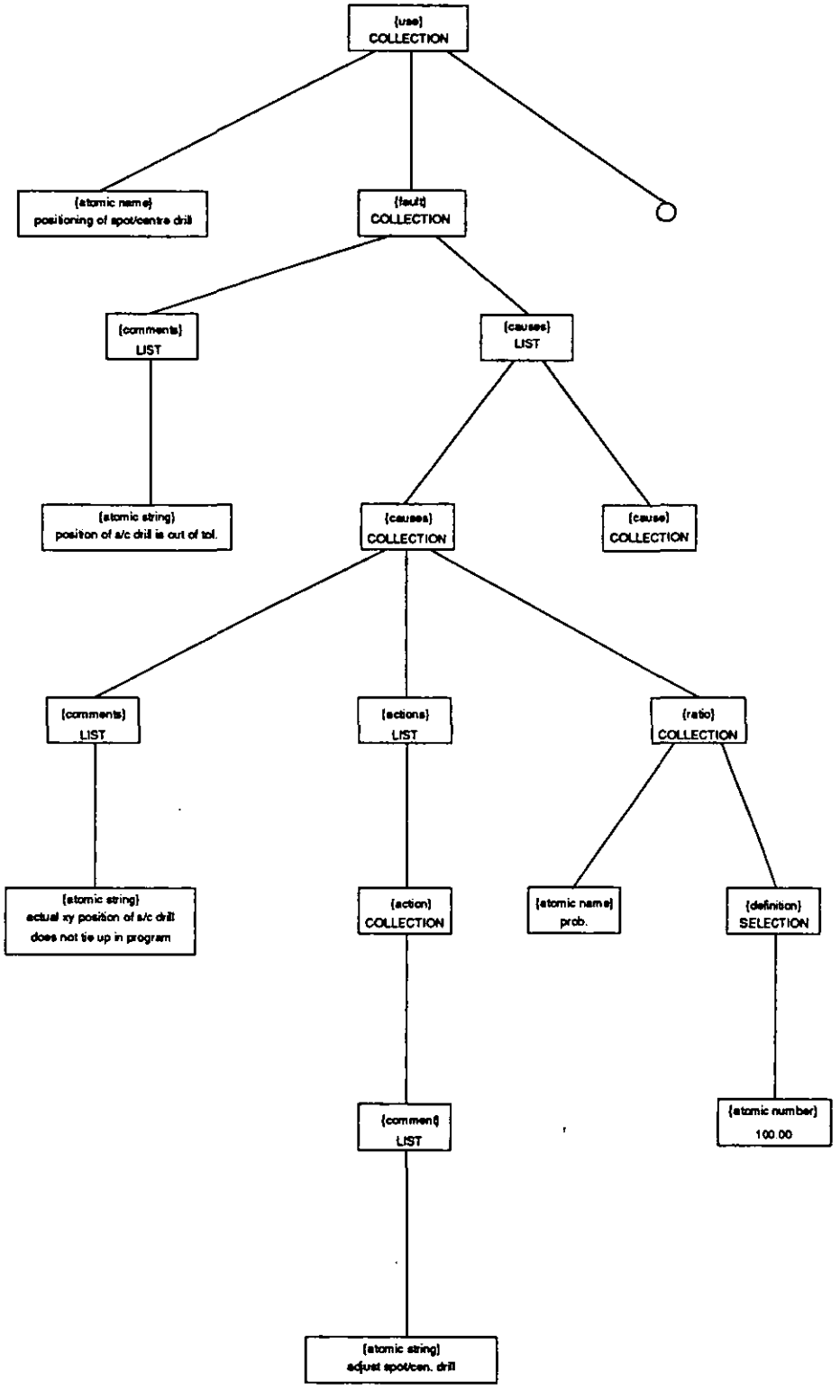


Figure 13.16 THE FAULT STRUCTURE

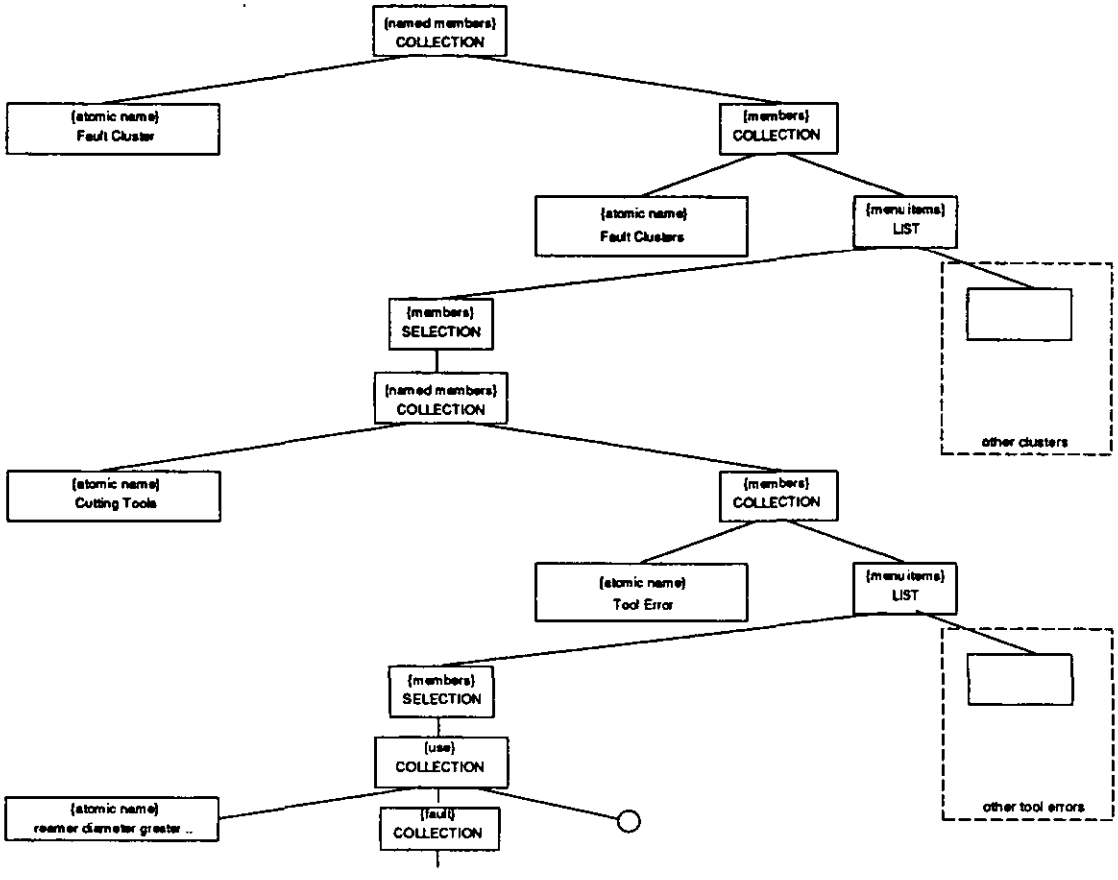


Figure 13.17 THE FAULT CLUSTER STRUCTURE

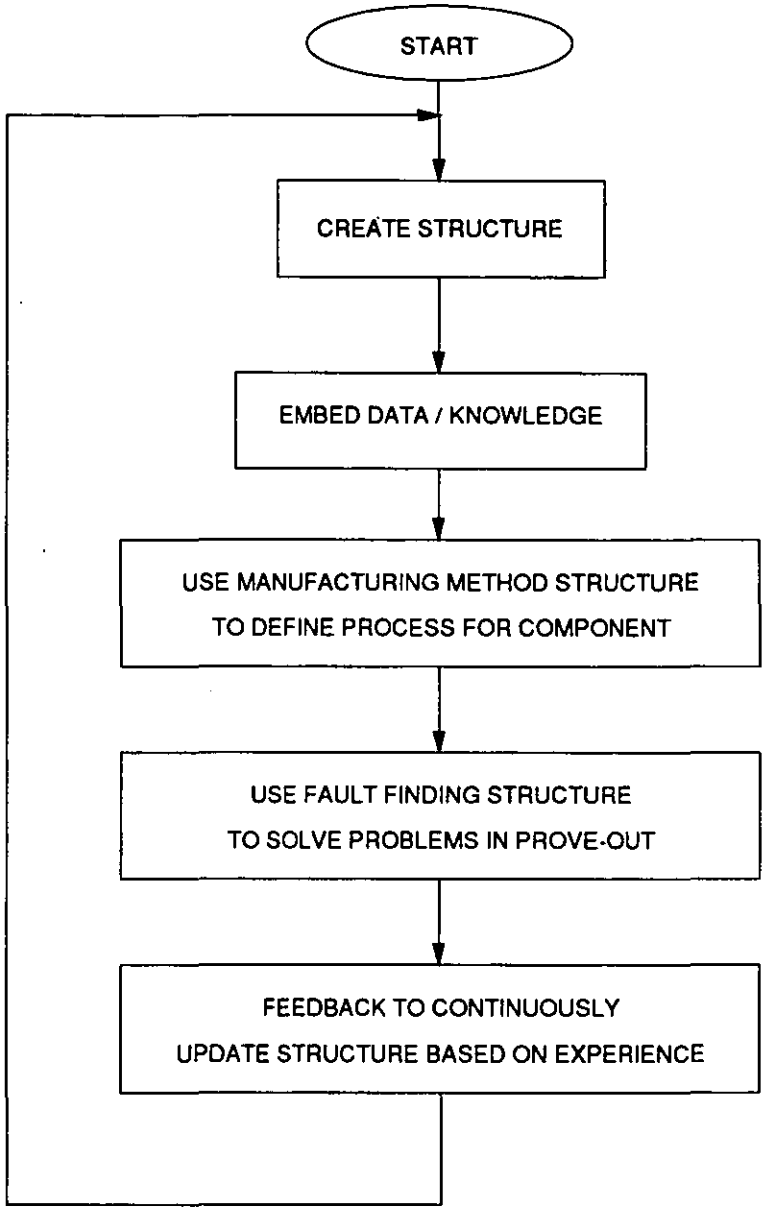


Figure 13.18 THE SOFTWARE TRIAL

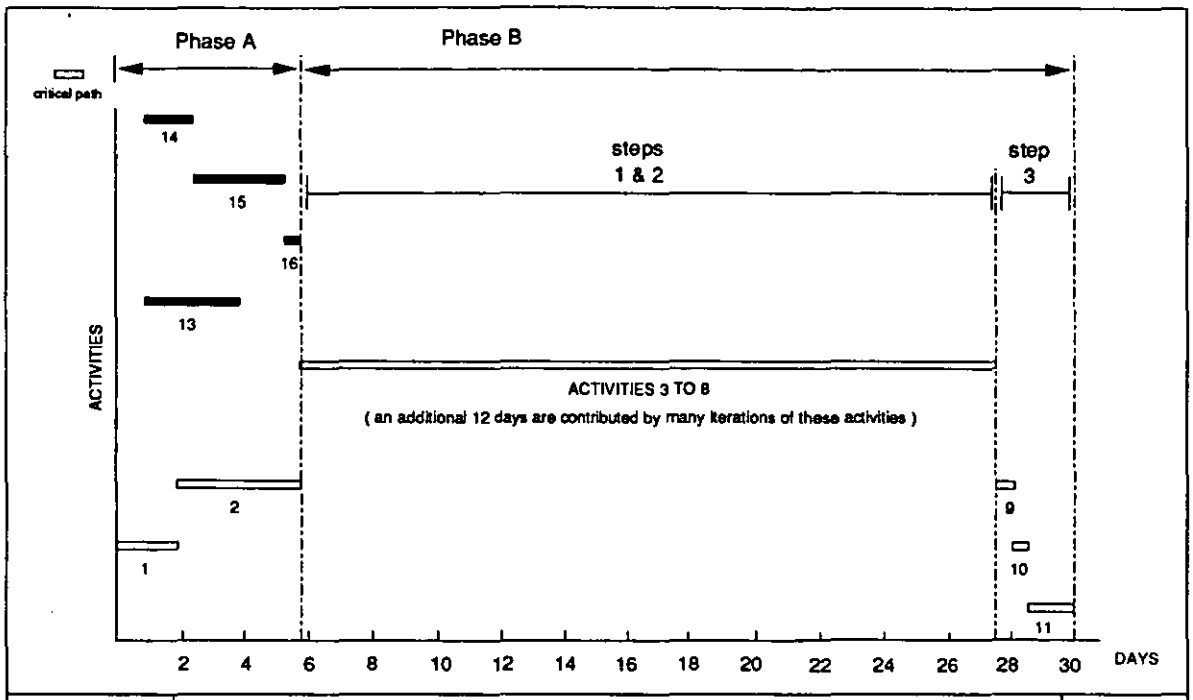


Figure 14.1 THE CURRENT PROTOTYPE LIFE CYCLE - 30 DAYS Renishaw

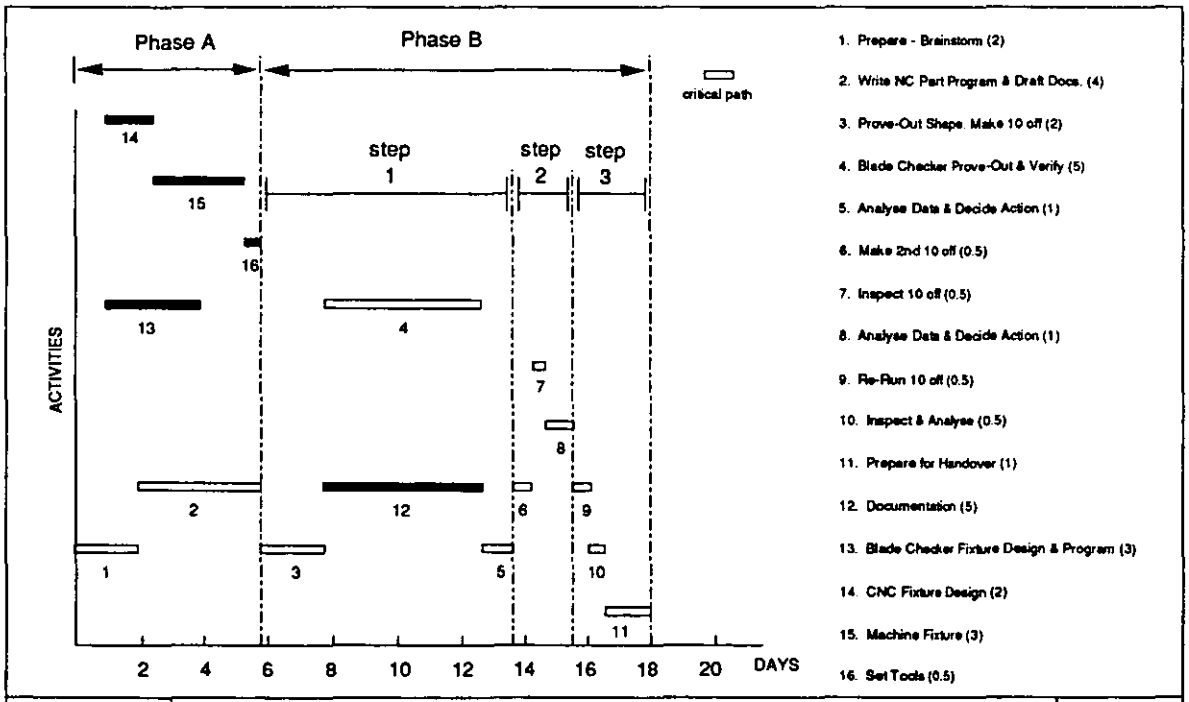


Figure 14.2 THE REDUCED PROTOTYPE LIFE CYCLE - 18 DAYS Renishaw

APPENDIX II.

THE USER VIEWPOINT

Appendix II :
The User Viewpoint

1. Introduction

The reader is introduced to the operation and implementation of the data feedback system in this appendix. Appendix II moves from a pictorial description of the data feedback system to an overview and use of the information support system.

2. The Data Feedback System

Appendix 2A provides a photographic view of the levels of detail in the Product Data Model. The series of photographs, Figures 2A.1 to 2A.16, show the data structures implemented and necessary for data feedback. The aim is to illustrate the data feedback system in the context of the information support system, see Figures 2A.17 and 2A.18, and to give the user some 'look and feel' of the feedback facilities themselves. These structures include the fault description, the taxonomic structure, the decision network, and the measurement graph. The building of these structures for a particular implementation have been described in Chapter 9, their use in an industrial context in Chapter 13, and the full implementation given in Appendix III.

3. The Information Support Systems Project

Appendix 2B describes all the applications of the information support system including the data feedback system. The information support system was described in Chapter 4. The research work was put in the context of the information support system in Chapter 6. The document, given in Appendix 2B, is not strictly intended as a user manual as to do so would exceed the bounds of this thesis. It is intended to assist the reader to appreciate the value of this research work in the context of the product data model. The document, though does provide the user with enough information to experiment with the software.

4. The Product Data Editor

Appendix 2C describes the Product Data Editor,Horses user interface to the Structure Editor. The appendix describes how to get started and the functions of the display mechanisms. The Product Data Editor allows the user to move about the structure, and to carry out editing and other sundry operations. The Horses interface to the Product Data Editor is the main utility for the data feedback system.

5. The Structure Editor

Appendix 2D describes the Structure Editor. The Structure Editor is a piece of software which can be used to define and edit structures. It has the power to guarantee that anything created conforms to the prescribed pattern. The Structure Editor was introduced in visualisation in Chapter 10. The document gives a description of the Structure Editor and its characteristics.

6. The ADA Code

Appendix 2E gives the ADA code for the data feedback facilities and the code for performing the analysis.

7. The Decision Network and Measurement Graph

Appendix 2F illustrates the implementation of the Decision Network and Measurement Graph for a top plate. This was part of a Glacier case study. This implementation is primarily intended to complement the results given in Appendix III and thus illustrate the full functionality of the data feedback system.

8. The Information Support System - References

A selection of references to documents, in addition to those in Appendix IA, to support all the facilities used for data feedback are given:

1. GMP Staff.
"User Manual for: ISS Distribution Software - Examples of Use".
Internal Document, University of Leeds & Loughborough University of Technology, iss-user-5, issue 1, July 1990.

2. Dawson, P.
"User Manual for : The Horses User Interface to the Product Data Editor".
Internal Document, University of Leeds & Loughborough University of Technology, iss-user-4, issue 2, September 1990.

3. McKay, A.
"The Role of an Information Support System".
Internal Document, University of Leeds & Loughborough University of Technology, iss-pds-report-5, October 1988.

4. McKay, A.
"A Framework for the Project Meta-Structure".
Internal Document, University of Leeds & Loughborough University of Technology, iss-pds-report-8, July 1989.

5. McKay, A.
"The Structure Editor Approach to Product Description".
Internal Document, University of Leeds & Loughborough University of Technology, iss-pds-report-4, June 1988.

6. Bloor, S.M. and de Pennington, A.
"Towards Integrated Design and Manufacturing System".
Internal Document, also presented at the Factory 2000 Conference.

7. Shaw, N.K. et al.
"Product Data Models".
Research in Engineering Design, June/July 1989.

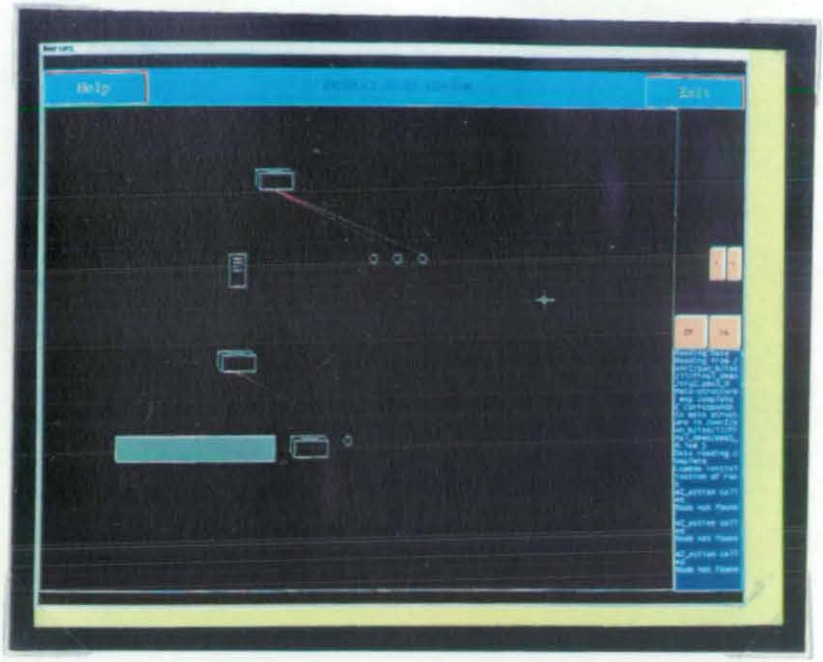
8. McKay, A. and Holdsworth, D.
"The Structure Editor".
Internal Document, University of Leeds & Loughborough University of Technology, user-12.

9. McKay, A.
"Update to the GMP2 Structure Editor (user-12)".
Internal Document, University of Leeds & Loughborough University of Technology, iss-user-1, July 1989.

10. McKay, A.
"Techniques for using the Structure Editor".
Internal Document, University of Leeds & Loughborough University of Technology, iss-user-2.

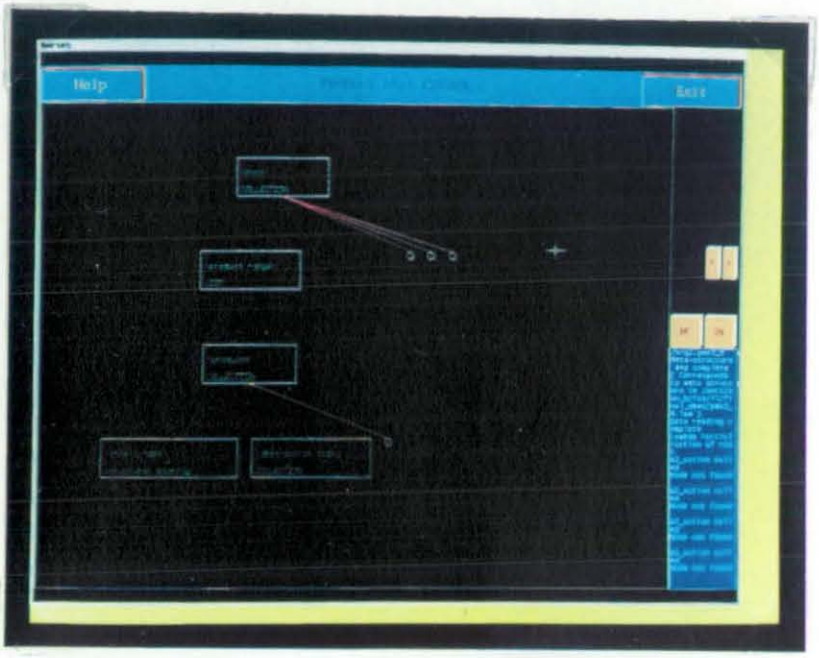
APPENDIX 2A.

THE DATA FEEDBACK SYSTEM



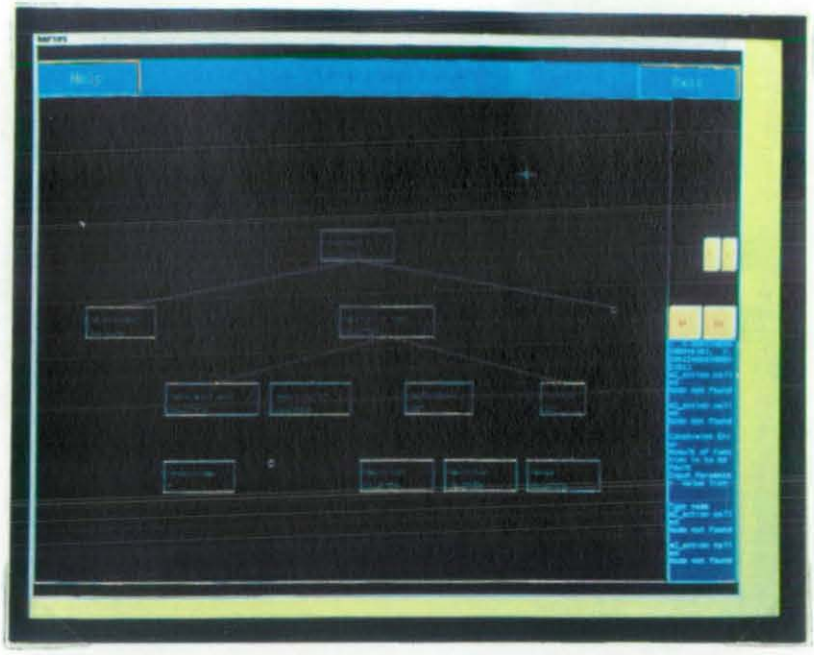
2A.1 An Iconic Representation of the Product Data Model

at the Product Level.



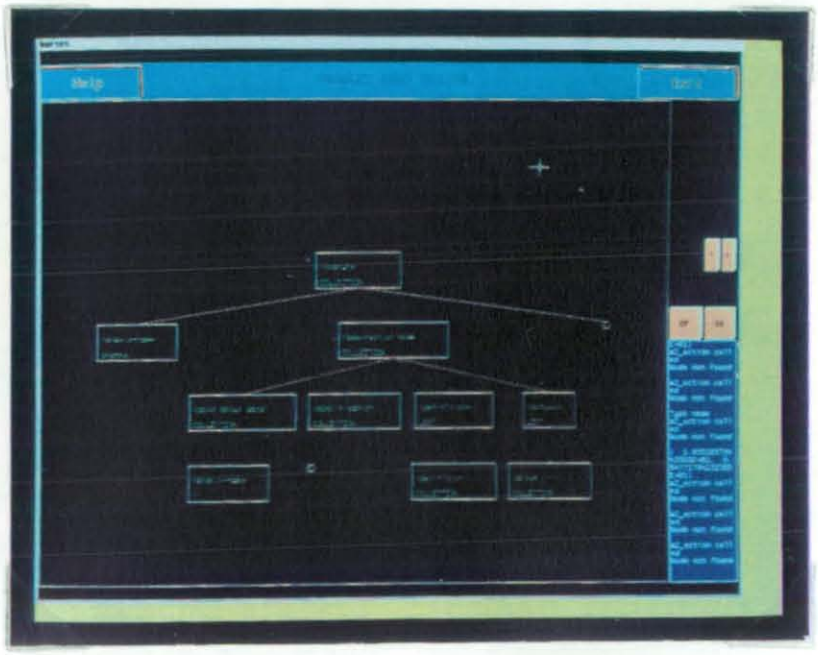
2A.2 A Textual View of the Product Data Model

at the Product Level.



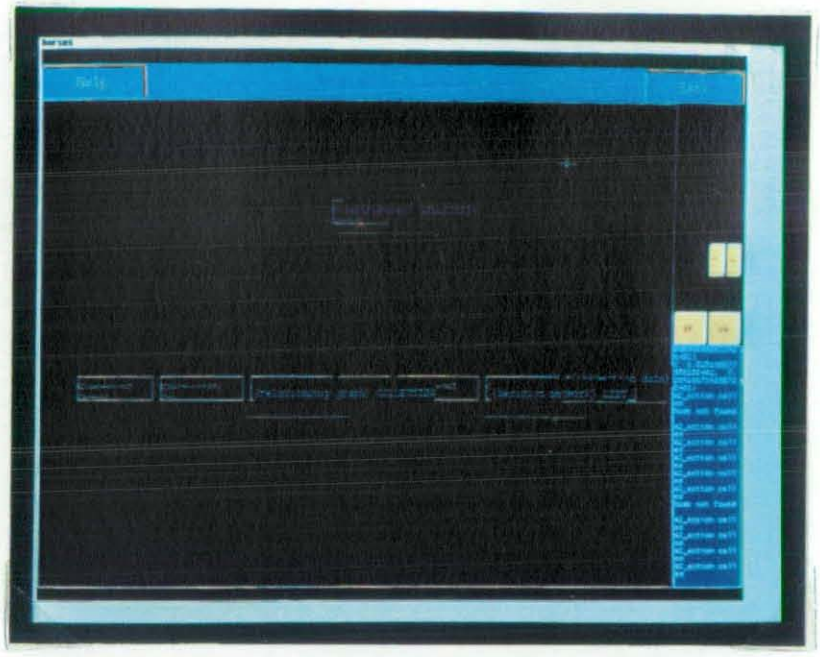
2A.3 A Textual View of the Product Data Model

at the Component Level.

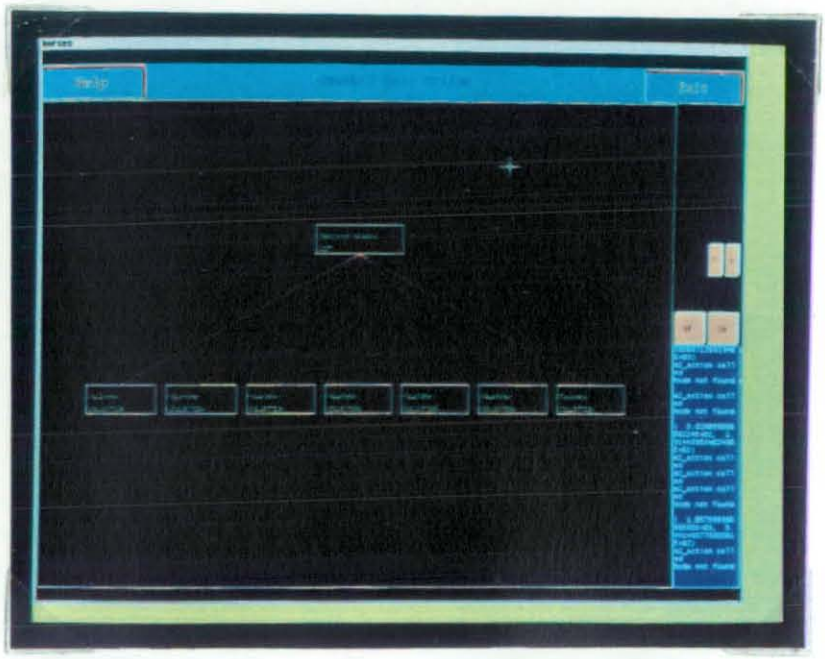


2A.4 A Textual View of the Product Data Model

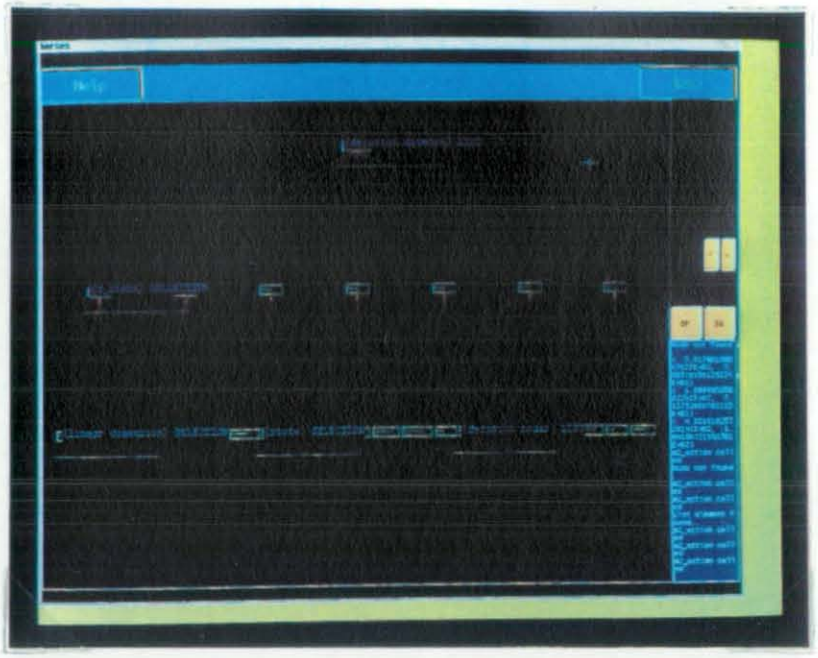
at the Feature Level.



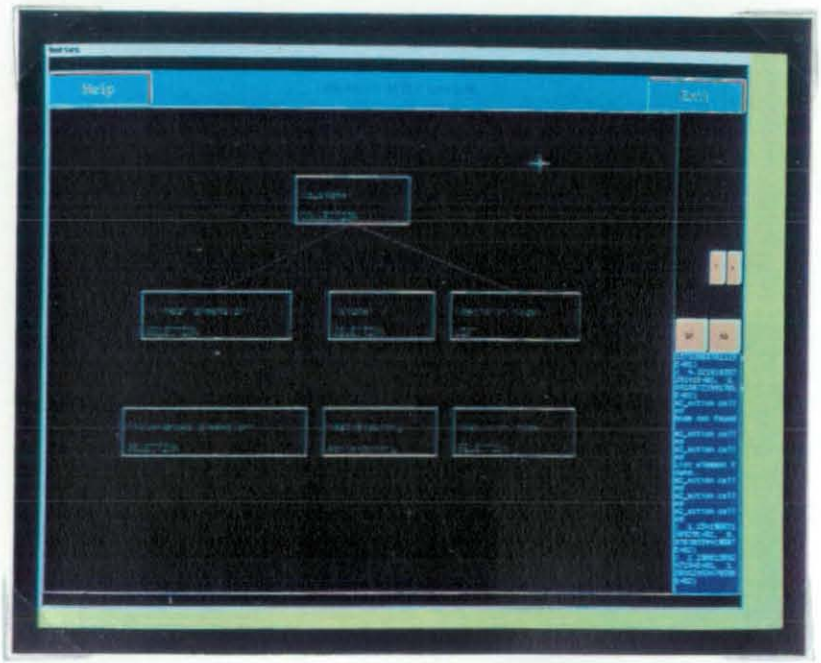
2A.5 The Feature Attributes of the Features Definition.



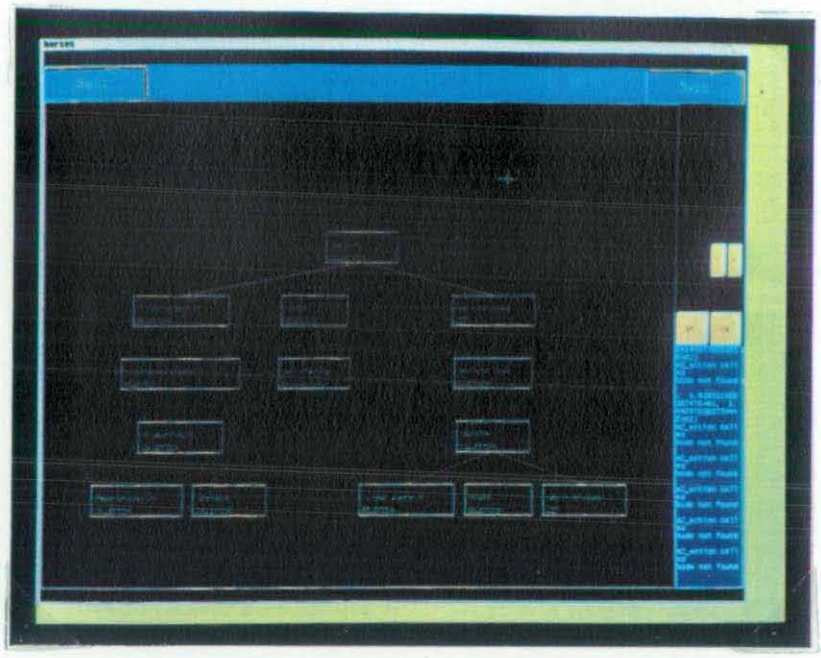
2A.6 The Decision Network at the Feature Level.



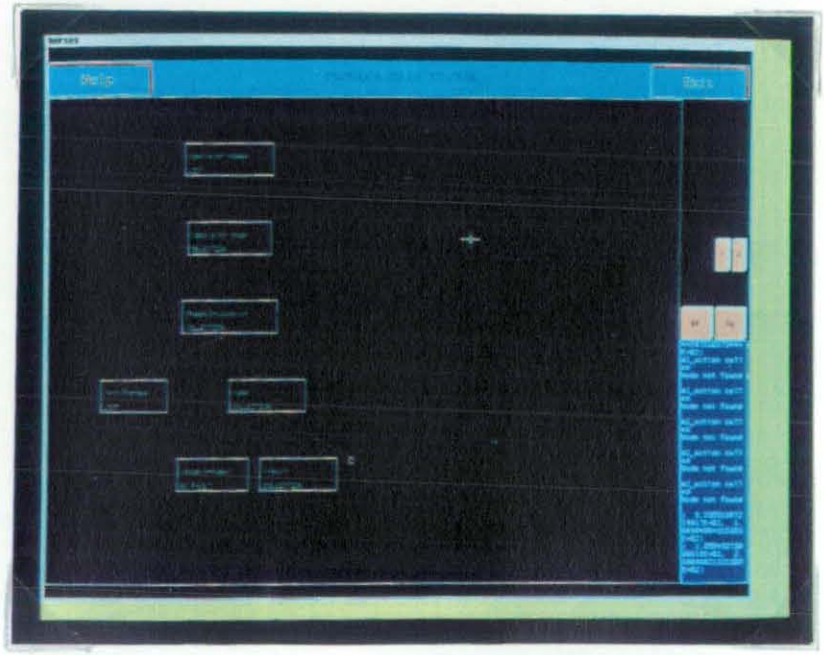
2A.7 An Expanded View of the Decision Network.



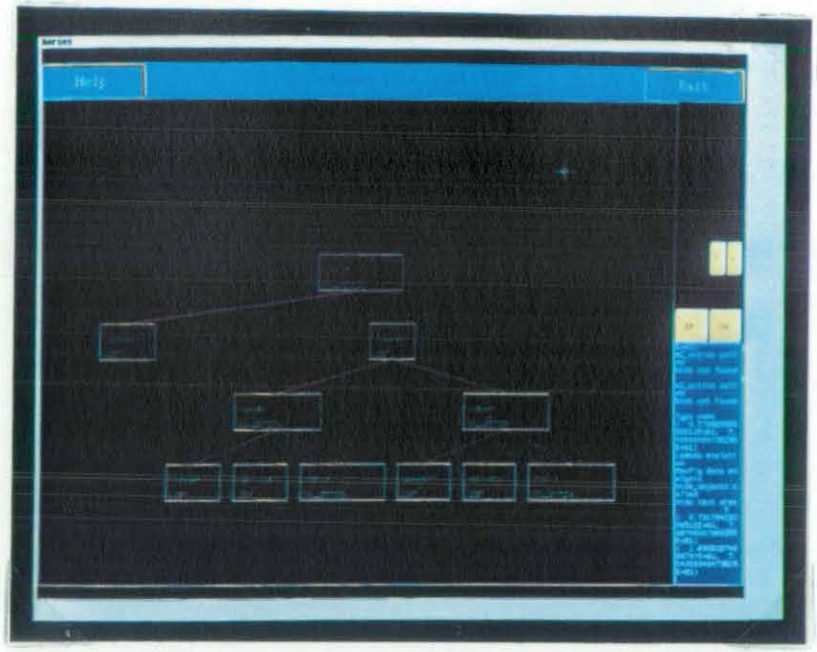
2A.8 A d-state.



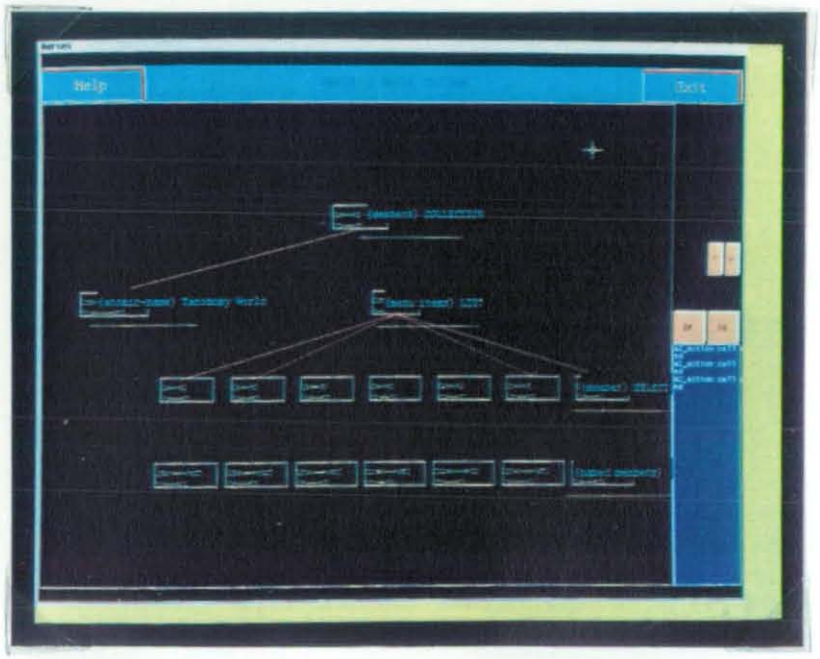
2A.9 A d-state of the Decision Network showing a Linear Dimension, a State, and a Decision Node of a d-state.



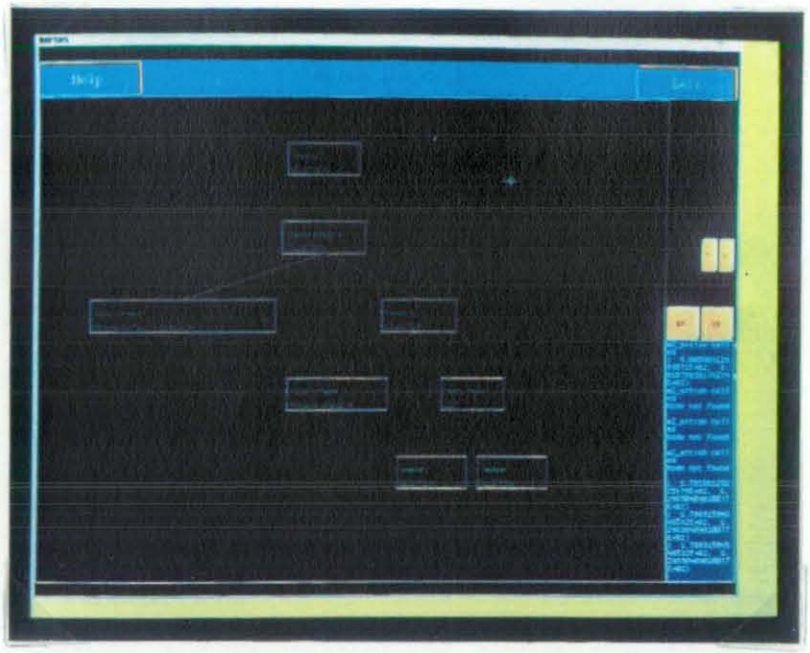
2A.10 The Decision Node as a Fault Type



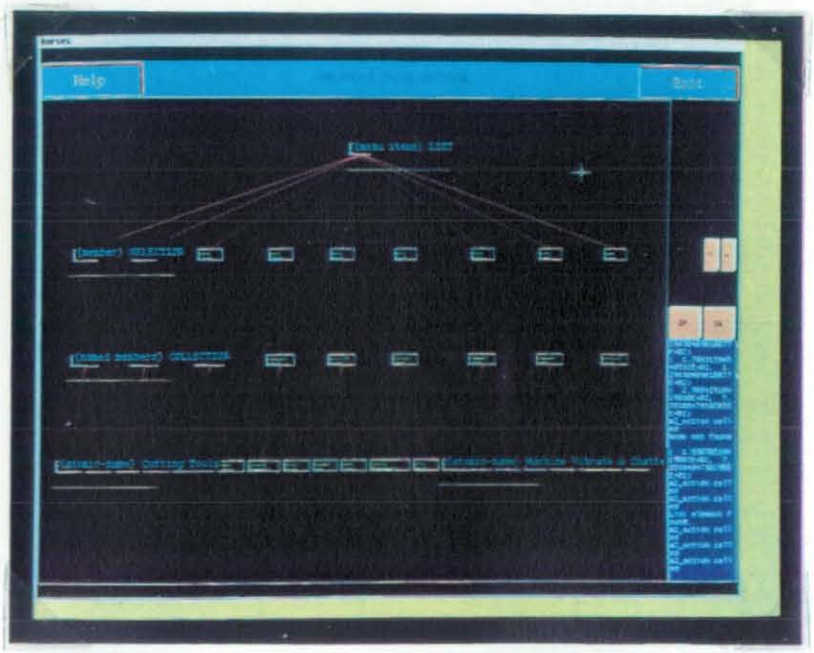
2A.11 The Fault Structure.



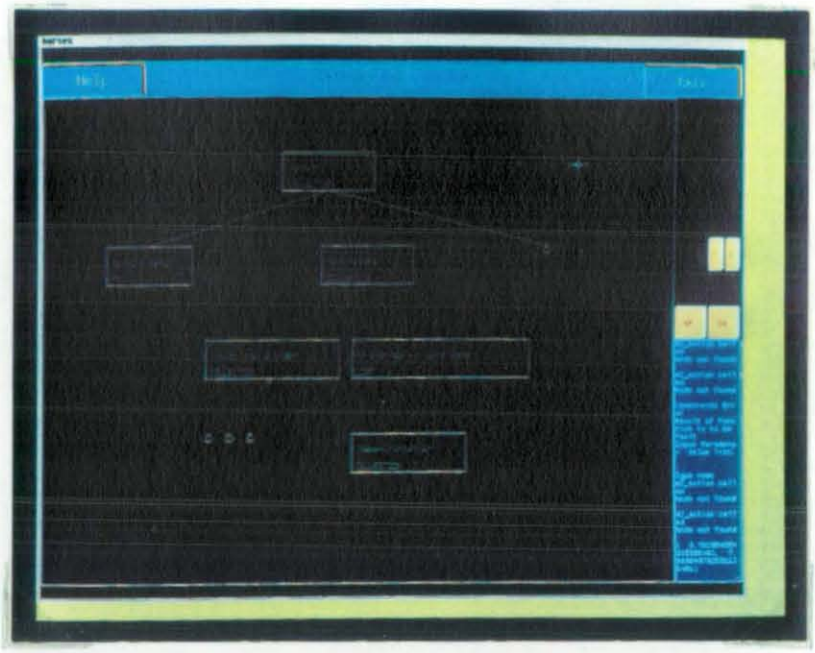
2A.12 The Top Level of the Taxonomic Structure.



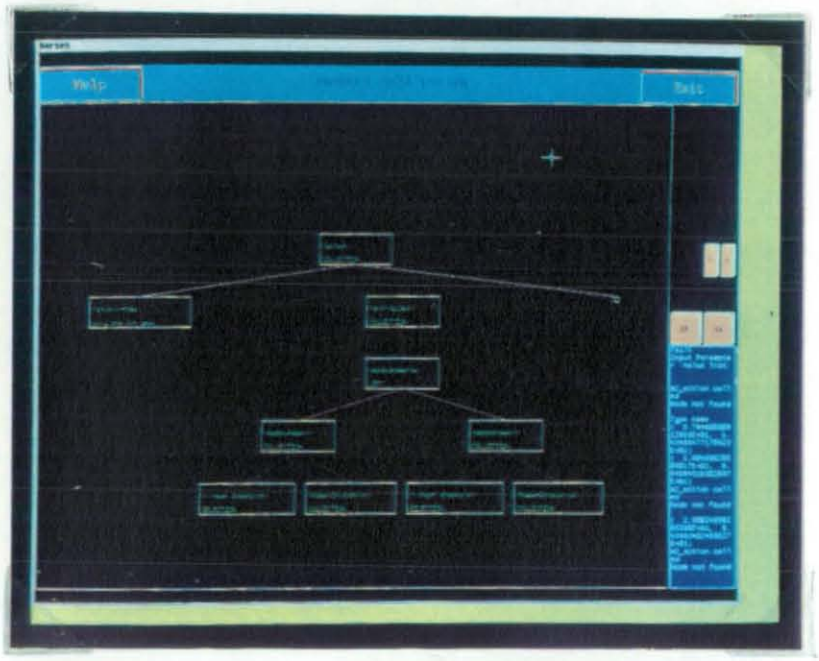
2A.13 The MDA Taxonomic Structure.



2A.14 The Fault Clusters at the Taxonomic Level.



2A.15 The Historical Analysis Data at the Actuals of the Component Level.



2A.16 The Measurements Graph at the Actuals of the Feature Level.

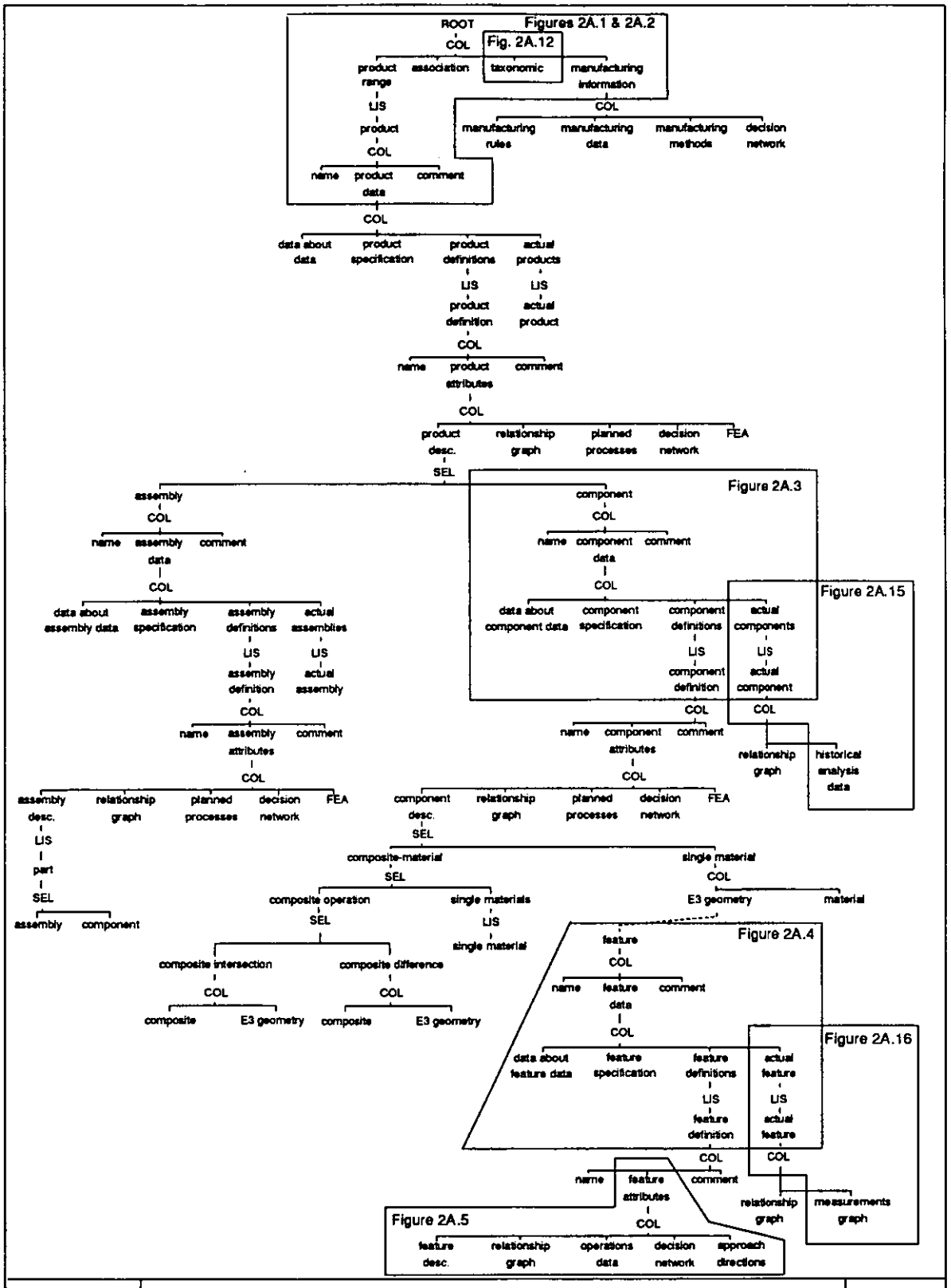


Figure 2A.17 THE DATA STRUCTURE OF THE PRODUCT DATA MODEL

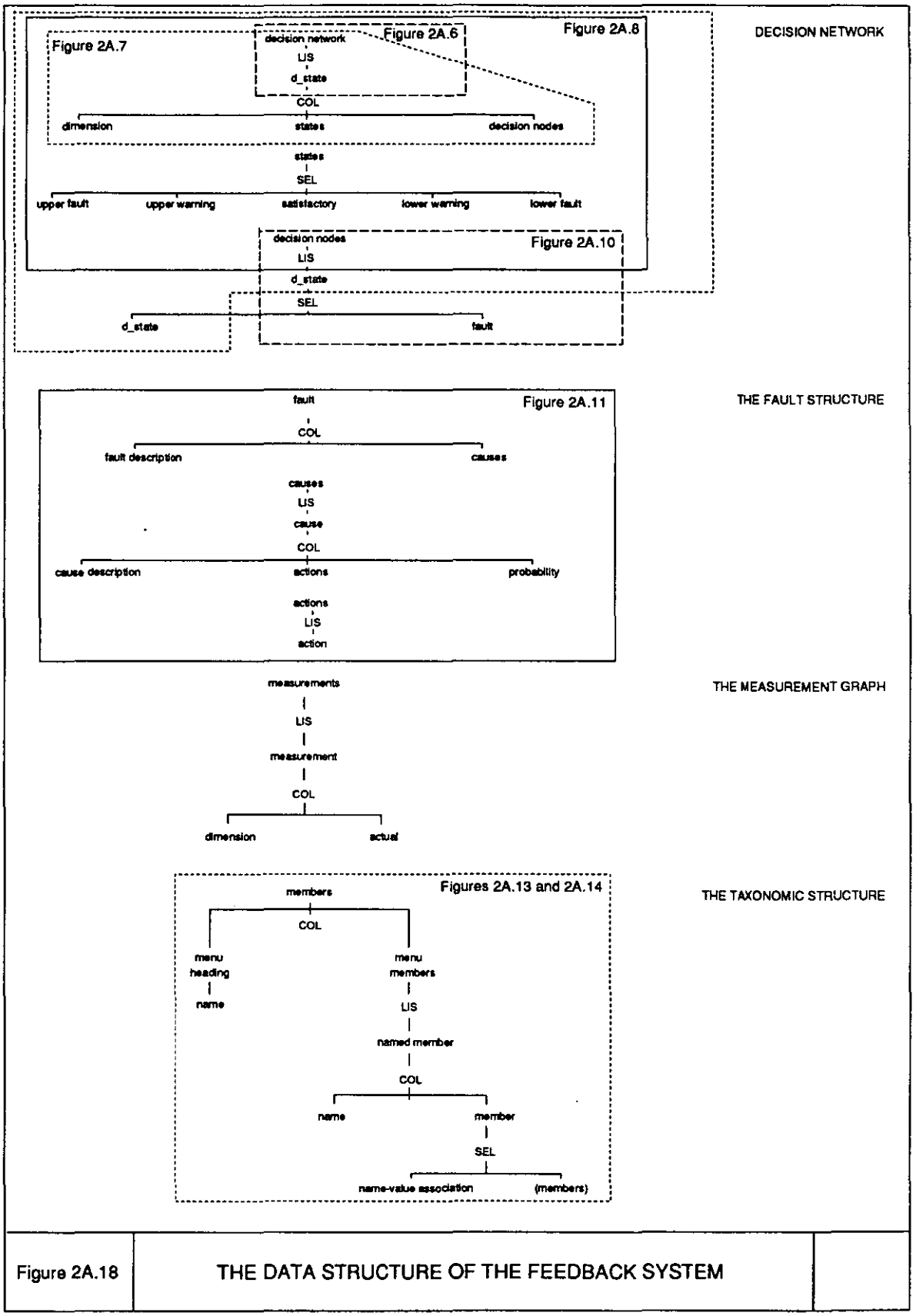


Figure 2A.18 THE DATA STRUCTURE OF THE FEEDBACK SYSTEM

APPENDIX 2B.

THE INFORMATION SUPPORT SYSTEM PROJECT

1 Introduction

This document is intended to support the software that is being distributed as part of the *deliverables* from the ISS project (see title page for project details). It gives some examples of how to use the software and follows, closely, the demonstration presented to Sponsors on June 5 1990 at the final Sponsors' Meeting.

Although not strictly speaking a User Manual, this document (in conjunction with [1,2,3,4]) should provide users with enough information to experiment with the software. It is mainly intended to assist the user to appreciate the value of the work achieved during the life of the recently completed project. Under each section, there is a paragraph explaining what each experimental application does, followed by a "script" guiding the user through a pre-set dialogue; the left-hand column contains the commands to type and the right-hand column, a brief description of what's happening. Occasionally a descriptive piece of text will appear in the script; this will be indented at bothe the left and right margins.

The software is available in two forms: A Sun 3 workstation version with a Horses[1] graphical user interface, and VAX/VMS version with a textual user interface. The use of the Horses version is described in [4]. Any differences in the use of the two versions will be highlighted in the following sections (where possible); the Horses instructions will be in **bold**.

The software will usually be distributed on a tape (type of which is dependent on the target machine). The details of the contents of the tape can be found in Appendix A.

Some of application examples assume that the previous one has been run. Where possible, instructions will be included for starting an application without this pre-requisite.

NB, the program uses a lot of virtual memory. If the machine, on which the program is being executed, runs out, it may manifest itself in some strange ways (eg, *Constraint Error* appearing when not expected). There is no alternative but to exit and start again (from where you left off).

2 Product Data Model

During the demonstration, much of this section was designed to display aspects of the Project Meta-Structure (see figure 1). This was done by "walking" around the Product Model and seeing the repeated patterns that make up the framework of Product, Assembly, Component and Feature. The Product Model used is based around a definition of a Structural Bearing, which is a product from Glacier, and is defined as an assembly of: *Base Plate, Piston* and *Top Plate.*

The demonstration was also used to show some of the features of the graphical user interface. Referring to [4], try changing the way in which the data is styled, changing the depth of displayed information, showing the node name and editing a node.

[1] Horses is a User Interface Management System from Pafec Ltd

3 Geometry in 2D and 3D

This is the first of the applications closely coupled to the Product Data Editor. It is a demonstration of Multi-Dimensional Geometry: 1D (curves), 2D (areas) and 3D (solids) all embedded in the same data structure (Geometry Graph) and each dimensional entity transformable into E3 space. The *Base Plate* component is defined as a rotational sweep of 2D areas and is displayed by converting to B-splines and faceting.

U	-- Start at the root of data structure.
'	-- Set the search string to...
base plate	-- ...the *base plate.*
n	-- Find the next occurence of that name and...
u	-- ...move up prior to...
'	-- ...setting the search string to...
E3 geometry	-- ...the geometry of that component and...
N	-- ...finding the next node of that type.
+=	-- Mark where we are in the structure for future reference.
+zz	-- Note that there is no data...
HHH	-- ...below the selection node at this point **(not necessary with the Horses version - the lack of broken lines under the node indicates this).**
D	-- Call up the applications menu...
B-spline evaluator	-- ...and select the required option. This will produce another menu.
Read GG file	-- Read data from a previously generated file. A definition will be loaded into the current Product Model at the node that we have just seen is empty.
demo2	-- Name of the file containing the data.
Create GG instance	-- Put it into the Product Model.
Enter GG sub-menu	-- Another menu!
convert to B-spline	-- Convert the data into a form that the system uses for displaying multi-dimensional geometry.
change display levels	-- Set up some of the display parameters for this object.
solid	-- This indicates to the display system...
2	-- ...the degree...
2	-- ...of facetting...
4	-- ...required.
operations on nodes	-- Yet another menu!
box node	-- Sets the graphical window to fit the object.
traverse node	-- Navigating...
traverse node	-- ...the...
draw node	-- ...internal...
finish with node	-- ...geometry...
draw node	-- ...graph...

finish with node	--	...and...
draw node	--	...drawing...
finish with node	--	...various...
draw node	--	...nodes...
finish with node	--	
finish with node	--	
finish with node	--	
quit	--	Exit from the...
Return	--	...submenus.
0	--	This gets us out of the menu system **(click on menu banner in Horses version).**

Kill applications windows using the <Esc> k <Esc> facility to hide the applications graphics and text windows - it makes the display tidier when you...

Reset display	--	**...re-display the Product Model.**
'	--	Earlier on, we saw that there was no data in the Product Model at this point, now we are going to look at some of the data that has been loaded by setting the search string to...
E3 solid	--	...a *solid* and...
N	--	...finding a node of that type...
'	--	...and then setting the search string for...
swept E2 area	--	...swept pieces of 2D geometry which has just been displayed and...
N	--	...find the next node of that type.
=	--	Now go back to where we were and...
s	--	...empty it! (we don't need it for the rest of the demonstration).

4 Constraint Definition System

This application demonstrates how the geometry of the Piston component can be created to satisfy its functional constraints. It uses an external software package called REDUCE[2] to solve the equations resulting from the constraint definitions. The output from the REDUCE system is then read into the Product Model and displayed using a 3D Wireframe Evaluator.

U	--	Start at the root again.
'	--	Look for the part called...
piston	--	...*piston.*
n	--	
u	--	Then move up to allow us to search for...
'	--	

[2]REDUCE is a product from the Rand Corp, Santa Monica

E3 geometry -- ...the geometric definition of that part.

N --

Walk down to E3 geometry definition node.

s -- Currently the node is empty. Once again, we are going to read some data in that was prepared elsewhere. We need to create the correct node type, so select...

E3 curves -- *...E3 curves.*

Walk down to E3 curves node.

+= -- Remember where we are.

D -- Call up the applications selection menu and choose...

CDS interface -- ...this one!

Create E3 curves from file -- Read the data in from...

pist3d.dat -- ...the file.

C -- Redraw the display to see what's been put in (**use Reset display option in the Horses version).**

Walk down to Regularized Union node.

-- Here we can see the form of data that has been read in. **Quite pretty in the Horses version.**

= -- Back again to where we were.

D --

Wireframe options -- We are going to draw what we have using a...

Evaluate Wireframe -- ...wireframe evaluator.

We can even look at it from many different viewpoints by electing to spin the object with, say, 5 different spin views. Or view it as defined (showing tangency, parallelism and concentricity) by setting the view vector to 0 0 1. Or as 2D geometry embedded in 3D by setting the view vector to 1 0 0.

NB, reset the view vector back to 4 2 3 before leaving this application.

Return -- Exit from applications...

0 -- ...menus (**click on Menu banner).**

5 Designing with Features

Features have been used as a facility for integrating the design and manufacture of the *Top Plate* component. In this demonstration, we see how the part has been made up as a combination of features. This was done using a facility within the Product Data Editor whereby a Taxonomy for classification and selection of features can be modelled. Finally, the component is displayed using the SDSM (Spatially Divided Solid Modeller) geometric evaluator.

U -- Top again!

' -- This time, look for the...

E3 solid -- ...solid part of the component.

N --

+=	--	Remember where we are.

Walk down to *application* node to see how the part is made up of some *geometry* plus *applied geometry* (features).

+g	--	This will get us into a series of menus which will allow us to walk through a taxonomy of features.

Choose which type of feature you want to look for and go through the taxonomy until a specific feature is reached. NB, it is probably a good idea not to select an actual feature, when you reach one, but to defer a choice by selecting option 0 (**select menu banner in Horses version**). Otherwise the Product Data Editor will attempt to insert that feature into the structure.

=	--	Back to where we were.
D	--	Go into the applications menu...
SDSM evaluator	--	...and choose the subdivision option to draw the part containing the features seen earlier.
Clear screen	--	
Create CSG tree	--	The next few options are to set up the drawing evaluator...
Universe Cell	--	
-100	--	
-100	--	
-100	--	
100	--	
100	--	
100	--	
Creat SDSM	--	
5	--	
Draw SDSM	--	It should now appear as a lot of boxes that approximate to the *base plate* part of the Structural Bearing.
Clear screen	--	When you've seen all you want to see!
Main menu	--	Exit from applications...
0	--	...menus (**click on Menu banner**).

6 Multi-dimensional Geometry

As already mentioned, the product modelled here is an assembly of the *Base Plate, Piston* and *Top Plate*. It has been defined using both solid (3D) and wireframe (2D) dimensions. There a several geometry evaluators in the system, including B-spline, wireframe and SDSM. This demonstrates the fact that they can all be pictured as a single product on a single graphics display despite the mixed dimensionality definitions.

U	--	Go to root...
'	--	...and look for an...
assembly	--	...*assembly* node.
N	--	

D	--	
Multiple evaluators	--	This application is going to look at the components making up the assembly and draw them all using an appropriate evaluator.
walk assembly	--	Finds out what there is and...
D	--	
draw assembly	--	...draws them.
4	--	Put in the values for the SDSM to evaluate....
-100	--	
-100	--	
-100	--	
100	--	
100	--	
100	--	
D	--	Exit from...
Return	--	...applications...
0	--	...menus **(click on Menu banner).**

7 Dimensions and Tolerances

This shows that dimensions, dimensional tolerances, geometrical tolerances and surface texture can all be associated with the geometric definition of a product. The application generates an evaluated representation called a Relationship Graph, and stores it in the Product Model. This graph is used by applications such as Tolerance Analysis and Inspection Planning (section 9).

U	--	
,	--	
wireframe definition	--	The application works on this definition.
n	--	
u	--	Move off the name onto the required node.
D	--	
Dimensions & Tolerances	--	Select the application and...
Evaluate Relationship Graph	--	...create the associated relationship graph.
Annotate Drawing	--	Then draw a wireframe picture with dimensions and tolerances annotated automatically.
Edit nominal dimension	--	To show that the dimensions define the actual geometry, we shall change one of the dimensions by pointing at it in the picture and altering its value.

Use cursor to select the length dimension (ie, click on the value which is currently set at 150.0.)

25.0	--	Input the new value...
Evaluate relationship graph	--	...and...

Annotate Drawing	--	...redraw it (correctly).
Tolerance analysis	--	Now analyse the tolerance build-up between two faces. The two faces will be selected using the cursor.

Use cursor to select a point to right of right face dimension post. Then use cursor to select a point to right of right slot face dimension post. At this point, the analysis data is displayed.

no	--	No need to file the edit.
Return	--	Exit from application...
0	--	...menus **(click on Menu banner).**

8 Setup and Region Determination

The software implementation for the General Machining activity of the integrated demonstration identifies *regions* on the post-setup component and then builds a *region graph* which defines the relationships between neighbouring regions. The region graph is used to identify accessibility to the regions and also to determine which regions can contribute to a machining region. Using this it determines the material removal requirement for each region and identifies the tool constraints for roughing. Then, it finds possible tools that can can be used for machining the region and for each tool determines and displays the cutter path. Finally, it builds an operation graph of the machinable regions and updates the Product Model with the operation graph data.

The software requires a file containing cutting tool data. This is included on the distribution medium.

U	--	
'	--	Set a search string to look for...
setup data	--	...the *setup data* node.
N	--	Find the node (if the search depth was only set to 30 this command will have to be repeated - this could take a long time!). This finds the first setup data node for the solid definition of the top plate. We require the second setup data node hence...
uurddr	--	...move to it. **(You can use the mouse to navigate with the Horses version.)**
+zz	--	Zoom in to see the structure.
D	--	
Machine planning	--	Select the required application...
General approach	--	...and then the required version.
Analyse Setup	--	Here we do all the work that was described in the introductory paragraph. A graphical representation of the regions that have been identified on the component will be shown plus additional information, including the cutter paths generated for each selected tool. Tool centre path data files are also generated; the file names of which are stored in the Product Model.

average	--	This determines the resolution of the decomposition using the SDSM. Eventually the graphics will appear!
D	--	Leave...
Main Menu	--	...the...
Main menu	--	...applications...
0	--	...menus **(click on Menu banner).**

9 Inspection Planning

This application will generate, automatically, the Inspection Plans from the Product Model for the *Top Plate* component. It makes use of the Relationship Graph and the SDSM evaluator to establish whether the component can be inspected with a CMM (Coordinate Measuring Machine). From the plans, it can also produce part programs for an actual CMM (in this case, a Ferranti controlled one).

U	--	
'	--	
E3 solid	--	
N	--	Look for the *Top Plate* geometry definition.
D	--	
Inspection	--	Select the required application.
Initialize	--	
Get probe data	--	Read in the information about the probes that are available for the CMM.
Create CSG tree	--	The next few options create the SDSM evaluations of the component...
Get object bounds	--	
80	--	
40	--	
15	--	
-80	--	
-40	--	
-15	--	
Decompose object	--	
Walk Relationship Graph	--	The Relationship Graph is interrogated and the...
Plan Inspection	--	...inspection plan is produced.
z pos	--	At this point we choose inspection setups that allow all the features to be inspected...
x pos	--	...in this case, viewing from the positive z and positive x directions
Generate Part Program	--	Now generate the CMM part program.

View one of the generated part program files (either test_Xpos.prog or test_Zpos.prog) through the *Review Window* (see [4]).

Return to Main Menu	-- Leave the applications...
0	-- ...menus **(click on Menu banner).**

10 Manufacturing Data Analysis

The final application closes the loop from design, through manufacture and inspection, back to design amd manufacture. It uses the actual values supplied by the Inspection package, and the Decision Networks in the Product Model, to enable process faults to be identified, as well as likely causes.

U	--
'	--
component	-- If we go to this node...
N	-- ...it allows us to evaluate...
D	-- ...all the lambda nodes under this one. (ie, the function calls are expanded). This is necessary for the remaining pàrts of this application to function correctly.
Lambda evaluation	-- Do the evaluation.
+=	-- Remember where we are for later.
'	-- Look for the...
channel	-- ...channel feature.
n	--
u	--
'	-- Then the...
actuals	-- ...actual...
N	-- ...measurements...
ddrd	-- ...of the channel. **(Use the mouse, here, in the Horses version).**

Look at measurements. There are only two values put in for this demonstration. Ideally, they would have been put there by the Inspection application (see previous section). These values are sufficient to show the MDA application in action.

=	-- Move back up to *component* node (which is what this application works on).
D	-- Call up...
Manf'g data analysis	-- ...the application.
Get Component Data	-- Get the data relating to the component from the Product Model. This includes measurements and decision network information.
Put Component Data	-- We can see all this data (lots, isn't there?). **The Horses version allows the user to scroll back the window containing the data.**
Run analysis(NO History)	-- Now analyse the data and make some decisions about the measurements taken. The results of the analysis are displayed.

Return	-- Leave this application
0	-- menus (Menu Banner)

The above illustrates the Dimensional Analysis of the feedback system. The process analysis is illustrated below. In process analysis the fault is identified by using either the fault cluster or verification checks. This done by using a facility within the product data editor whereby a taxonomy for grouping and organising the data can be modelled.

U	-- Top again if not already at component level.
'	-- look for
component	-- component level
N	--
'	-- look for the abstraction node called
actuals	--
N	--
'	-- look for the historical analysis node of the actuals
historical analysis data	--
N	--
d	-- down one level to fault node
+=	-- remember where you are
g	-- This will get us into a series of menus which will allow us to walk through a taxonomy of fault clusters or verification checks
dr+zz	-- look at the slected fault type and its associated causes and actions
=	-- return to where you were and repeat the procedure

Other functions included in the data feedback system, see Figure 10.2, are:

Run W/P M'ment Analysis	-- does the same as Run Analysis (NO HISTORY) except the results are put back into the product model
Get Feature Data	-- get the data relating to the feature from the product model. This includes measurements and decision network information
Put Feature Data	-- all the data can be seen as in Put Component Data
Get Historical Data	-- get the analysed results of component
Put Historical Data	-- all the data can be seen as in Put Component Data
View Fault	-- operates at the fault node. A lambda evaluation has to be done before this is selected.
Manufacturing Process Analysis	-- instructions for running Process Analysis as described above

Redirect Output to File	-- this applicable for all the Put commands described above. All data are stored in files instead of appearing on the screen.
Return	-- return to main menu

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1. Alison McKay.
"The Structure Editor".
GMP User Manual, user-12, Leeds & Loughborough University, May 1987

2. Alison McKay.
"Update to the GMP Structure Editor User Manual (User 12)".
ISS User Documentation, iss-user-1, Leeds & Loughborough University, July 1989

3. Alison McKay.
"Techniques for using the Structure Editor".
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4. Pete Dawson
"The Horses User Interface to The Product Data Editor".
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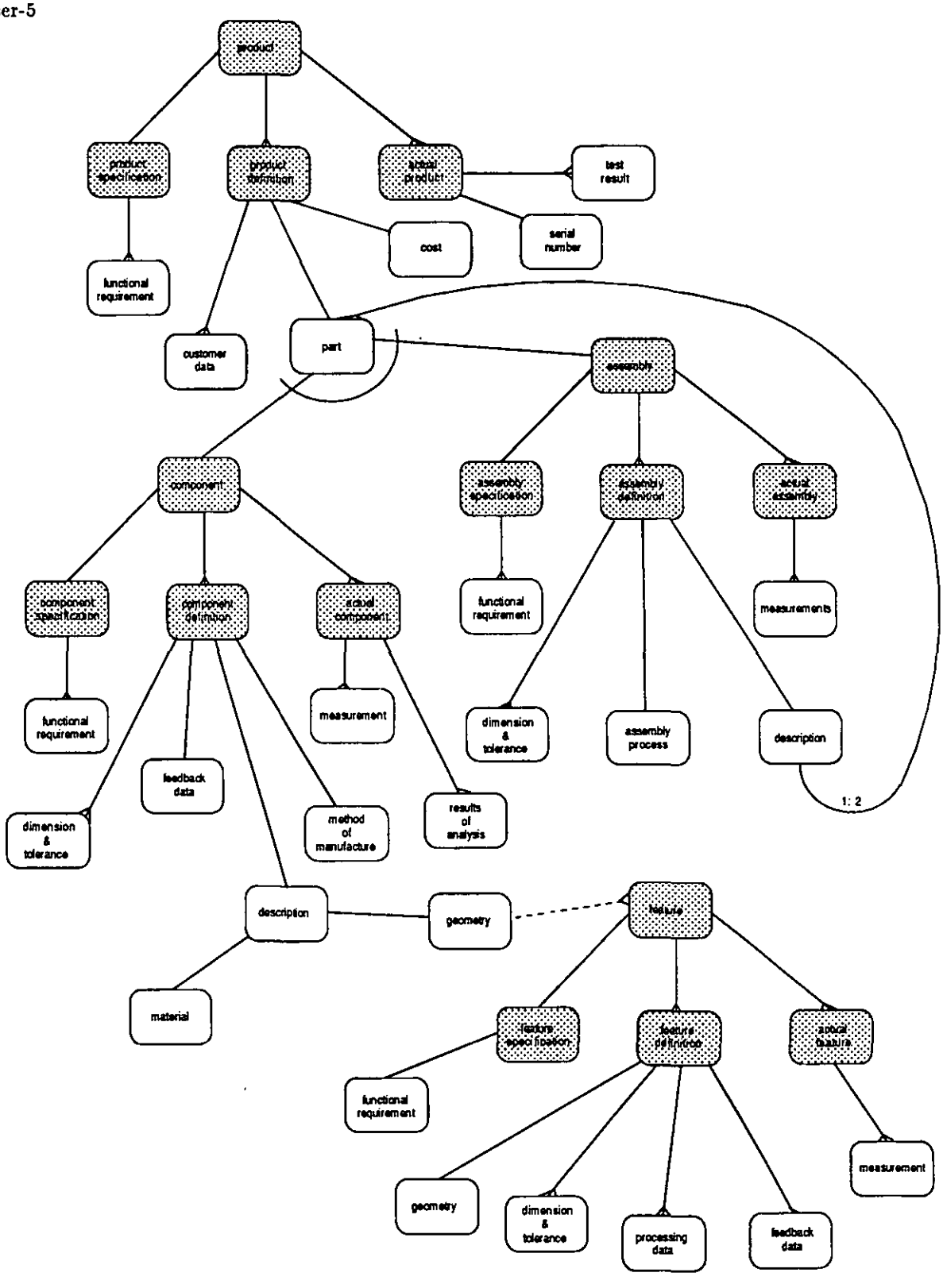


Figure 1: ISS Project Meta-Structure

APPENDIX 2C.

THE PRODUCT DATA EDITOR

1 Introduction

This document describes the user interface[1] written for the GMP3 Product Data Editor[2] using Horses[3]. It is assumed that the user is familiar with the Structure Editor, from which this software has been developed. If not, please refer to [3,4,5].

The user interface is based around the use of windows and menus with much of the user input obtained using a mouse.

NB, this software was developed on a Sun 3 workstation and may be run under SunOS versions 3.5 or 4.0. Remarks pertinent to this particular platform will be indicated by a right marginal line, as is shown here.

2 Getting Started

2.1 Required files

In order for the program to run properly, the following files need to be available in the directory from which the program is to be executed:

mane	-	A C-shell script to run the executable program.
horses_main	-	The executable program.
horses.net	-	The network description file.
graph_font	-	Character definition file for graphical text.
horicon.fnt	-	Icon definition file.
gse_main_help	-	Help file.

The following files need to be accessible, but not neccesarily in the current directory:

a Product Data Model	-	A meta-structure describing the data which models the product (eg **pms3_8.lam**).
a Product Model	-	An instance of the Product Data Model (eg **demo.pms3_8**).

2.2 Running the program

In order to run this version of the Product Data Editor, it is necessary to enter the Sunview© environment. This is done by typing **suntools** at the Unix prompt. Then, whilst in a suitable window, run the program by typing **mane**; eventually the screen will display two items of interest:

[1] The word *User* here describes the person who is sitting in front of the workstation, as opposed to some other software.

[2] The GMP Structure Editor when used with the GMP3 project meta-structure [1,2].

[3] Horses is a User Interface Management System from Pafec Ltd.

- A blue area in the bottom right corner. This is a window which contain all sorts of useful (and useless) information. It is essentially used for debugging purposes. This will be referred to as the *Throw-away Text Window* for obvious reasons.
- a menu on the left side as follows:

Input a character string	**Menu banner**
	.... Input Area

Menu 1

This is an example of an input menu, where the program requests information from the user.

The Input Area is where the cursor must be positioned before typing anything.

The *Throw-away Text Window* contains the words "...Please supply file name...". At this point, move the curser (by moving the mouse) into the Input Area (the cursor will change from a cross to a dinky little hand) and type in the name of the Product Data Model file (eg, **pms3_8.lam**).

After a while, another menu will appear as follows:

Make selection from:	..... **Menu banner**
load from file	..... Read existing Product Model
interactive mode	Create new Product Model completely
skeleton	... Create new skeletal Product Model
ditto nil lists	..... as above but with empty lists

Menu 2

load from file means that the user is going to edit an existing Product Model, and is the most likely to be used at this point.

The next three options are for creating a Product Model from scratch:

interactive mode would cause the editor to create a complete structure without allowing the user to quit prematurely. It 'walks' down the Product Data Model creating Product Model nodes until it reaches *atoms*, where it prompts the user for a value. It also prompts the user for a choice when it reaches a *selection*. **NB, it is inadvisable to use this option with pms3_8.lam as it is rather a large Product Data Model.**

skeleton means that the system creates a skeletal structure; again, it walks down the Product Data Model creating Product Model nodes, but when it reaches an *atom* or *selection*, it stops, leaving it undefined.

ditto nil lists is similar to skeleton, except that it stops infinitely deep cyclic structures from being generated (this is only a problem if a *list* element refers to itself) by leaving all lists empty, ie, it creates all lists with no elements.

If load from file is selected, then another menu identical to Menu 1 will request a file name. Again, move the cursor to the Input Area and type in the name of the Product Model file.

Eventually, the screen will contain the following:

- A header banner containing **Help** and **Exit** buttons.
- A footer banner containing a copyright message
- A large area containing a graphical view of the Product Model. This is the *Graphical Display Window*. It represents Product Model nodes as boxes and connects them with straight lines. The initial display draws different box styles for different node types (see Section 3).
- The *Throw-away Text Window*.
- A set of buttons just above the *Throw-away Text Window* which will be referred to as the *Review Menu*.

At this point, we are ready to use the Product Data Editor.

3 Display Mechanisms

Before going any further, an explanation of the philosophy behind the use of mouse buttons, key strokes and menu selection is given as well as a description of the *Graphical Display Window* that you can see.

3.1 Mouse buttons

The LEFT mouse button is intended as a *pointer*, ie, it does nothing unless the cursor is over one of the displayed node boxes in the *Graphical Display Window* (see Section 4), or over a selectable menu item, and then CLICKED (pushed down, then released).

The MIDDLE mouse button is intended as an *information supplier*. It will supply different information depending on whether it is over a node box or empty space in the *Graphical Display Window*. A more detailed description follows later in this section.

The RIGHT mouse button is intended as an *editor*. Again, it does nothing unless the cursor is over a node (see Section 5).

3.2 Keypad

Most of the character keys respond in the same way as when using the textual version of the Structure Editor (see [3,4,5]) unless in the *Alternate User Mode* (see Section 6). This is entered using the ESCAPE key which would need to be pressed again to get back to the *Normal User Mode*.

3.3 Menus

Most menus have a BANNER which is generally selectable using the cursor. If it is selected, then it means that none of the options is required (eg, ignore this menu or defer a choice until later).

Some menus contain a large number of selectable items. If there are more than 15 items to choose from, then the initial menu that pops up will look like:

Header	..... **Menu banner**
Option 1	.....
Option 2	.....
⋮	.....
Option 15	.....
More >	Select this for more options

Menu 3

and the next menu will look like either:

Header		..... **Menu banner**
Option 1		.....
Option 2		.....
⋮		.....
Option 15		.....
< Back	More >	Select either for previous or next options

Menu 4

or:

Header	..... **Menu banner**
Option 1	.....
Option 2	.....
⋮	.....
Option $\mathcal{X}$	where $\mathcal{X}$ is less than or equal to 15
< Back	.... Select this for previous options

Menu 5

3.4 Graphical display window

The amount of Product Data that can be digested by the user at one time in the *Graphical Display Window* is limited. The user decides on the quantity of displayed data by defining:

1. the node that is at the top of the display (display *root*)

2. the number of *levels* of data that are displayed below that *root*

These manipulations use Menus 6 and 7, which are described below.

When text is written in the node boxes, its size is proportional to the size of the surrounding box. If the box size gets too small, the text becomes unreadable, and is then represented as a bow-tie (⋈). Section 6 describes ways of making it legible.

The next part describes what can be done by clicking the MIDDLE mouse button.

If the cursor is over a node box, then a menu pops up:

Ignore	..... **Menu banner**
Show name	Node type and form is displayed at current cursor position
Make root	.... Node is displayed at top of *Graphical Display Window*

Menu 6

Show name causes the indicated node's type and form to be displayed, at the cursor, in large text. This is a useful facility, as will become obvious later.

Make root forces the indicated node to become the root, or top, of the current display in the *Graphical Display Window*. It doesn't affect the depth of the display (see next menu). This is equivalent to **+zz** when using the Structure Editor.

If the cursor is in the *Graphical Display Window* but NOT over a node box, a different menu pops up:

Ignore	..... **Menu banner**
Reset display	*Graphical Display Window* is redisplayed
Change style	..... Alter the style of the presentation
Increase depth	..... Increase level of displayed data
Decrease depth	..... Reduce level of displayed data

Menu 7

Reset display causes the *Graphical Display Window* to be redisplayed with all zoom and pan functions reset (see Section 6) and all names (as generated using Menu 6) removed.

Change style alters the way in which the nodes are represented in the *Graphical Display Window*. There are 4 styles catered for in the system. The first (and default) one uses *icons* to represent nodes as show in Figure 1.

The second style uses a simple box with the node type and form written inside it. The next style is for future use and, currently, is the same as the second, and the fourth style is somewhat terse: representing a node with a small circle. The two most useful styles are the first and second. Repeatedly selecting this menu option will cycle round the four styles.

Increase depth means that the next 'level' down into the Product Model will be added to the current display, thereby increasing the amount of information showing. This is equivalent to **H** when using the Structure Editor.

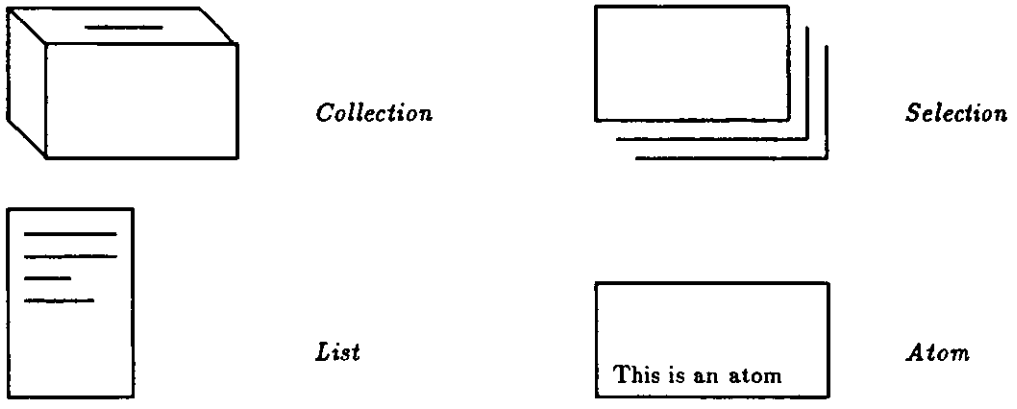


Figure 1: Icon representation of Product Data nodes

Decrease depth means that the bottom 'level' of the part of the Product Model that is currently displayed will be removed from the display UNLESS the current cursor (see Section 4) is at that level. This is equivalent to **h** when using the Structure Editor.

3.5 Other windows

At various times, more windows will appear and disappear. They include:

Edit Window	-	This is a graphics window that will appear in the top left corner of the *Graphical Display Window* during an editing session. It's use is explained in Section 5.
Applications Graphics Window	-	This is a graphics window that also appears in the top left corner of the *Graphical Display Window* when an application is run that produces graphical output. It currently has a pink background (yuk!) in order to distinguish it from other graphical windows.
Review Window	-	This is a textual window that appears in the top right corner of the *Graphical Display Window* when either the *Review Menu* is used (see Section 8) or an application is run. It has a white background.
Help Window	-	This is a textual window that pops up in the top left corner when the **Help** button is pushed. It will contain helpful information.

4 Moving About

The method used for moving about (navigating) the Product Model is to place the cursor over a node box and click the LEFT mouse button. This causes that node to become the *current cursor* (see [3]). This is indicated on the screen by making the data that is outside the scope of the *current cursor* a different colour from the rest; thereby allowing you still to see it.

When there is more data above or below that which is displayed in the *Graphical Display Window*, broken lines coming in at the top (into the display *root* node), or going out at the bottom (from a display *leaf* node) will indicate this. Under these circumstances, clicking on the node to which the broken line is connected, will cause the display to change as follows:

***root* node** - The new *root* node will be calculated by knowing the path taken to reach the current position and moving back up that path by an amount equal to the current depth value. This makes the previous *root* node a *leaf* node in the new display.

***leaf* node** - The selected *leaf* node becomes the new *root* node. The depth displayed remains unaltered.

5 Editing

In order to edit a node in the Product Model, the *current cursor* must be on that node. When the required node is visible in the *Graphical Display Window*, click on it with the RIGHT mouse button. A menu will pop up, the contents of which is dependent on the type of node:

- For any of a *collection*, *selection* or *atom* node that is an element of a *list*:

Ignore	..... **Menu banner**
Insert	Insert a new element in the *list* AFTER this node
Edit	..... Edit this node

Menu 8

- For any of a *collection*, *selection* or *atom* node that is NOT an element of a *list*:

Ignore	**Menu banner**
Edit	. Edit this node

Menu 9

- For a *list* node that is an element of another *list*:

Ignore	..... **Menu banner**
Add To List	..... Add a new element at the front of this *list*
Insert	Insert a new element in the other *list* AFTER this node
Edit	..... Edit this node

Menu 10

- For a *list* node that is NOT an element of another *list*:

Ignore	..... **Menu banner**
Add To List	Add a new element at the front of this *list*
Edit	..... Edit this node

Menu 11

Currently, nothing happens if either the Insert or Add To List options are chosen. In order to insert in a list, use the methods described in [3].

If the Edit option is chosen, then, again, the response is dependent on the node type:

- For an *atom*, the user will be prompted for a value using a menu similar to Menu 1, except that the banner will contain a message pertinent to the type of atom (*real, integer, name* or *string*). The *Graphical Display Window* will then be re-displayed with the new value.
- For a *selection*, a menu will pop up with all the selection values in it. The user will select one of them (or defer a choice by selecting the banner). Having done that, an *Edit Window* will appear in the with a skeleton of the chosen node in it.
- For either a *list* or *collection*, the *Edit Window* will appear with a skeleton of the node in it.

When in the *Edit Window*, the LEFT and RIGHT mouse button responses change. Nothing happens when clicking on the RIGHT button. The result of clicking the LEFT button on a node box will depend on the form of the node:

- For either a *list* or *collection*, no action will take place.
- For an *atom*, the user will be prompted for a value using a menu similar to Menu 1, except that the banner will contain a message pertinent to the type of atom.
- For a *selection*, a menu will pop up with all the selection values in it. The user will select one of them (or defer a choice by selecting the banner).

Clicking on the LEFT button when not on a node box results in the following menu:

Ignore	..... **Menu banner**
Merge	Merge the edit into the *Graphical Display Window*
QUIT	..... Quit out of edit

Menu 12

Merge will insert the contents of the *Edit Window* into the *Graphical Display Window* at the node originally selected with the RIGHT button. All previous data below that node will be lost.

QUIT will forget about the contents of the *Edit Window* and return back to the *Graphical Display Window*.

Key or Mouse Button	Result
w	Start to define an area in a graphics window which is to be zoomed. Press the key AFTER moving the cursor to one corner of the window. The defined area will be zoomed to fit the current physical size of the graphics window.
m	Start to move an object (window or menu). The object to move should be under the cursor when the key is pressed. **NB, it is not advisable to move the textual windows as information displayed in them will be lost. This is a feature of Horses.**
g	Start to resize a window. The window to resize should be under the cursor when the key is pressed.
e or **LEFT** button	Finishes off a **w**, **m** or **g** action.
p	Pop an object to the front. If an object has been covered by another one, pressing this key should make it completely visible.
k	Remove an object from the screen. This should only be used on windows that are recoverable (eg, the *Applications Graphics Window*) as it is NOT the inverse of **p**.
u	Pan upwards in the graphics window under the cursor.
d	Pan downwards in the graphics window under the cursor.
l	Pan left in the graphics window under the cursor.
r	Pan right in the graphics window under the cursor.
z	Zoom into the graphics window under the cursor, using the cursor as the focus.
Z	Zoom out of the graphics window under the cursor, using the cursor as the focus.

Table 1: *Alternate User Mode* key strokes

6 User Modes

There are 2 ways in which keys and mouse buttons can be used. They are the *Normal User Mode* (which has just been described) and the *Alternate User Mode* (which is just about to be).

Pressing the ESCAPE key will move the user from one mode to the other. In the *Alternate User Mode*, the graphics windows can be moved, enlarged, reduced, zoomed, panned, hidden or exposed, textual windows can be hidden or exposed and menus can be moved, hidden or exposed (generally). Table 1 shows the various options.

7 Finishing

When an editing session is completed, click on the **Exit** button in the top right of the screen. This will cause another menu to appear:

Make selection from:	..... Menu banner
save in new file	.... Save current Product Model in a file
updave old file	Save current Product Model in input file
discard edit	..... Forget everything and exit

Menu 13

save in new file will write the contents of the Product Model that has just been edited into a new file. This will cause the user to be prompted for a filename by a menu like Menu 1. Then the program will exit.

update old file will update the contents of the file that was read in at the beginning of the session. Then the program will exit. **(Important: please read Section 9).**

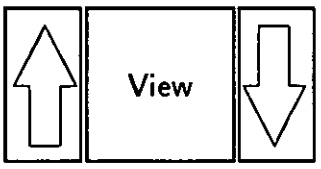
discard edit will forget everything that has happened during the session and then exit.

8 Sundries

8.1 Review Menu

The *Review Menu* can be used for 2 things:

1. To view an external file through *Review Window.* The menu as shown in Menu 14 is used by clicking on the View option. This will prompt the user for a filename as in Menu 1. Assuming the file exists and is printable, it will be scrolled into the *Review Window.* There are no facilities for temporarily halting the file during reading, however, when it has finished, clicking on the up- and down-arrow buttons will scroll the window back and forward (NB if the file is large, the beginning of the file may be lost).



Menu 14

2. To restore the *Applications Graphics Window* after a previous <Escape> k <Escape> sequence (see Table 1). In this case, click on Pop AGW in Menu 15.

Menu 15

9 Known Unexpected Features

- The code implementing the *Edit Window* is slightly fragile!! Sometimes, it doesn't always do what you expect (particularly when trying to edit a *list* node). However, if all else fails, it is possible to use the Structure Editor commands **s** and **e** (see [3]).
- The way in which nodes invoking *lambda* functions are displayed is wrong. If you set the *current cursor* to be such a node, the only way to get back to a 'correct' display is to type **U**, which will take you back to the root of the Product Model.
- Occasionally, the user is prompted for some numerical or textual input. In some versions of the software, the cursor is not automatically placed over the point at which input is required. If the user does not move the cursor to the correct point prior to typing in the response, some strange things might happen that could result in the need to re-load the data structures.
- Currently, there is no on-line help system. Hitting the **HELP** button produces a less-than-useful message!
- If you attempt to exit from a session using the option update old file in Menu 13, having entered the session using option interactive mode, skeleton or ditto nil lists in Menu 2, then the program will attempt to save the current Product Model in the file containing the Product Data Model. This also applies if you use the Structure Editor command **+W**. The safest thing to do is to create a skeleton, save it by exiting using the save in new file option, and then re-enter, using the load from file option on the saved file.
- If any 'pop-up' menus are visible (eg, most of the menus in this document), then 'fixed' menus (eg, the *Review Menu*) will not respond. The answer is either to defer a decision on the 'pop-up' menu, by clicking on the banner, or to finish off the 'pop-up' menu.
- The Structure Editor options **(+)P** will not work.
- Sometimes, the display algorithm gets its k??????s in a twist. The error manifests itself by showing the whole contents of the *Graphical Display Window* in a single colour (as if none of it was within the current cursor). The only known case to date (too complex to describe) was remedied by using the Structure Editor command **u**. If a similar situation arises, try that. If this fails, then **U** will ALWAYS (fingers crossed!) work.

References

[1] Alison McKay. *A Framework for the Project Meta-structure.* ISS Project PDS Working Party Report, **iss-pds-report-8**, Leeds University and Loughborough University of Technology, July 1989.

[2] Alison McKay, MS Bloor, and A de Pennington. *A Framework for a Product Data Model.* ISS Project Research Report, **iss-report-series-19**, Leeds University and Loughborough University of Technology, August 1989. (in preparation).

[3] Alison McKay. *The Structure Editor.* Geometric Modelling Project user manual **USER-12**, Leeds University and Loughborough University of Technology, May 1987.

[4] Alison McKay. *Update to the GMP2 Structure Editor User Manual (USER12).* ISS Project User Documentation, **iss-user-1**, Leeds University and Loughborough University of Technology, July 1989.

[5] Alison McKay. *Techniques for using the Structure Editor.* ISS Project User Documentation, **iss-user-2**, Leeds University and Loughborough University of Technology, February 1990.

APPENDIX 2D.

THE STRUCTURE EDITOR

Appendix 2D :
THE STRUCTURE EDITOR [1]

2D.1 What is a Structure Editor ?

A structure editor (SE) is a piece of software which can be used to define and edit structures. It has the power to guarantee that anything created conforms to the prescribed pattern. This prescription is essentially syntactic and does not include constraints. When in use the SE needs to know about two structures: one which describes the prescribed pattern and one which conforms to the pattern.

Obviously, the SE cannot be an all-knowing piece of software with the in-built ability to process structures relating to any type of problem. However, we can describe the type of structure that we wish to process by means of another structure, which we may think of as a "meta-structure". By constructing an appropriate meta-structure, we can persuade a SE to operate on our chosen type of structure.

2D.1.1 Meta-Structures

A "meta-structure" describes the style and content of instances of the structure itself. The previous sentence can, perhaps, be explained using the following analogy: a type declaration in Ada (the meta-structure) describes the form of an object of that type (the instance).

2D.1.2 The Meta-Meta-Structure

Whenever the SE is used it needs to know about two structures: the meta-structure (the controlling structure) and the instance of that meta-structure which is known as the "meta-meta-structure".

The meta-meta-structure is hardwired into the SE. It is itself definable as a meta-structure. This definition forms a seed for the system, and is used as the defining meta-structure for the editing of meta-structures.

2D.2 How Structures are Stored

The SE may store structures which are cyclic and contain sharing. The structure is a hierarchy of nodes. Each node is a pointer to a description. Nodes which are shared, point to the same thing. Each node also points to other things, such as the thing below it in the structure.

2D.3 Defining Meta-Structures

All meta-structures are instances of the meta-meta-structure. The meta-meta-structure allows the user to define structures in terms of eight types of entity. Each entity is a node.

---

1 adapted from : "The Structure Editor". McKay & Holdsworth, user-12.

- "Collections" contain a fixed number of elements, which can be of different types, but each one must occur in an instance of the meta-structure.

- "Selections" are choices. In an instance of the meta-structure the user must choose one of the elements of the selection.

- "Lists" can contain none or more elements but each element must be of the same type.

- "Atoms" are at the end of each branch of the structure. Each atom can be either a number, a name, a string, or null (nil atom).

  * "Number Atoms" are real or integer numbers.

  * "Name Atoms" are character strings of upto 16 characters. In an instance of a meta-structure it is possible to search for specific instances of the name atom.

  * "String Atoms" are character strings of any length. (Upto 2000 characters in this implementation). The difference between a name atom and a string atom is that a name atom is more like a label whereas a string atom is more like a comment. Facilities exist for searching for a name but not strings.

  * "Nil Atoms" are character strings which are defined in the meta-structure and which are displayed in an instance.

- A "Named Node" is a collection of a name and a node. It is used to ensure that the form name of a shared node can be defined by the user.

- "Displayed Selections" are not implemented yet.

- "Big Collections" are the same as ordinary collections except that the unparse string is a list of strings rather than a single one. This makes the editing of collection unparse strings less cumbersome.

- "Abstract Nodes" are used for modular code generation and, in the future, modular meta-structure design. They are a collection of a node and two strings. The first string is the function call which the code generator will generate and the second is a file name which at the moment is not used.

2D.4 Summary of Commands

Command	Description	Current Cursor Form
c	copy the current cursor.	any
+c	copy node and nodes between it and latch pointer.	any
C	clear and repaint the screen.	any

d	move down a node.	any
D	invoke external procedures.	application specific
+D	D but move cursor to result of menu option.	application specific
e	edit the current node.	any
f	function application - only those of correct type.	any
+f	function application - all types.	any
g	choose function from taxonomy - only those of correct type.	any
+g	choose function from taxonomy - all types.	any
+F	load from an external file to the latch pointer.	any
h	decrease holophraxis level.	any
H	increase holophraxis level.	any
i	insert a skeleton into a list.	list element
+i	insert a skeleton at the beginning of a list.	list element
I	insert and edit a new element in a list.	list element
+I	insert and edit a new element at the start of list.	list element
k	delete a list element.	list element
l	move one node to the left.	list element
+l	move to the left-most node.	list element
L	latch onto the current cursor.	any
n	find an instance of the search name.	any
+n	latch onto the parent of the current cursor.	any
N	find an instance of the form of the search name.	any
p	overwrite current cursor with latch pointer.	same as latch
+p	plug all shared nodes of current cursor.	same as latch
P	generate "output.lis".	any
+P	generate "output.lis" with sharing.	any
q	exit.	any
Q	on-line help for current meta-node.	any
r	move one node to the right.	list element
+r	move to the right-most node.	list element
+R	recover from previous e, s, g, or f.	same as last e, s, g, or f
s	overwrite the current node with a skeleton.	any
S	reset search depth.	any
u	move up a node.	any
U	return to root.	any

+W	update input file.	any
z	zoom into current cursor.	any
+z	zoom almost completely in.	any
Z	zoom out from current cursor.	any
+Z	zoom almost completely out.	any
-	flip display.	any
'	set the search name.	any
''	set the search name from a menu.	any
"	move up to the next list element.	any
=	flip to other cursor.	any
+=	copy current cursor.	any
+?	help for big mode commands.	any
?	help for standard commands.	any
!	invoke a new command shell.	any
+!	revise a meta-structure.	any

APPENDIX 2E.

THE ADA CODE

Appendix 2E :
The ADA Code

2E.1 DECISION NETWORK - ADA SPECIFICATION

```
package sei_mda_dec_net is

   subtype linear_dimension_typ is sei_pms_utils.sei_lin_dim.linear_dim_tp ;

   subtype fault_typ is sei_mda_fault.root_typ ;

   type state_knd is ( unknown , upper_fault , upper_warning , satisfactory ,
                lower_warning , lower_fault ) ;
   type state_typ is access state_knd ;

   type d_state_rec ;
   type d_state_typ is access d_state_rec ;

   type decision_node_knd is ( unknown , d_state , fault ) ;
   type decision_node_rec ( k : decision_node_knd ) is
    record
     case k is
      when d_state =>
        the_d_state : d_state_typ ;
      when fault =>
        the_fault : fault_typ ;
      when unknown => null ;
     end case ;
    end record ;
   type decision_node_typ is access decision_node_rec ;

   package decision_nodes_pack is new linked_list ( decision_node_typ ) ;
   subtype decision_nodes_typ is decision_nodes_pack.list ;

   type d_state_rec is
    record
     the_linear_dimension : linear_dimension_typ ;
     the_lin_dim_node : instance_definitions.node_inst ;
     the_state : state_typ ;
     the_decision_nodes : decision_nodes_typ ;
    end record ;

   package root_pack is new linked_list ( d_state_typ ) ;
   subtype root_typ is root_pack.list ;

end sei_mda_dec_net ;
```

2E.2 FAULT - ADA SPECIFICATION

```
package sei_mda_fault is

   subtype atomic_string_typ is  sundries.access_string ;

   package comment_pack is new linked_list ( atomic_string_typ ) ;
   subtype comment_typ is comment_pack.list ;

   type action_rec is
    record
      the_action_description : comment_typ ;
    end record ;
   type action_typ is access action_rec ;

   package actions_pack is new linked_list ( action_typ ) ;
   subtype actions_typ is actions_pack.list ;

   subtype ratio_typ is sei_pms_utils.sei_ratio.root_typ ;

   type cause_rec is
    record
      the_cause_description : comment_typ ;
      the_actions : actions_typ ;
      the_probability : ratio_typ ;
    end record ;
   type cause_typ is access cause_rec ;

   package causes_pack is new linked_list ( cause_typ ) ;
   subtype causes_typ is causes_pack.list ;

   type root_rec is
    record
      the_root_description : comment_typ ;
      the_causes : causes_typ ;
    end record ;
   type root_typ is access root_rec ;

end sei_mda_fault ;
```

2E.3 MEASUREMENT GRAPH - ADA SPECIFICATIONS

```
package sei_mda_measurements is

   type measurement_rec is
    record
      the-linear_dimension : sei_pms_utils.sei_lin_dim.linear_dim_tp ;
      the_lin_dim_node : instance_definitions.node_inst ;
      the_measured_dimension : sundries.number ;
      the_state : sei_mda_dec-net.state_typ ;
    end record ;

   type measurement_tp is access measurement_rec ;
```

```
   package root_pack is new linked_list (measurement_tp) ;
   package root_tp is root_pack.list ;

end sei_mda_measurements ;
```

2E.4 MEASUREMENT ANALYSIS - ADA CODE

```
 function make_measurement_tp( t1 : linear_dimension_tp ;
                    t2 : atomic_number_tp )
                    return measurement_tp is

   x : sei_pms_utils.sei_lin_dim.linear_dim_tp ;
   t3 : state ;
   nx : gmp.real ;

   tdim : toleranced_dimension_tp ;
   ud : gmp.real ;
   ld : gmp.real ;
   dd : gmp.real ;

   begin
    x := t1.the_linear_dim  ;
    nx := sei_pms_utils.sei_lin_dim.nominal ( x ) ;

    if x /= null then
     case x.k is
       when nominal_dimension =>
        put_line ("Nominal dimension not handled") ;

       when true_dimension =>
        put_line ("True dimension not handled") ;

       when toleranced_dimension =>
        tdim := x.the_toleranced_dimension ;
        case tdim.k is
         when plus_minus_tol =>
          ud :=     sei_distance.nominal (tdim.the_plus_minus_tol.the_nominal_dimension).the_value +
              sei_distance.nominal (tdim.the_plus_minus_tol.the_tolerance_value).the_value ;
          ld := sei_distance.nominal (tdim.the_plus_minus_tol.the_nominal_dimension).the_value -
              sei_distance.nominal (tdim.the_plus_minus_tol.the_tolerance_value).the_value ;

         when minus_plus_tol =>
          ud := sei_distance.nominal (tdim.the_minus_plus_tol.the_nominal_dimension).the_value +
              sei_distance.nominal (tdim.the_minus_plus_tol.the_tolerance_value).the_value ;
          ld := sei_distance.nominal (tdim.the_minus_plus_tol.the_nominal_dimension).the_value -
              sei_distance.nominal (tdim.the_minus_plus_tol.the_tolerance_value).the_value ;

         when max_min_tol =>
          ud := sei_distance.nominal (tdim.the_max_min_tol.the_nominal_dimension).the_value +
              sei_distance.nominal (tdim.the_max_min_tol.the_tolerance_value1).the_value ;
          ld := sei_distance.nominal (tdim.the_max_min_tol.the_nominal_dimension).the_value +
              sei_distance.nominal (tdim.the_max_min_tol.the_tolerance_value2).the_value ;
```

```
          when limit_dimensions =>
           ud := sei_distance.nominal (tdim.the_limit_dimensions.the_max_dimension).the_value ;
           ld := sei_distance.nominal (tdim.the_limit_dimensions.the_min_dimension).the_value ;

          when undefined =>
           put ( "Undefined toleranced dimension found" ) ;
         end case ;

         if ud < ld then
           dd := ld ;
           ld := ud ;
           ud := dd ;
         end if ;

         if t2 > ud then
           t3 := upper_fault_k ;
          elsif t2 < ld then
           t3 := lower_fault_k ;
          else
           t3 := satisfactory_k ;
          end if ;

        when iso_fit =>
           put_line ("ISO fit not handled") ;

        when undefined =>
           put_line ( "Undefined linear dimension found" ) ;

       end case ;

    else
     put_line ( "WARNING: Null dimension found" ) ;
     t3 := undefined ;
    end if ;

   return new measurement_rec ' ( t1 , t2 , t3 ) ;

 end make_measurement_tp ;
```

2E.5 DIMENSIONAL ANALYSIS ALGORITHM - ADA CODE

```
package body sei_mda_comp_analysis is

 procedure compare ( c : sei_mda_features_of_comp.utils.root_typ;
              add_hist : boolean ;
              actuals_list : node_inst ) is

    fault_list : sei_mda_comp_history_data.historical_analysis_data_typ
    := sei_mda_comp_history_data.historical_analysis_data_pack.null_list ;
    cd : sei_mda_features_of_comp.definitions_pack.list ;
    cda : sei_mda_comp_defn_atts.root_pack.list ;
    wl , ww : sei_mda_measurements.root_pack.list ;
    wd : sei_mda_dec_net.root_pack.list ;
    wn : sei_mda_dec_net.decision_nodes_pack.list ;
```

```
 wc : sei_mda_fault.causes_pack.list ;
 wa : sei_mda_fault.actions_pack.list ;
 fcc : sei_mda_fault.comment_pack.list ;

procedure put ( a : sei_mda_fault.comment_typ ) is

 begin
  fcc := a ;

  while fcc /= comment_pack.null_list loop
   put ( this (fcc).all ) ;
   new_line ;
   fcc := next (fcc) ;
  end loop ;
  new_line ;

 end ;


procedure put ( x : sei_mda_fault.action_typ ) is

 begin
  if x /= null then
   put ( " the action_description : " ) ;
   put ( x.the_action_description ) ;
  end if ;

end ;


procedure put ( a : sei_mda_fault.actions_typ ) is

 begin
  wa := a ;
  while wa /= actions_pack.null_list loop
   put ( this ( wa ) ) ;
   wa := next ( wa ) ;
  end loop ;

end ;


procedure put ( c : sei_mda_fault.cause_typ ) is

 begin
  if c /= null then
   put ( " the cause_description : " ) ;
   put ( c.the_cause_description ) ;
   new_line ;

   put ( "the actions : " ) ;
   put ( c.the_actions ) ;
   new_line ;
```

```
    put ( "probability: " ) ; sei_ratio.put ( c.the_probability ) ;
    new_line ;
   end if ;

  end ;


procedure put ( c : sei_mda_fault.causes_typ ) is

  begin
   wc := c ;
   while wc /= causes_pack.null_list loop
    put ( this ( wc ) ) ;
    wc := next ( wc ) ;
   end loop ;

end ;


procedure put ( f : sei_mda_dec_net.fault_typ ) is

  begin
   if f /= null then
    put_line ( "FAULT:" ) ;
    put ( f.the_root_description ) ;
    put ( "the causes : " ) ;
    put ( f.the_causes ) ;
   end if ;

end ;


procedure add_history ( fault_lists : sei_mda_comp_history_data.
                        historical_analysis_data_typ ) is

  ft_kd   : sei_mda_comp_history_data.root_typ ;
  history : sei_mda_comp_history.actual.root_typ ;

  begin

   ft_kd := new sei_mda_comp_history_data.root_rec ;
   ft_kd.the_historical_analysis_data := fault_lists  ;

   history :=  new sei_mda_comp_history.actual.root_rec'
         ( the_name => rep ( "Results of Analysis"),
           the_node => ft_kd ,
           the_comment => sei_mda_comp_history.actual.comment_pack.null_list ,
           the_se_node => null ) ;
           sei_mda_comp_history.append ( history, actuals_list ) ;

  end add_history ;


  procedure check_inst ( id: sei_mda_dec_net.d_state_typ ; im :
                 sei_mda_measurements.root_pack.list ) is

  d : sei_mda_dec_net.decision_node_typ ;
```

```
  begin
    wn := id.the_decision_nodes ;
    ww := wl ;

    if id.the_lin_dim_node =
     this(im).the_lin_dim_node
     and then
     id.the_state.all = this(im).the_state.all then
      while wn /= decision_nodes_pack.null_list loop

      d := this(wn) ;

      case d.k  is
        when d_state => check_inst ( d.the_d_state , next(im) );

        when fault =>
         fault_list := d.the_fault & fault_list ;

         put_line ( "Measurements  " )  ;
         while ww /= next(im) loop
          if ww /= next(im) then
           sei_pms_utils.sei_lin_dim.put
           (this(ww).the_linear_dimension ) ;
           put ( " ; Measured Dim : " ) ;
           put ( this(ww).the_measured_dimension ) ;
           new_line ;
          end if ;

          ww := next (ww) ;
         end loop ;

         put ( d. the_fault ) ;

         if next(wn) = decision_nodes_pack.null_list then
           exit ;
          end if ;

        when unknown => put ( "Workpiece is satisfactory! OR No error is detected" ) ;

      end case ;

      wn := next(wn) ;

    end loop ;

   end if ;

end check_inst ;


procedure begin_compare ( d : sei_mda_feat_defn_atts.root_typ ;
                  m : sei_mda_actual_feat_atts.root_typ ) is

 begin  ---- BEGIN WITH EACH DECISION NETWORK

 wl := m.the_measurements ;
 wd := d.the_decision_network ;
```

```
    while wd /= sei_mda_dec_net.root_pack.null_list loop
     check_inst ( this(wd) , wl ) ;

     wd := next(wd) ;
    end loop ;

   end begin_compare ;


   procedure check_feat ( d : sei_mda_comp_defn_atts.root_typ ) is
    begin  ---- AT FEATURE LEVEL
    cda := d ;

    while cda /= sei_mda_comp_defn_atts.root_pack.null_list loop

      put_line ( "Begin Analysing Feature " ) ;

      begin_compare ( this (cda).the_feature_defn_atts  ,
                 this (cda).the_actual_feature_atts ) ;
      put_line ( "Analysing Feature Complete " ) ;
      new_line ;
      cda := next (cda) ;
    end loop ;

   end check_feat ;



   begin  ---- AT COMPONENT LEVEL

    put_line ( "Run Analysis : " ) ;
    new_line ;
    cd := c.the_node.the_definitions ;
    while cd /= sei_mda_features_of_comp.definitions_pack.null_list loop

      check_feat ( this (cd). the_node ) ;  ---- TO FEATURE LEVEL

      cd := next (cd) ;  ---- NEXT FEATURE

    end loop ;

    if add_hist then
      add_history ( fault_list ) ;
    end if;

 end compare ;
 end sei_mda_comp_analysis ;
```

APPENDIX 2F.

DECISION NETWORK AND MEASUREMENT GRAPH

Appendix 2F :
Decision Networks and Measurement Graphs

2F.1 DECISION NETWORKS AND MEASUREMENT GRAPHS

The purpose of this appendix is to illustrate the implementation of the decision networks and the measurement graphs. This is based on the case study on Glacier top-plate, see Figure 2F.1. The top plate consists of a channel, which is made up of width and depth, and four holes which consider only the diameter.

2F.2 DECISION NETWORK FOR CHANNEL

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : satisfactory
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : satisfactory
decision nodes :
NO FAULT

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : satisfactory
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : lower fault
decision nodes :
tool wear/worn
tool length offset

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : upper fault
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : satisfactory
decision nodes :
tool diameter(greater)

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : upper fault
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : lower fault
decision nodes :
tool length offset
tool diameter(greater)

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : lower fault
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : satisfactory
decision nodes :
tool diameter(smaller)

D-STATE:
dimension reference : width plus/minus
process tolerance : (0.125 mm)
state : satisfactory
decision nodes :

D-STATE:
dimension reference : depth plus/minus
process tolerance : (0.25 mm)
state : upper fault
decision nodes :
insufficient speed/feed
stability of w/p and cutter
tool length offset

2F.3 MEASUREMEENT GRAPH FOR CHANNEL

linear dimension : width plus/minus
process tolerance : (0.125 mm)
measured dimension : measured width

linear dimension : depth plus/minus
process tolerance : (0.25 mm)
measured dimension : measured depth

2F.4 DECISION NETWORK FOR HOLE

D-STATE:
dimension reference : diameter plus/minus
process tolerance : (0.25 mm)
state : upper fault
decision nodes :
tool radius offset
tool diameter(greater)

D-STATE:
dimension reference : diameter plus/minus
process tolerance : (0.25 mm)
state : lower fault
decision nodes :
tool diameter(smaller)
tool radius offset

D-STATE:
dimension reference : diameter plus/minus
process tolerance : (0.25 mm)
state : satisfactory
decision nodes :
NO FAULT

2F.5 MEASUREMENT GRAPHS FOR HOLE

linear dimension : diameter plus/minus
process tolerance : (0.25 mm)
measured dimension : measured diameter

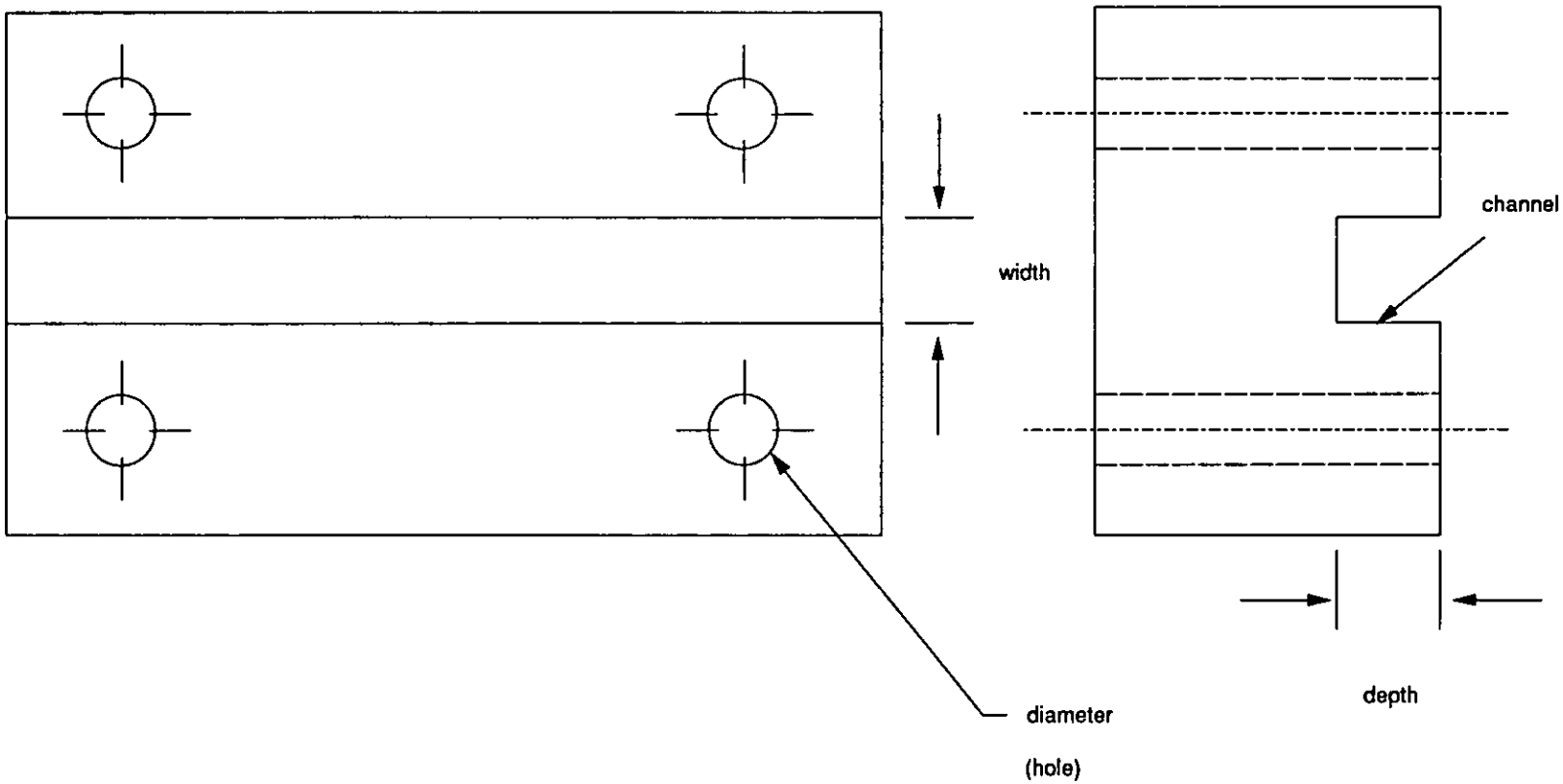


Figure 2F.1 THE GLACIER TOP PLATE

APPENDIX III.

THE RENISHAW METROLOGY CASE STUDY

Appendix III :
The Renishaw Metrology Case Study

This appendix provides the detailed input derived from Renishaw's prototyping environment. This environment was described in Chapter 12. The data feedback implementation is provided in descriptive format in Chapter 13.

Appendix 3A provides a typical Renishaw's process plan for a particular component.

Appendix 3B describes the procedure for advanced 'prove-out' used in the Renishaw environment.

Appendix 3C is the raw data collected in the form of flow-charts. The flow-charts describe two types of data, the fault-finding solution and the manufacturing method selection respectively.

Appendix 3D shows the data feedback implementation of the data given in Appendix 3C.

APPENDIX 3A.

THE PROCESS PLAN

RENISHAW PROCESS LAYOUT

SHEET 1 OF 1	PART NUMBER	ISSUE	DESCRIPTION	ORDER No.	PART NUMBER
	M-1023-2537-08	D E	PH9 TOP HOUSING		M-1023-2537-08

ORDER MULTIPLE	BATCH QUANTITY MIN / MAX	QUANTITY PER	METHOD	QTY
12	240			

MATERIAL SPEC	SIZE	UNIT LENGTH	DUE WEEK
R-2022-0208 AL ALLOY	3 1/4" DIAMETER BAR	24mm	

ISSUE	01	02	03	04	05	06	07		
DATE	271089	060290	200390	210590	070790	170890	16-10-90		
REF.	MH	JCSP	JC		MH	MH	11099		

OP NO	WORK CENTRE	OPERATION DESCRIPTION	TOOLING. TAPE NO.	INSPECT RECORD	QUANTITY REJECTED	SET TIME	RUN. TIME
010	AS01	ISSUE MATL 24mm +0.5/-0mm LG					
020	AM07/1	MULTI-FIXTURED MACHINING	T4425-01			0.50	0.13
		TOOL KITTING IS NOT REQUIRED	QS00041-01				
		OPERATOR CONTROLLED INSPECTION	C0015B				
030	DB01	MANUAL DEBURR					
040	IN04	INSPECTION					
		INSPECT DEBURRING ONLY					
050	PS02	ROUTE TO STORES					

RENISHAW	SETTING SHEET	Sheet 1 of 3	Tape Number T4425-01	Issue date ~~08/09/91~~ 16-10-90

Component Description.	Component Part No.	Drg. Iss.	Op. No.	Eng. MH
PH9 TOP HOUSING	M-1023-2537-08	~~B~~ E	020	First iss. 10/10/90

Workcentre code	Machine Description	Operation Description
AM07/1	MAZAK	MULTI-FIXTURED MACHINING

MACHINE SETTING :-

USE TOOL PACKAGE T4425.

TAPE NO. 4425 CONTAINS PROGRAMS 4425;4426;4427.
LOAD BILLETS TO FIXTURE WINGS AND TORQUE DOWN TO 7NM.
LOAD FIXTURE WINGS TO INDEXER AND TORQUE DOWN TO 70NM.
MACHINING CYCLE MUST COMMENCE WITH FIRST WING HORIZONTAL AND TOWARDS THE OPERATOR.
SET INDEXER CONTROLLER TO 30 DEGREE INCREMENTS.
SETTING VALUE OF 1.0 TO OFFSET 128 WILL MACHINE ONE COMPONENT ONLY.
SETTING VALUE OF 4.0 TO OFFSET 128 WILL MACHINE 12 COMPONENTS PER 3 WINGS.

TOOL SETTING :-

* in Q (Quantity) column = M/C based tool

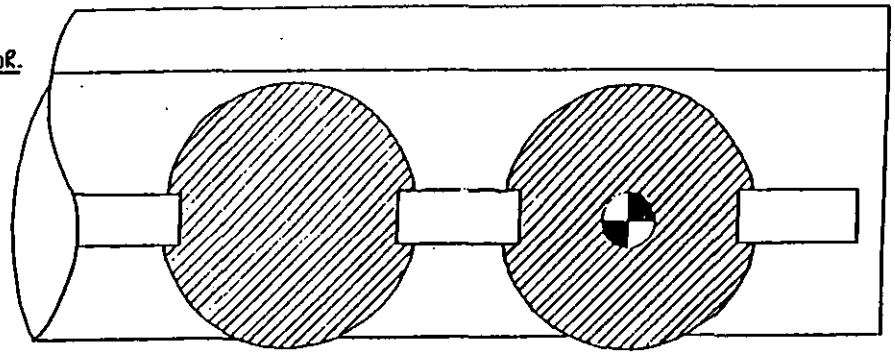
Tool Station	Tool No.	Q	Tool Description.	Tool Projection. X	Tool Projection. Z	Tool Projection. Rad.	Gauge Line Length.
	NCF1522	1	SET OF 3 FIXTURE WINGS				
1	D427	1	Ø12 BILZ DRILL		65		
		1	ZURN Ø12-11 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
2	A558	1	Ø3.2 Q/H DRILL		29		
		1	PCM Ø4-3 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		23		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
3	NCT1589	1	Ø12 SLOT DRILL		43	6.0	
D33	NCT1586	1	S/L HOLDER MODIFIED				
		1	PCM PS-MAZAK PULL STUD				
4	A175	1	Ø7 SLOT DRILL		26	3.5	
D34		1	DORNAG 150.440.08.00 S/L HOLDER				
		1	PCM PS-MAZAK PULL STUD				
5	D453	1	Ø2.527 MICRO DRILL		10		
		1	PCM Ø3-2 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		22		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
6	NCT1636	1	Ø8 SLOT DRILL		30		
D36		1	ZURN Ø8-7 ESX25 COLLET			4.0	
D37		1	ZURN 40.05.16.2 COLLET CHUCK			4.0	
		1	PCM PS-MAZAK PULL STUD				

SETTING SHEET - CONTINUATION

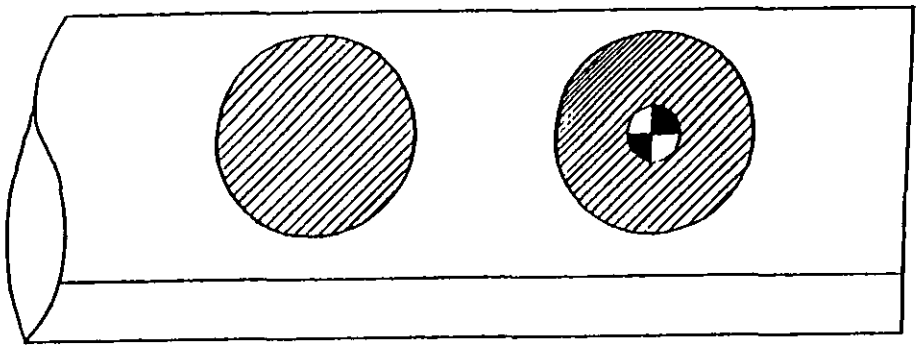
Sheet 2 of 3 | Tape Number T4425-01 | Issue date ~~08/09/90~~

Tool Station	Tool No.	Q	Tool Description.	Tool Projection. X	Tool Projection. Z	Tool Projection. Rad.	Gauge Line Length.
7	A174	1	Ø6 SLOT DRILL		24		
		1	PCM Ø6-5 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		30		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
8	C900	1	Ø6 SPOT DRILL		34	1.0	
D38		1	PCM Ø6-5 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		29		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
9	A372	1	Ø2.5 JOBBER DRILL		32		
		1	PCM Ø2.5-2 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		37		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
10	D354	1	M3 X 0.5 TAP		40		
		1	PCM Ø4-3 ESX 12 COLLET				
		1	PCM PPP.16.12-80 MINI-CHUCK		37		
		1	ZURN Ø16-15 ESX 25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				
11	C090	1	Ø5.5 SLOT DRILL		23		
		1	DORNAG 150.440.06.00 S/L HOLDER				
		1	PCM PS-MAZAK PULL STUD				
12	A169	1	Ø4.5 SLOT DRILL		20		
D42		1	DORNAG 150.440.06.00 S/L HOLDER			4.5	
		1	PCM PS-MAZAK PULL STUD				
13	A634	1	Ø14 STUB DRILL		50		
		1	ZURN Ø14-13 ESX25 COLLET				
		1	ZURN 40.05.16.2 COLLET CHUCK				
		1	PCM PS-MAZAK PULL STUD				

G54 WORK OFFSET.
HORIZONTAL WING TOWARDS OPERATOR.
XO YO IS CENTRE OF BILLET.
ZO IS 1MM BELOW SAWN FACE
OF BILLET.



G55 WORK OFFSET
HORIZONTAL WING AWAY FROM
OPERATOR.
XO YO IS CENTRE OF BILLET.
ZO IS APPROX 1MM BELOW
SAWN FACE.



N-1023-2537-08
SETTING INSTRUCTIONS.
T4425-01
OP 020
SHEET 3 OF 3

RENISHAW TOOL SEQUENCE SHEET	Sheet 1 of 1	Tape Number: T4425 Part No.: M-1023-2537-08	Issue date: [illegible] Issue level: ~~D~~ E

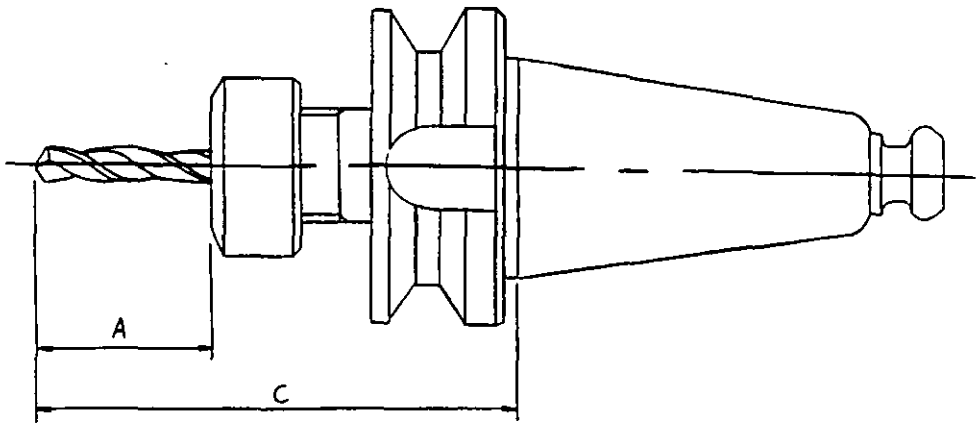
SEQ. NO.	TOOL NO.	LGTH OFF	RAD. OFF.	WORK OFF.	ROTARY AXIS POS	LINE NUMBERS	SUB-PROG.	OPERATIONS
COMMENCE MACHINING WITH FIRST WING HORIZONTAL TOWARDS FRONT OF MACHINE								
1	1	01	--	654	HORIZ	N10-N30	4426	ROUGH DRILL THREE HOLES.
2	3	03	33	654	HORIZ	N30-N80	4426	ROUGH INTERNAL FEATURES,FINISH JOINT FACE + 14 DIA
3	8	08	--	654	HORIZ	N80-N20	4426	SPOT DRILL 4 HOLES
4	2	02	--	654	HORIZ	N20-N40	4426	DRILL FOUR HOLES 3.2 DIA
5	4	04	34	654	HORIZ	N40-N130	4426	FINISH INTERNAL FEATURES
6	13	13	--	654	HORIZ	N130-N110	4426	PRODUCE 110/120 DEG CONE
7	11	11	--	654	HORIZ	N110-N80	4426	PRODUCE 5.5 DIA COUNTER BORE
8	8	08	38	654	HORIZ	N80-N50	4426	DEBURR ACCESSIBLE FEATURES
9	5	05	--	654	HORIZ	N50-M99	4426	DRILL THREE HOLES
10	7	07	--	655	A180	N70-N30	4427	PRODUCE FIVE REAR COUNTER BORES
11	3	03	33	655	A180	N30-N80	4427	FINISH 6.5 SPIGOT 41.525 C/BORE AND 13.25 CORNER
12	8	08	38	655	A180	N80-N90	4427	SPOT DRILL AND DEBURR
13	9	09	--	655	A180	N90-N100	4427	DRILL 4 TAPPING HOLES
14	10	10	--	655	A180	N100-M99	4427	TAP FOUR HOLES

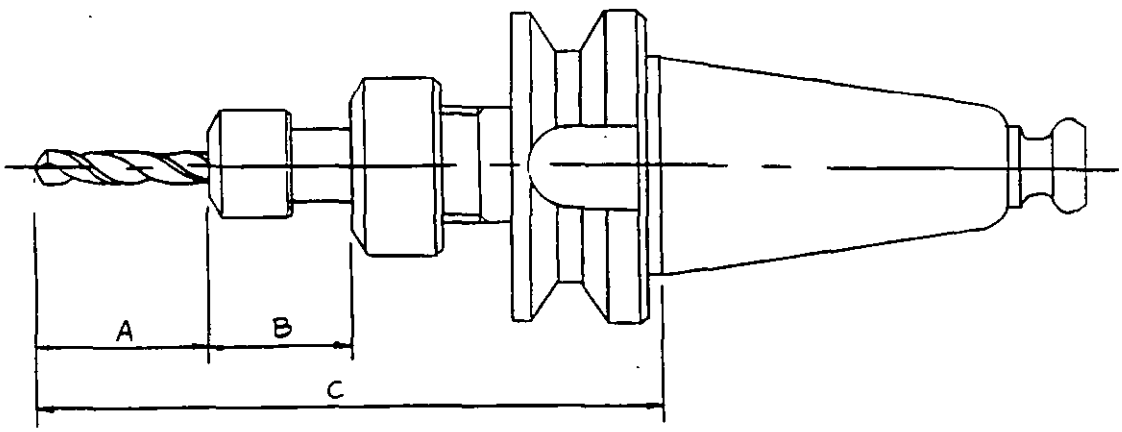
RENISHAW METROLOGY LIMITED REF: 909PE331

ENGINEERING MANUAL

TITLE: MULTI-FIXTURED MACHINING PROCEDURE

ISSUE: 1
DATE: 07.03.90





,where A = Tool projection from tool tip to collet uut
B = Tool projection from collet nut to collet nut
C = Gauge length

Tool dimensions along the Z-axis.

Tool Setting Guidelines.

RENISHAW

QUALITY SCHEDULE

Number:	Issue	Date	Originator	Part No:	Issue	Sheet
QS 00041	01	17-08-90	M HONEY	M-1023-2537-08	E	1 / 1

Desc./Process: MULTI-FIXTURED MACHINING

Item	Feature & Check Criteria	Method	Freq	WI Ref	REJECT NOTE	Chart	1 = Operator 2 = Setter 3 = Inspector	Batch No.	Op No. (If any) 020
1	FULL CHECK	BLADECHECKER	1ST OFF	C0015B					
2	FULL CHECK	BLADECHECKER	1:12	C0015B					
3	MANUAL CHECK FEATURES (SEE BLADECHECKER REPORT)	VARIOUS	1:12	C0015B					

Workcentre AM07/1		Date	
Sample Sizes (If relevant)		Time	
SIGN OR STAMP 1ST OFF		Corrective Action or Product Serial Number	SIGN OR STAMP
SIGN OR STAMP LAST OFF			

Doc #: 910PE401 Issue 3 10-06-90

01 Set

Time taken to obtain a first off including the following: breakdown of the previous job, inspection time (not waiting time).

02 Run

Time the machine ran producing components that have a process layout with a order number. Always check cycle times for accuracy. This must not include any time during which scrap work was produced or any time taken to re-work components.

03 Prove Out

This can only be booked if there is a prove out request on the operation being done. It equals the amount of time in excess of the standard set time given on the process layout. 01 set must be booked before any 03 prove out is booked. NB: Any specific problems such as tooling problem or waiting PED should be booked under the relevant code.

02 Tooling Problems

To be booked if tooling is out of stock, or if tooling breaks or fails causing downtime when changing this tool.

05 PED

This is the time the machine does not run, while waiting for PED or while PED are working on the job. If no PED cover, the time taken by Machine Shop personnel to do any problem solving/alteration. If a prove out request states "set days only", night shift will book the complete shift to PED.

06 Breakdown

This is the time from when maintenance are called (or time of machine stoppage on night shift) to the time the machine is fixed and handed back.

07 Planned Maintenance

This is the time when the machine is stopped until it is handed back.

08 Planned No Work

This will only be booked by Supervision and must not exceed the hours capacity shown on the Machine Shop loading report.

09 No Operator

This is the time when the machine is stopped due to a shortage in personnel ie. operator running more important machines, no setter available, etc. Supervision must be informed that a machine will not run or be set because of no operator (Supervision to initial all no operator bookings).

10 Waiting Inspection

This is time spent waiting to use inspection equipment that is being used by other people, ie. waiting to use a CMM. It is not the time taken on a set up to inspect the component.

98 Prototype

This can only be booked on "PA" or "MA" batches of work and includes all time taken to set and run the batch off.

99 Others

This can only be booked having first consulted Supervision. Reasons must be given (Supervision to initial all code 99 bookings). Rework time will be booked under this code, examples:-

4.0 - Rework M-1051-0117-01

APPENDIX 3B.

ADVANCED PROVE-OUT PROCEDURES

PROVE-OUT PROCEDURE

STEP 1

ESTABLISH REPEATABILITY OF MEASUREMENT

Purpose

- To establish the viability of the bladechecker programme. Does it give the correct results? Does it give acceptable repeatability?

- To establish the viability of the machining process to produce features able to be repeatably inspected. Roundness, surface, finish, taper etc.

Method

1. Use a "model" or modified component which reflects the state of the new component to prove-out the bladechecker programme.

   Establish that the programme inspects the part without collision.

   Establish that the results format is correct.

   Establish that the maths is not giving obviously erroneous results.

   Check that the graph generation of the programme is formatted correctly.

2. Use a Manual CMM to check the numerical value of the results obtained for the Bladechecker.

   Establish that the Bladechecker programme results are a true representation of the part.

3. With a component manufactured using the production process establish the repeatability of measurement for each feature.

   Establish that the Bladechecker programme inspects the part without collision.

   Establish that the repeatability of measurement is acceptable ie. spread of results less than 10% of tolerance band, by measuring the component ten times and generating graphs.

N.B It is important that, between measurements, the component is unclamped and reclamped in the fixture, and that the stylus is requalified, to simulate the operation which occurs in production. If the spread is unacceptable on any feature it must be established whether the cause is in the inspection programme or the component.

Programme modifications need to be done as required. A modification to the process may be necessary to achieve acceptable inspection in which case another component is made and this section is repeated

At this point there should be a set of graphs showing that ten runs on the same component give a measurement of 10% or less of the design tolerance.

If a measurement capability, of 10% cannot be achieved on any feature due to the tightness of the tolerance, the size and form of feature or the type of feature (eg. cone) a meeting needs to be convened to discuss, including the designer, P.E.D. supervision and the programmer.

Measurement "flyers" are unacceptable. If they occur, a cause needs to be established and eliminated.

PROVE-OUT PROCEDURE

STEP 2

DETERMINE REPEATABILITY OF MANUFACTURE

Purpose

- To establish that the production process gives an acceptable level of repeatability on each feature.

Method

1. Without modification to the programme or offsets between components make ten off.

2. Engrave serial number 1-10 on the components in the order of manufacture.

3. Inspect the components on the Bladechecker in the order of manufacture generates the graphs.

4. Analyse the graphs feature by feature to determine if acceptable repeatability has been achieved.

   A feature is said to be "capable" if ten consecutive components are manufactured with a spread of result less than 50% of the allowable tolerance.

   For the purposes of this analysis the repeatability of manufacture is defined as the repeatability found when ten components are measured once MINUS the repeatability found when one component is measured ten times.

   ie. A specific feature when measured ten times on the same component was shown to have a repeatability of measurement of 7%.

   When ten components were measured, the total repeatability was shown to be 54% The repeatability of Manufacture = 59% - 7% = 47%.

5. Separate all non acceptable processes for further analysis.

PROVE-OUT PROCEDURE

STEP 3

ESTABLISH ACCEPTABLE REPEATABILITY OF MANUFACTURE ON ALL FEATURES

Purpose

- To arrive at a situation in which all the features have a repeatability spread of 50% or less of the allowable tolerance.

Method

1. Using the graphs of all non-acceptable features, together with the Bladechecker printout and tool sheet fill out the process analysis sheet. (See appendix II).

2. Use the procedure in Appendix I to account for any flyers.

3. Does the analysis sheet show that a significant number of maximums or minimums are attributed to a particular component?

   If so re-inspect that component on the Bladechecker. Have the dimensions for the features in question changed significantly? If not accept results. If they have, then take the component and measure these features ten times on a Manual C.M.M. Is the spread of results less than 10% of measurable tolerance. If not, then check manufacturing process to find course of repeatability problem. If spread is o.k. calculate the average and substitute this figure into the relevant graph and re-calculate the spread of results. If this is now below 50% add this feature to the acceptable ones.

N.B. It is the responsibility of the prove-out programmer to organise these Manual C.M.M. checks.

4. All features type T need to be addressed individually. The problem is likely to be:-

   a. Chipped or damaged tool.

   b. Blunt tool.

   c. Run-out/damaged collet.

   d. Loose pull stud.

   e. Swarf on taper.

f. Speeds/feeds/canned cycle (peck, depth, etc).

g. Stiffness. Tool projection.

h. Interaction between two tools.

5. Features type P are often inter-related. Use the process analysis sheet to find common factors between features eg:-

   a. Same tool.

   b. Same offset.

   c. Same datum.

   Is there one feature which , if corrected, would correct many others?

6. Derive a logical series of corrective measures. Implement the changes and run another ten off.

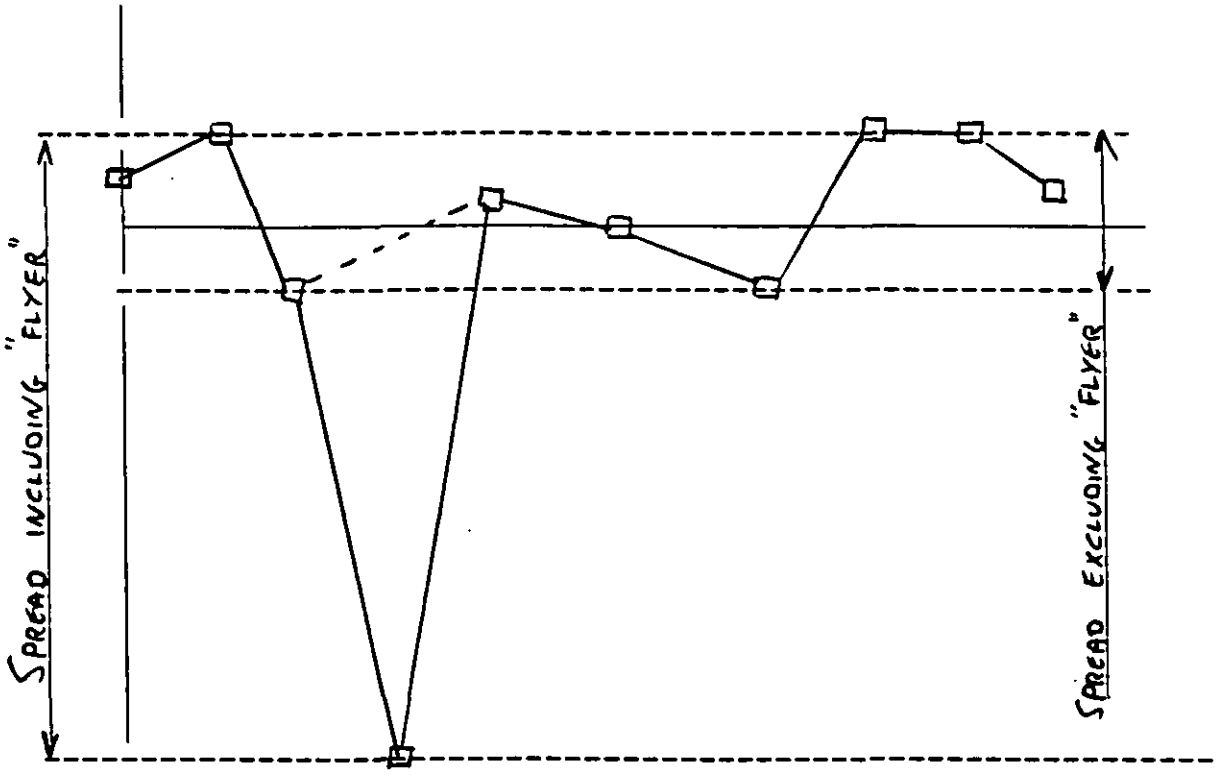
7. Repeat procedure from Step 2.

APPENDIX I

"FLYERS"

DEFINITION

A point can be described as a "flyer" if the percentage spread including the point is 2 times or more greater than the spread excluding the point.



How To Deal With "Flyers"

Step 1

Establish that the point is a "flyer".

Method

Calculate the spread of the results using the nine remaining points.

Is this spread less than 50% of the original spread? If so, then the point is a "flyer". If not accept result.

Step 2

Establish validity of measurement.

Method

Using a Manual C.M.M. inspect the feature in question on the component in question ten times.

Is the spread of the results obtained less than 10% of allowable tolerance? If it is, then calculate the mean of the results and substitute this result into the graph.

If not, then check manufacturing process to find cause of repeatability problem.

Step 3

Re calculate spread using new point.

Method

On relevant graph Mark on the position of the point calculated and join to previous and following points. Find maximum and minimum points on the distribution and calculate spread and %. Use this new % to determine capability.

APPENDIX II

PROCESS ANALYSIS SHEET

Purpose

- To document the non capable processes found during prove out.
- To highlight relationships between features to aid problem solving.

Method

Feature - enter the description from Bladechecker printout.

Type - for the purposes of this analysis features have beer split into two basic types:-

T- tooling controlled features. These features like size of drilled or bored holes which are controlled by the physical attributes of the tool.

P - Programme controlled features. These features like slot widths, positions etc controlled by offsets or programme parameters.

Control Datum - For type P features only. Which datum is the feature controlled from.

Max Comp No. - The number (1-10) on graph which corresponds to the maximum value.

Min Comp No. - The number (1-10) on graph which corresponds to the minimum value.

Flyer No - The number (1-10) on graph which corresponds to an obviously wayward result.

PROCESS ANALYSIS SHEET

COMPONENT	NO:- M/1023/2537/08/E	ITERATION
	DESCRIPTION:-	

FEATURE	TYPE	TOOL NO.	OFFSET NO.	CONTROL DATUM	%	MAX COMP NO.	MIN COMP NO.	FLYER NO.
A7 63.0 D.M	P	3	3	A	73	1	7	–
C8 2.55/2.53 D.M	T	7	–	A	57	3	2	–
C2 $\boxed{13.25}$	P	7	7	C	62	3	7	–
D4 $\boxed{\Phi 6.5}$	T	13	–	A	53	2	5	–

COMMENTS

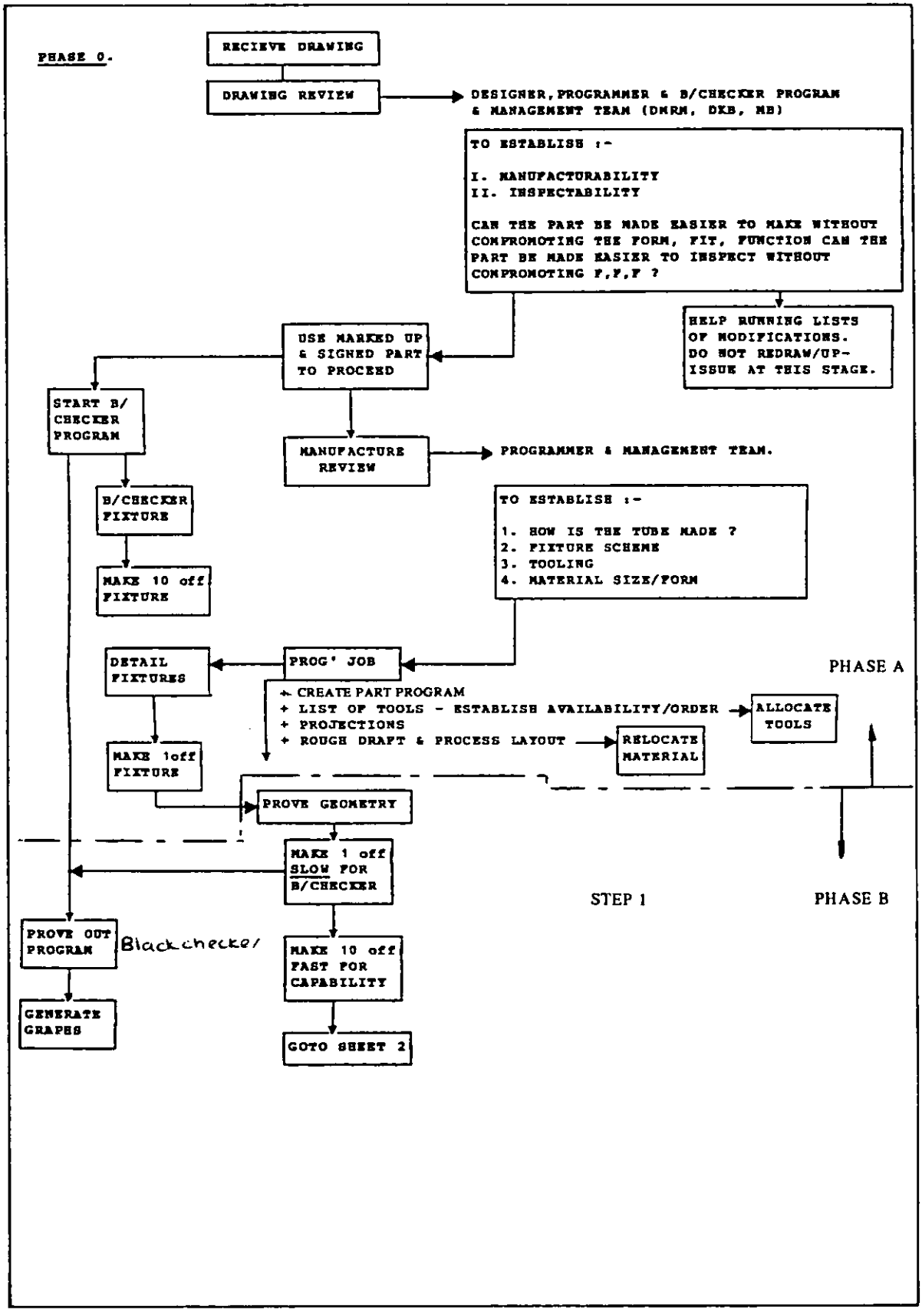
Generally Good

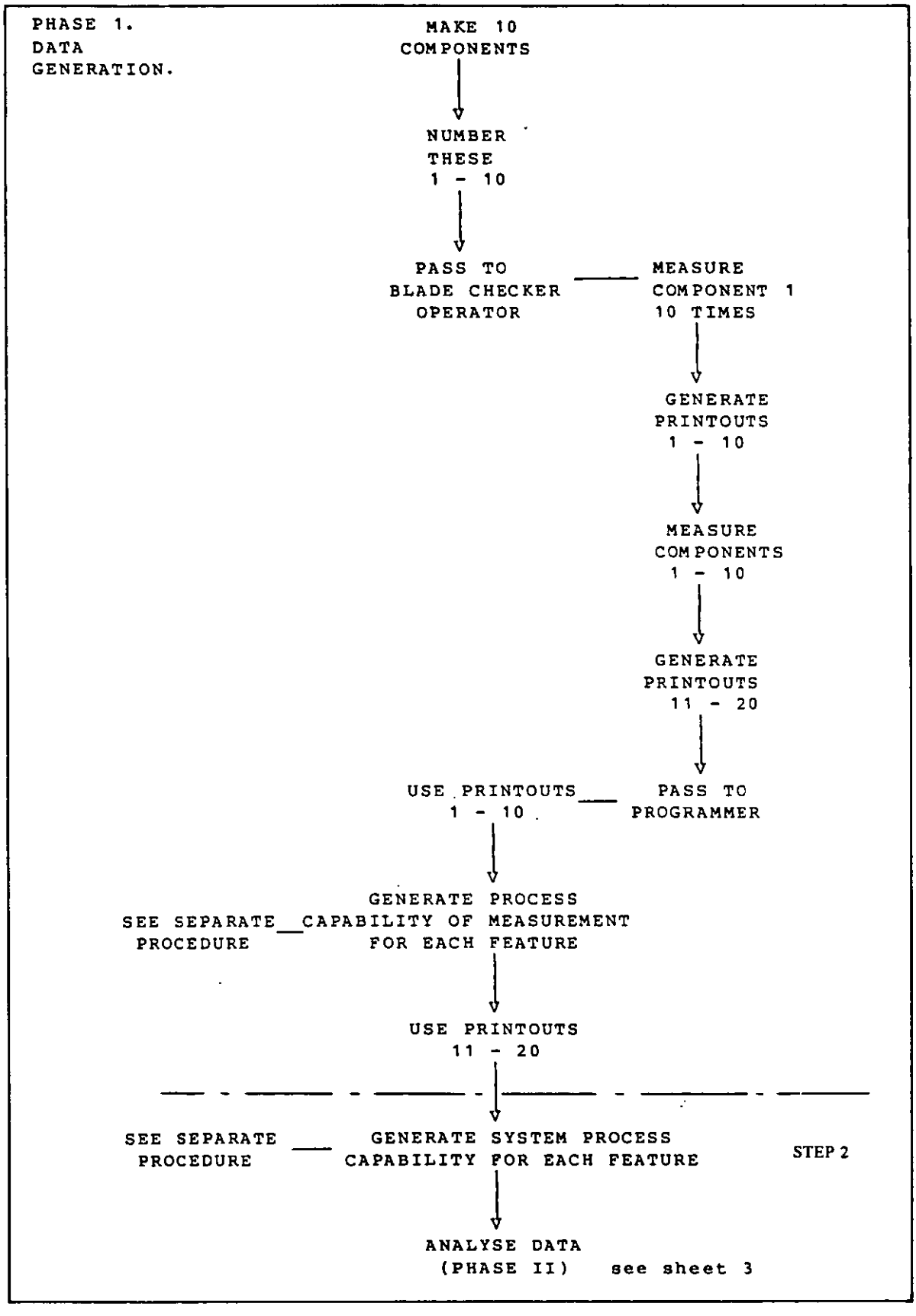
Check Torque on Bolts.

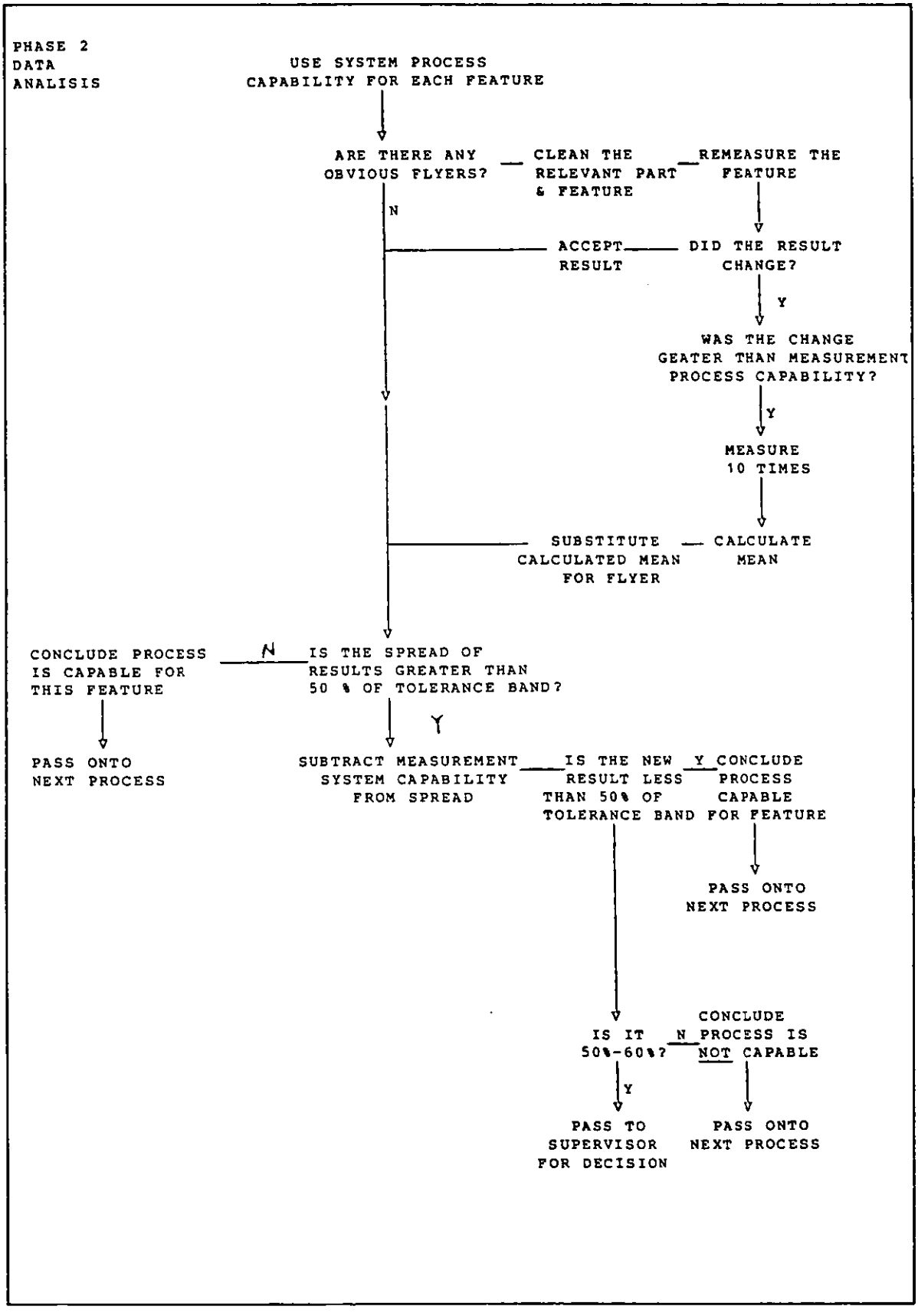
Possibly moving in future.

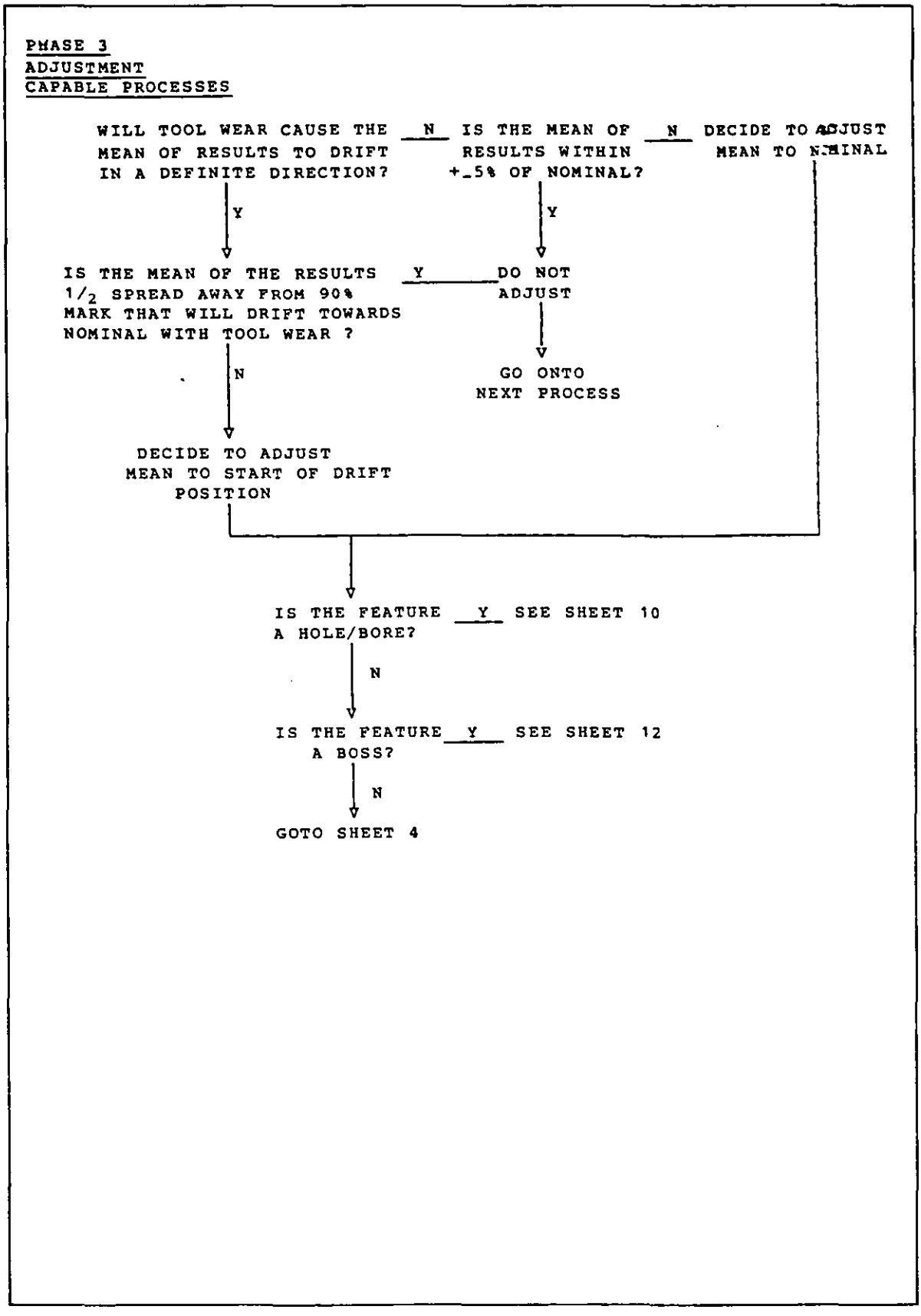
APPENDIX 3C.

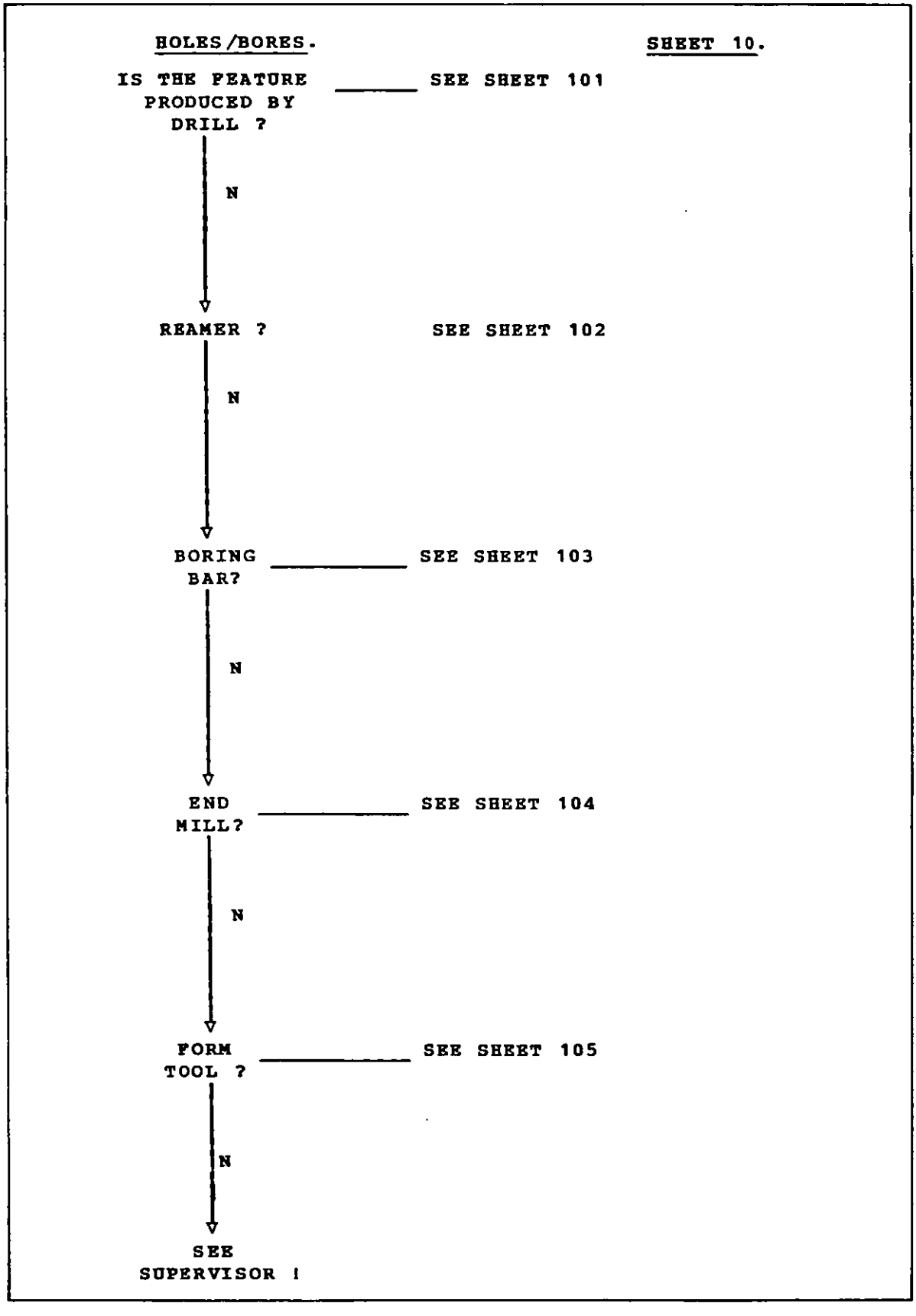
THE COLLECTED DATA

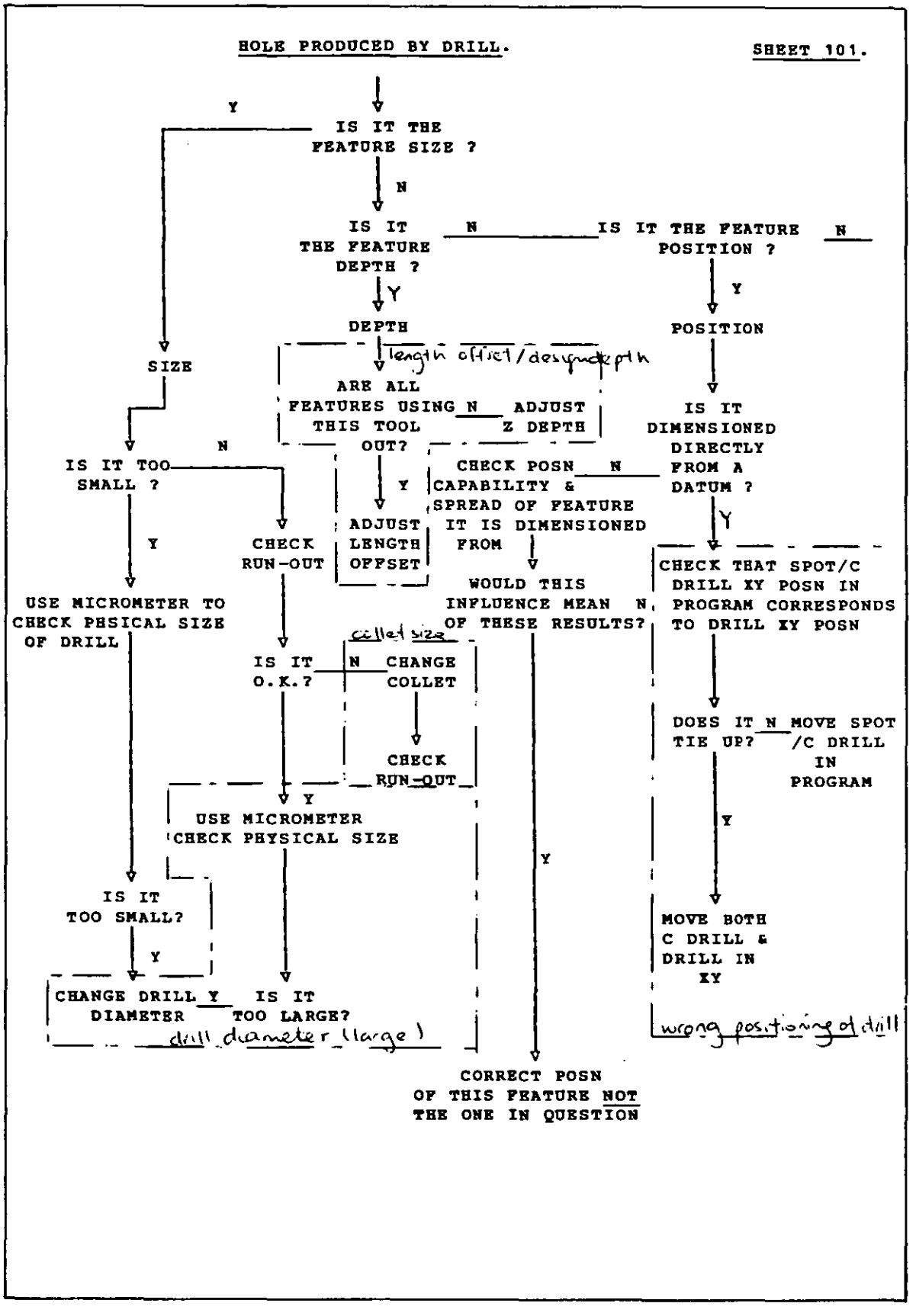

PHASE 0.
RECIEVE DRAWING
DRAWING REVIEW
DESIGNER, PROGRAMMER & B/CHECKER PROGRAM & MANAGEMENT TEAM (DMRM, DKB, MB)
TO ESTABLISH :-
I. MANUFACTURABILITY
II. INSPECTABILITY
CAN THE PART BE MADE EASIER TO MAKE WITHOUT COMPROMOTING THE FORM, FIT, FUNCTION CAN THE PART BE MADE EASIER TO INSPECT WITHOUT COMPROMOTING F,F,F ?
HELP RUNNING LISTS OF MODIFICATIONS. DO NOT REDRAW/UP-ISSUE AT THIS STAGE.
USE MARKED UP & SIGNED PART TO PROCEED
START B/ CHECKER PROGRAM
MANUFACTURE REVIEW
PROGRAMMER & MANAGEMENT TEAM.
B/CHECKER FIXTURE
TO ESTABLISH :-
1. HOW IS THE TUBE MADE ?
2. FIXTURE SCHEME
3. TOOLING
4. MATERIAL SIZE/FORM
MAKE 10 off FIXTURE
DETAIL FIXTURES
PROG' JOB
PHASE A
+ CREATE PART PROGRAM
+ LIST OF TOOLS - ESTABLISH AVAILABILITY/ORDER
ALLOCATE TOOLS
+ PROJECTIONS
+ ROUGH DRAFT & PROCESS LAYOUT
RELOCATE MATERIAL
MAKE 1off FIXTURE
PROVE GEOMETRY
MAKE 1 off SLOW FOR B/CHECKER
STEP 1
PHASE B
PROVE OUT PROGRAM
Blackchecker
MAKE 10 off FAST FOR CAPABILITY
GENERATE GRAPHS
GOTO SHEET 2

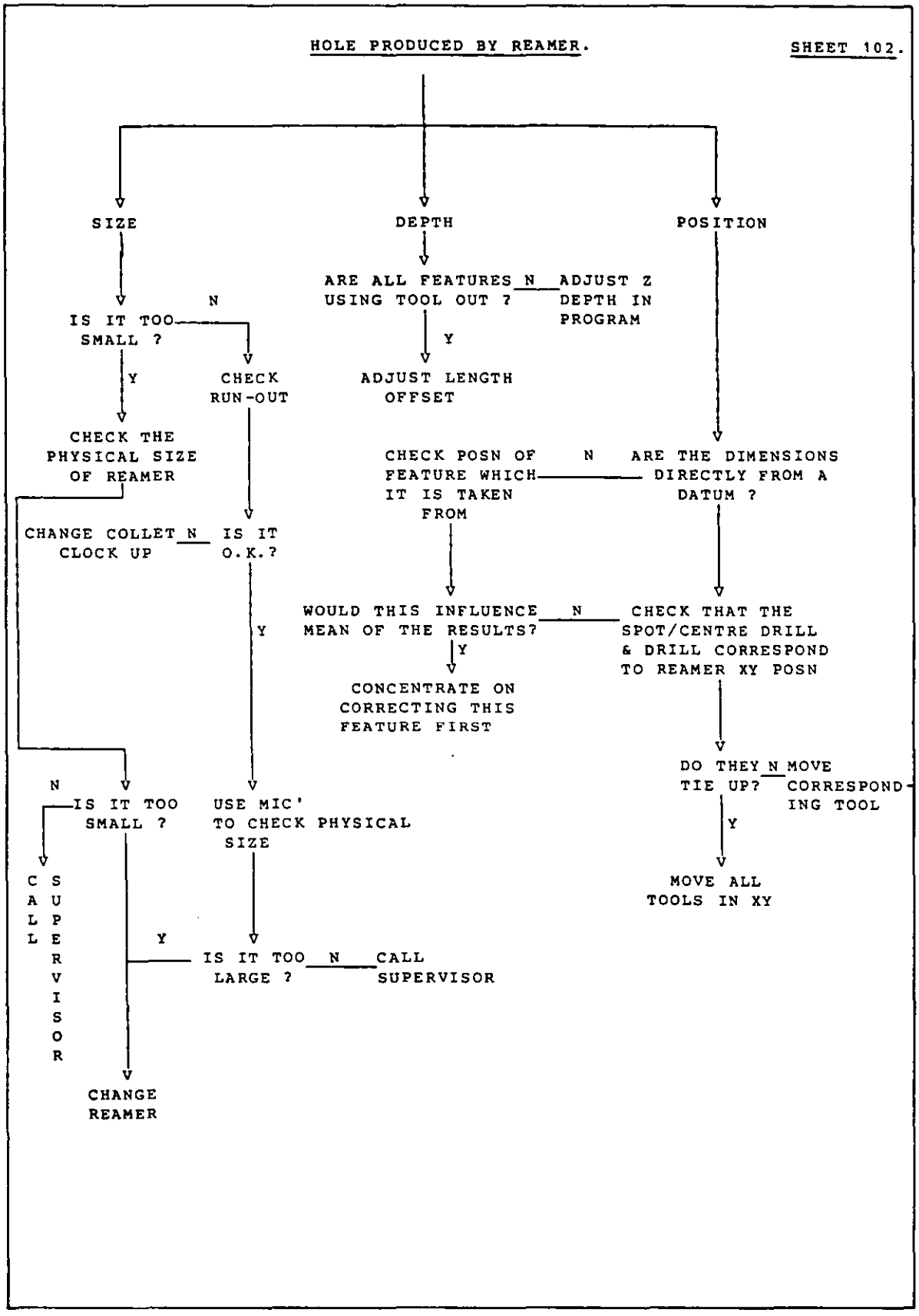

PHASE 1.
DATA
GENERATION.
MAKE 10
COMPONENTS
NUMBER
THESE
1 - 10
PASS TO
BLADE CHECKER
OPERATOR
MEASURE
COMPONENT 1
10 TIMES
GENERATE
PRINTOUTS
1 - 10
MEASURE
COMPONENTS
1 - 10
GENERATE
PRINTOUTS
11 - 20
PASS TO
PROGRAMMER
USE PRINTOUTS
1 - 10
GENERATE PROCESS
CAPABILITY OF MEASUREMENT
FOR EACH FEATURE
SEE SEPARATE
PROCEDURE
USE PRINTOUTS
11 - 20
SEE SEPARATE
PROCEDURE
GENERATE SYSTEM PROCESS
CAPABILITY FOR EACH FEATURE
STEP 2
ANALYSE DATA
(PHASE II)
see sheet 3

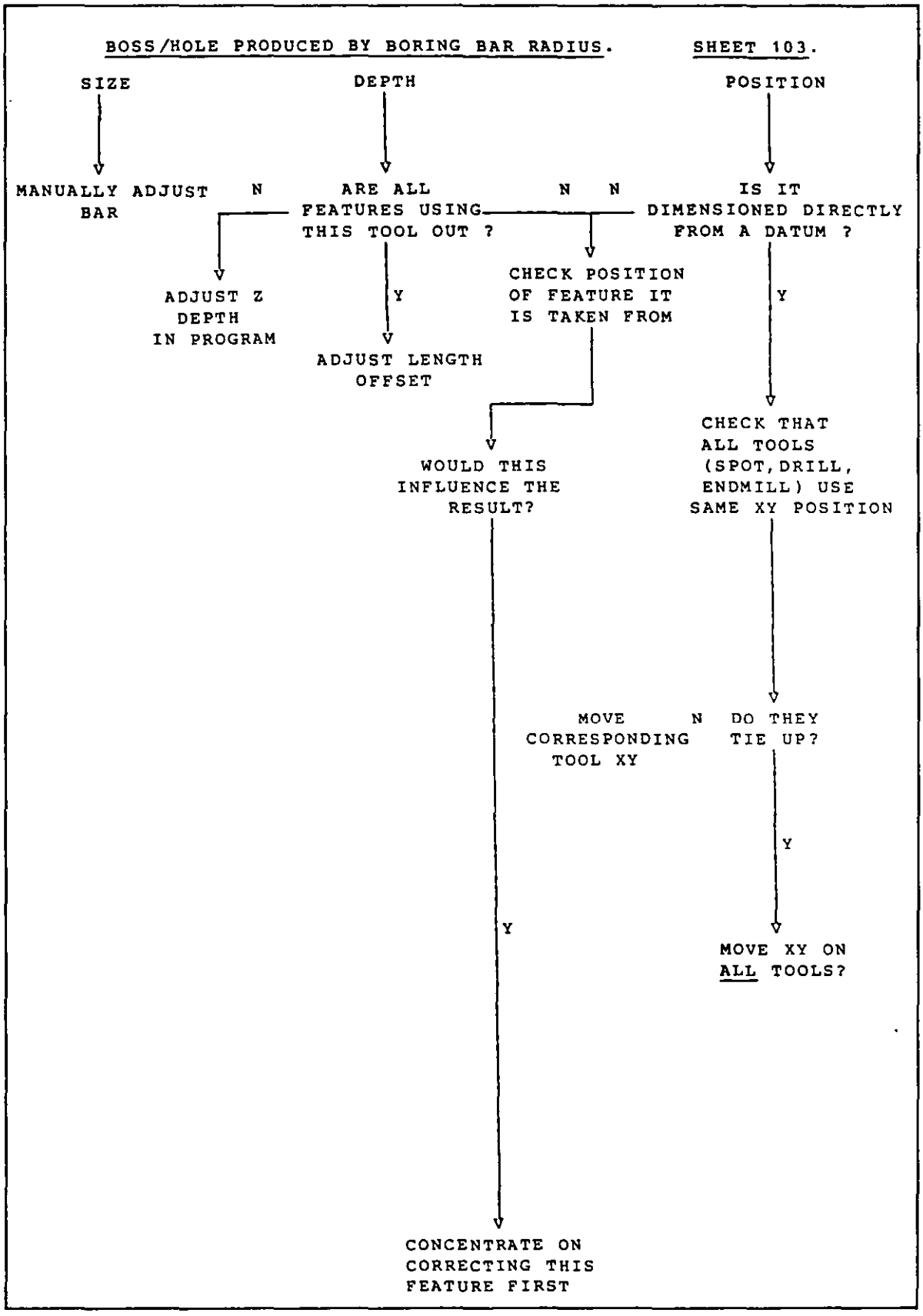

PHASE 2
DATA
ANALISIS
USE SYSTEM PROCESS
CAPABILITY FOR EACH FEATURE
ARE THERE ANY
OBVIOUS FLYERS?
CLEAN THE
RELEVANT PART
& FEATURE
REMEASURE THE
FEATURE
N
ACCEPT
RESULT
DID THE RESULT
CHANGE?
Y
WAS THE CHANGE
GEATER THAN MEASUREMENT
PROCESS CAPABILITY?
Y
MEASURE
10 TIMES
SUBSTITUTE
CALCULATED MEAN
FOR FLYER
CALCULATE
MEAN
CONCLUDE PROCESS
IS CAPABLE FOR
THIS FEATURE
N
IS THE SPREAD OF
RESULTS GREATER THAN
50 % OF TOLERANCE BAND?
Y
PASS ONTO
NEXT PROCESS
SUBTRACT MEASUREMENT
SYSTEM CAPABILITY
FROM SPREAD
IS THE NEW
RESULT LESS
THAN 50% OF
TOLERANCE BAND
Y
CONCLUDE
PROCESS
CAPABLE
FOR FEATURE
PASS ONTO
NEXT PROCESS
IS IT
50%-60%?
N
CONCLUDE
PROCESS IS
NOT CAPABLE
Y
PASS TO
SUPERVISOR
FOR DECISION
PASS ONTO
NEXT PROCESS

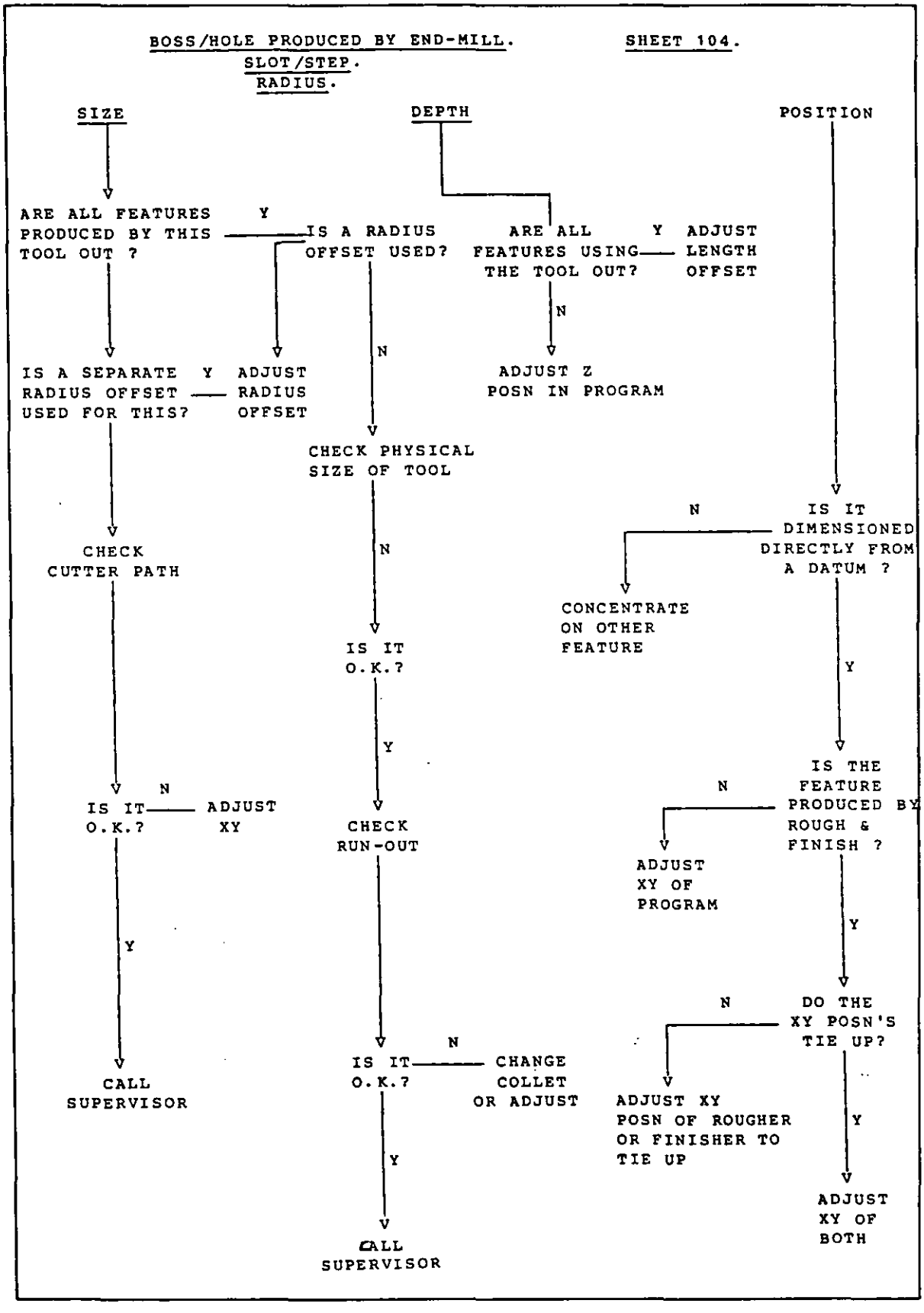

PHASE 3
ADJUSTMENT
CAPABLE PROCESSES
WILL TOOL WEAR CAUSE THE MEAN OF RESULTS TO DRIFT IN A DEFINITE DIRECTION?
N
IS THE MEAN OF RESULTS WITHIN +_5% OF NOMINAL?
N
DECIDE TO ADJUST MEAN TO NOMINAL
Y
Y
IS THE MEAN OF THE RESULTS 1/2 SPREAD AWAY FROM 90% MARK THAT WILL DRIFT TOWARDS NOMINAL WITH TOOL WEAR ?
Y
DO NOT ADJUST
GO ONTO NEXT PROCESS
N
DECIDE TO ADJUST MEAN TO START OF DRIFT POSITION
IS THE FEATURE A HOLE/BORE?
Y
SEE SHEET 10
N
IS THE FEATURE A BOSS?
Y
SEE SHEET 12
N
GOTO SHEET 4


HOLES/BORES.
SHEET 10.
IS THE FEATURE PRODUCED BY DRILL ?
SEE SHEET 101
N
REAMER ?
SEE SHEET 102
N
BORING BAR?
SEE SHEET 103
N
END MILL?
SEE SHEET 104
N
FORM TOOL ?
SEE SHEET 105
N
SEE SUPERVISOR !

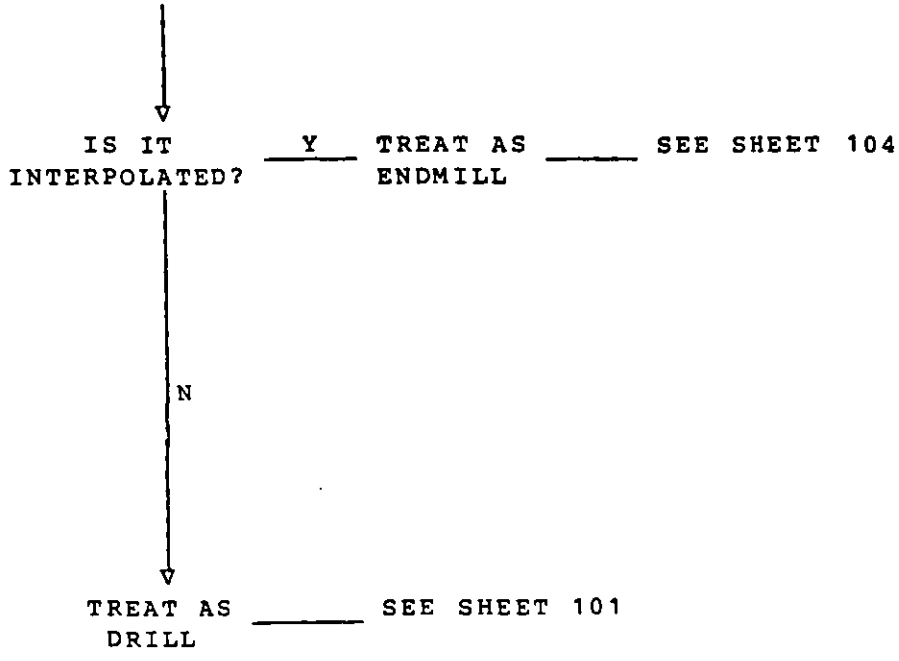

HOLE PRODUCED BY DRILL.
SHEET 101.
IS IT THE FEATURE SIZE ?
Y
N
IS IT THE FEATURE DEPTH ?
N
IS IT THE FEATURE POSITION ?
N
Y
DEPTH
POSITION
SIZE
length offset / designed depth
ARE ALL FEATURES USING THIS TOOL OUT?
N
ADJUST Z DEPTH
IS IT DIMENSIONED DIRECTLY FROM A DATUM ?
IS IT TOO SMALL ?
N
Y
CHECK POSN CAPABILITY & SPREAD OF FEATURE IT IS DIMENSIONED FROM
N
Y
ADJUST LENGTH OFFSET
CHECK RUN-OUT
Y
USE MICROMETER TO CHECK PHSICAL SIZE OF DRILL
WOULD THIS INFLUENCE MEAN OF THESE RESULTS?
N
CHECK THAT SPOT/C DRILL XY POSN IN PROGRAM CORRESPONDS TO DRILL XY POSN
collet size
IS IT O.K.?
N
CHANGE COLLET
CHECK RUN-OUT
DOES IT TIE UP?
N
MOVE SPOT /C DRILL IN PROGRAM
Y
USE MICROMETER CHECK PHYSICAL SIZE
Y
IS IT TOO SMALL?
Y
MOVE BOTH C DRILL & DRILL IN XY
CHANGE DRILL DIAMETER
Y
IS IT TOO LARGE?
drill diameter (large)
wrong positioning of drill
CORRECT POSN OF THIS FEATURE NOT THE ONE IN QUESTION


HOLE PRODUCED BY REAMER.
SHEET 102.
SIZE
DEPTH
POSITION
IS IT TOO SMALL ?
N
Y
CHECK RUN-OUT
CHECK THE PHYSICAL SIZE OF REAMER
CHANGE COLLET CLOCK UP
N
IS IT O.K.?
Y
ARE ALL FEATURES USING TOOL OUT ?
N
ADJUST Z DEPTH IN PROGRAM
Y
ADJUST LENGTH OFFSET
CHECK POSN OF FEATURE WHICH IT IS TAKEN FROM
N
ARE THE DIMENSIONS DIRECTLY FROM A DATUM ?
WOULD THIS INFLUENCE MEAN OF THE RESULTS?
N
Y
CONCENTRATE ON CORRECTING THIS FEATURE FIRST
CHECK THAT THE SPOT/CENTRE DRILL & DRILL CORRESPOND TO REAMER XY POSN
DO THEY TIE UP?
N
MOVE CORRESPONDING TOOL
Y
MOVE ALL TOOLS IN XY
N
IS IT TOO SMALL ?
CALL SUPERVISOR
USE MIC' TO CHECK PHYSICAL SIZE
Y
IS IT TOO LARGE ?
N
CALL SUPERVISOR
CHANGE REAMER


BOSS/HOLE PRODUCED BY BORING BAR RADIUS.
SHEET 103.
SIZE
DEPTH
POSITION
MANUALLY ADJUST BAR
N
ARE ALL FEATURES USING THIS TOOL OUT ?
N
N
IS IT DIMENSIONED DIRECTLY FROM A DATUM ?
ADJUST Z DEPTH IN PROGRAM
Y
CHECK POSITION OF FEATURE IT IS TAKEN FROM
Y
ADJUST LENGTH OFFSET
CHECK THAT ALL TOOLS (SPOT, DRILL, ENDMILL) USE SAME XY POSITION
WOULD THIS INFLUENCE THE RESULT?
MOVE CORRESPONDING TOOL XY
N
DO THEY TIE UP?
Y
Y
MOVE XY ON ALL TOOLS?
CONCENTRATE ON CORRECTING THIS FEATURE FIRST


BOSS/HOLE PRODUCED BY END-MILL.
SLOT/STEP.
RADIUS.
SHEET 104.
SIZE
DEPTH
POSITION
ARE ALL FEATURES PRODUCED BY THIS TOOL OUT ?
Y
IS A RADIUS OFFSET USED?
ARE ALL FEATURES USING THE TOOL OUT?
Y
ADJUST LENGTH OFFSET
N
IS A SEPARATE RADIUS OFFSET USED FOR THIS?
Y
ADJUST RADIUS OFFSET
N
ADJUST Z POSN IN PROGRAM
CHECK PHYSICAL SIZE OF TOOL
N
IS IT DIMENSIONED DIRECTLY FROM A DATUM ?
CHECK CUTTER PATH
N
CONCENTRATE ON OTHER FEATURE
IS IT O.K.?
Y
IS THE FEATURE PRODUCED BY ROUGH & FINISH ?
N
IS IT O.K.?
N
ADJUST XY
CHECK RUN-OUT
N
ADJUST XY OF PROGRAM
Y
Y
DO THE XY POSN'S TIE UP?
N
CALL SUPERVISOR
IS IT O.K.?
N
CHANGE COLLET OR ADJUST
ADJUST XY POSN OF ROUGHER OR FINISHER TO TIE UP
Y
Y
ADJUST XY OF BOTH
CALL SUPERVISOR

RADIUS/PROFILE /HOLE PRODUCED BY FORM TOOL. SHEET 105.



BOSS. SHEET 12.

IS THE FEATURE PRODUCED BY A BORING BAR ? —— Y —— SEE SHEET 103

N

IS THE FEATURE PRODUCED BY AN END MILL ? —— Y —— SEE SHEET 104

N

SEE SUPERVISOR

SLOT/STEP. SHEET 14.

IS THE FEATURE PRODUCED BY AN END MILL ? — Y → SEE SHEET 104

N ↓

FACE MILL ? — Y → SEE SHEET 104

N ↓

BORING BAR ? — Y → SEE SHEET 141

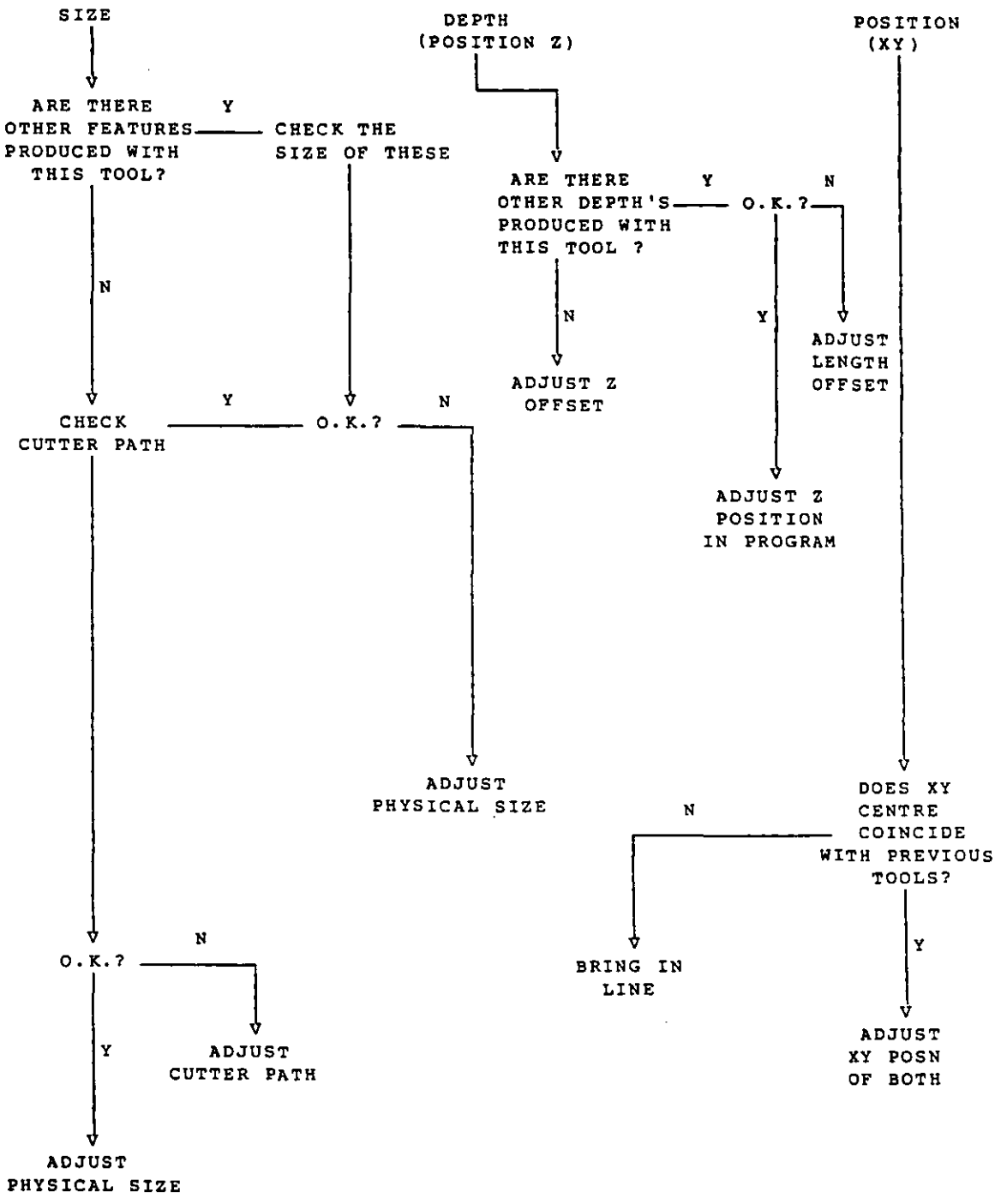
N ↓

SLITTING SAW — Y → SEE SHEET 141

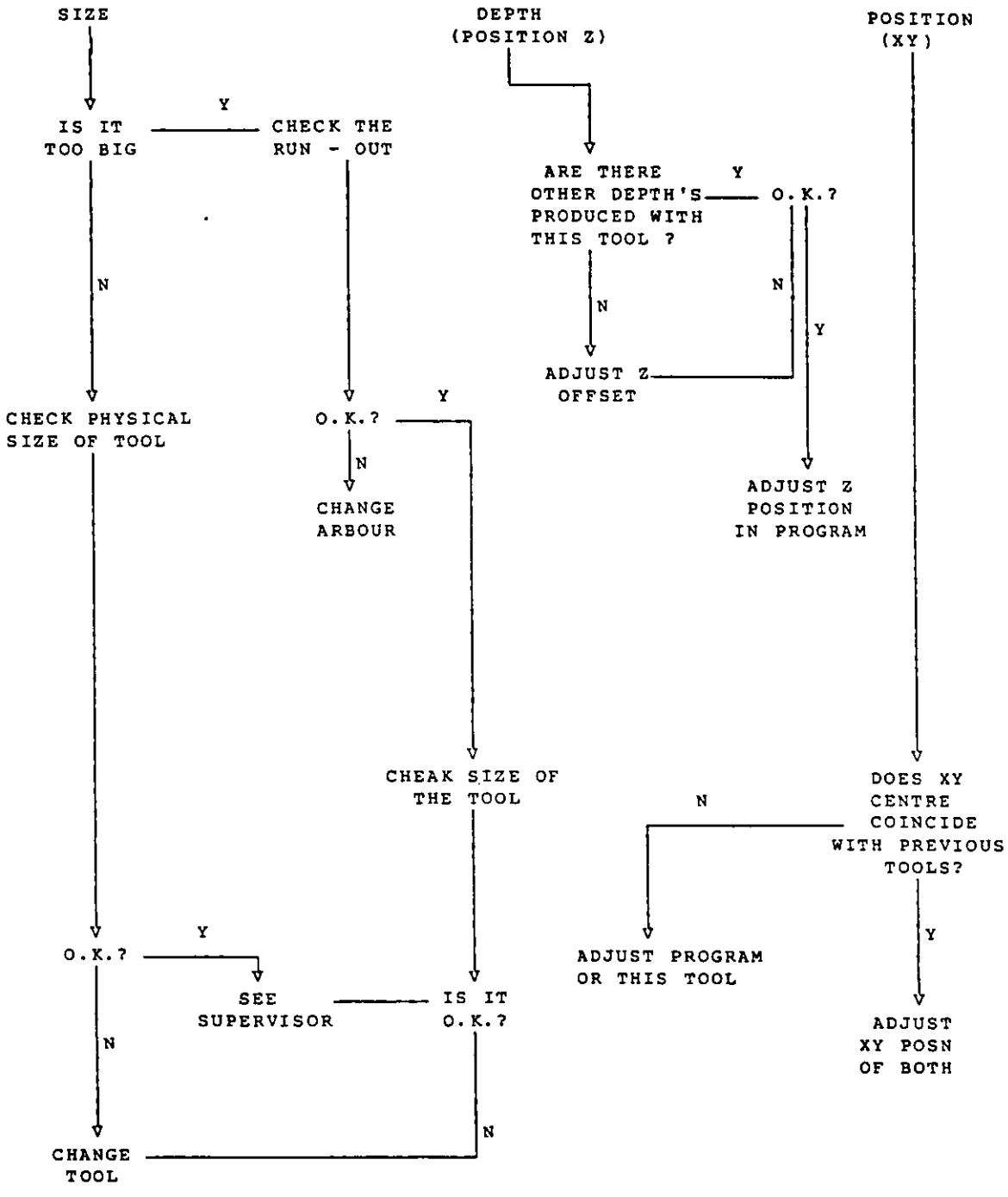
N ↓

SEE SUPERVISOR

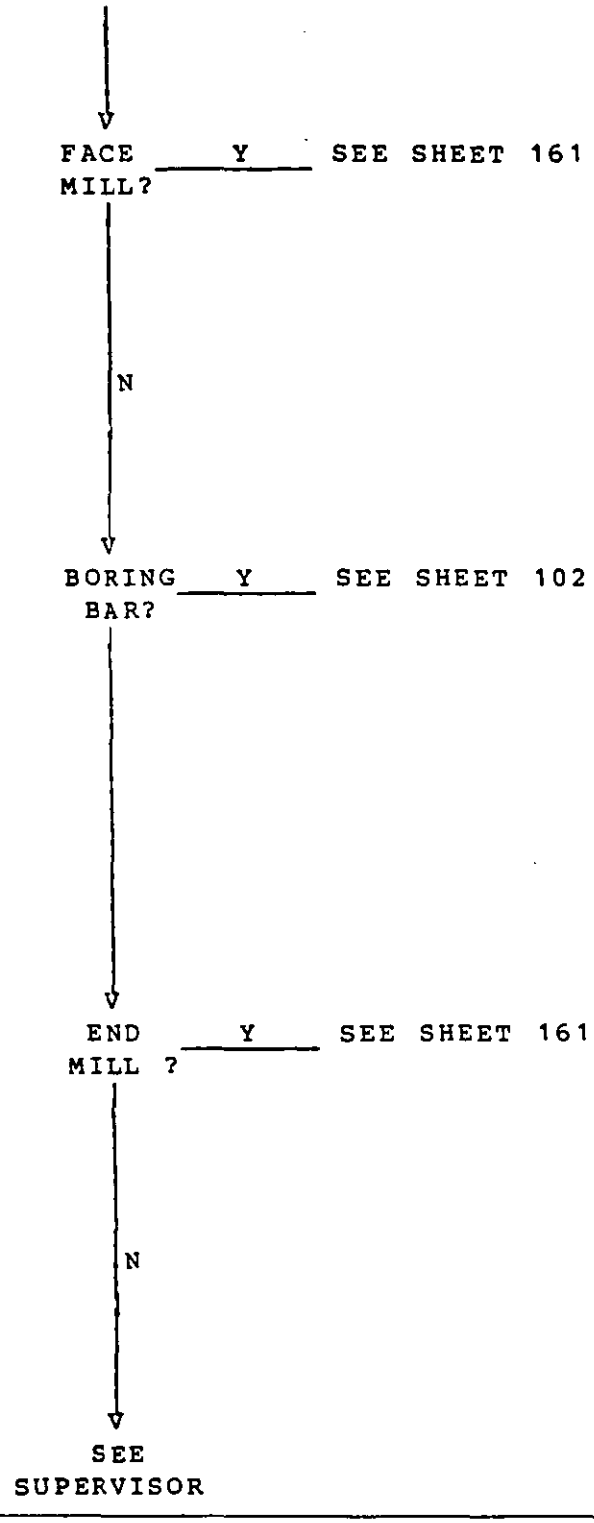
SLOT/STEP(PRODUCED BY BORING BAR). SHEET 141.



SLOT/STEP(PRODUCED BY SLITTING SAW). SHEET 142.

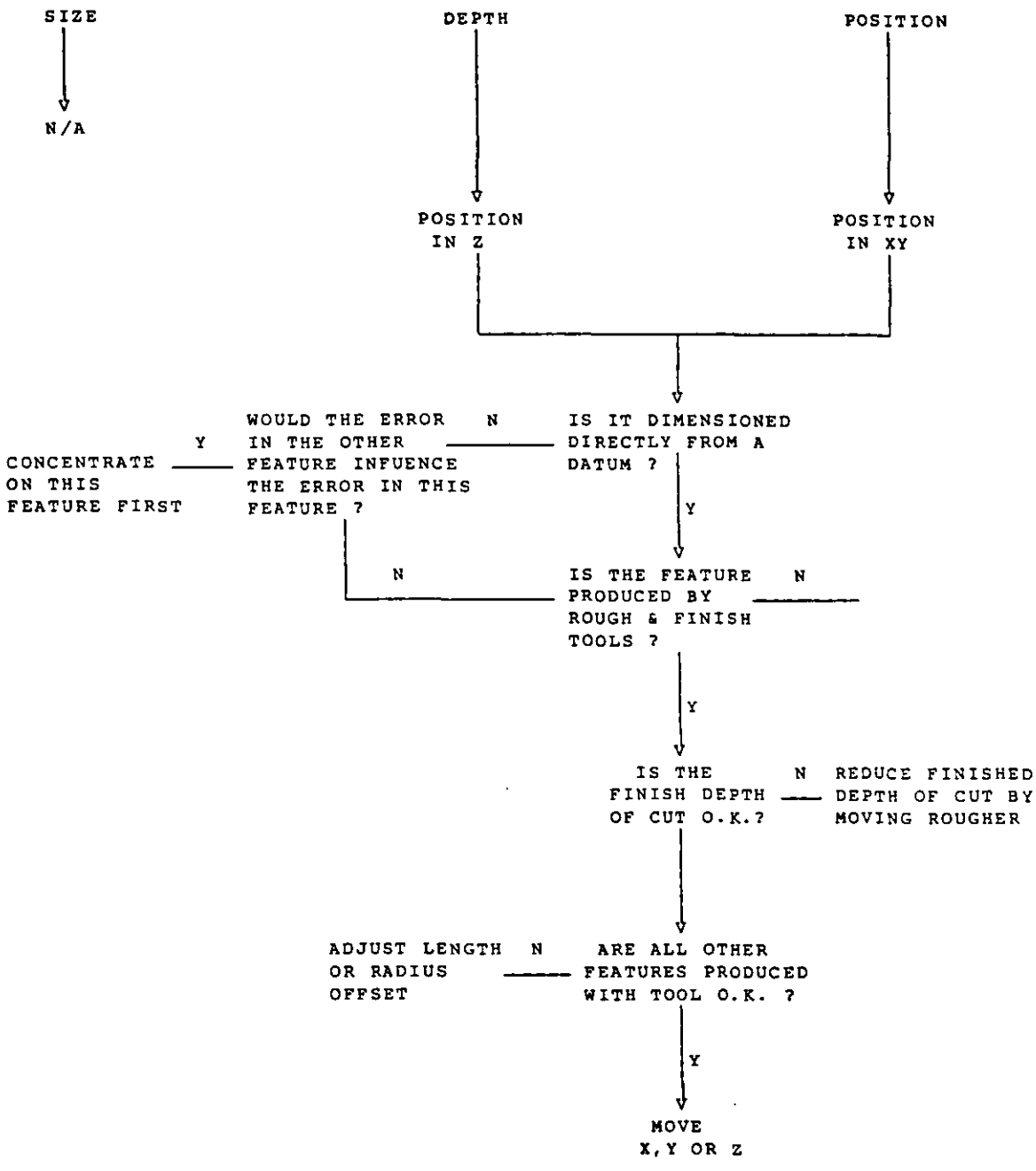


FACE. SHEET 16.

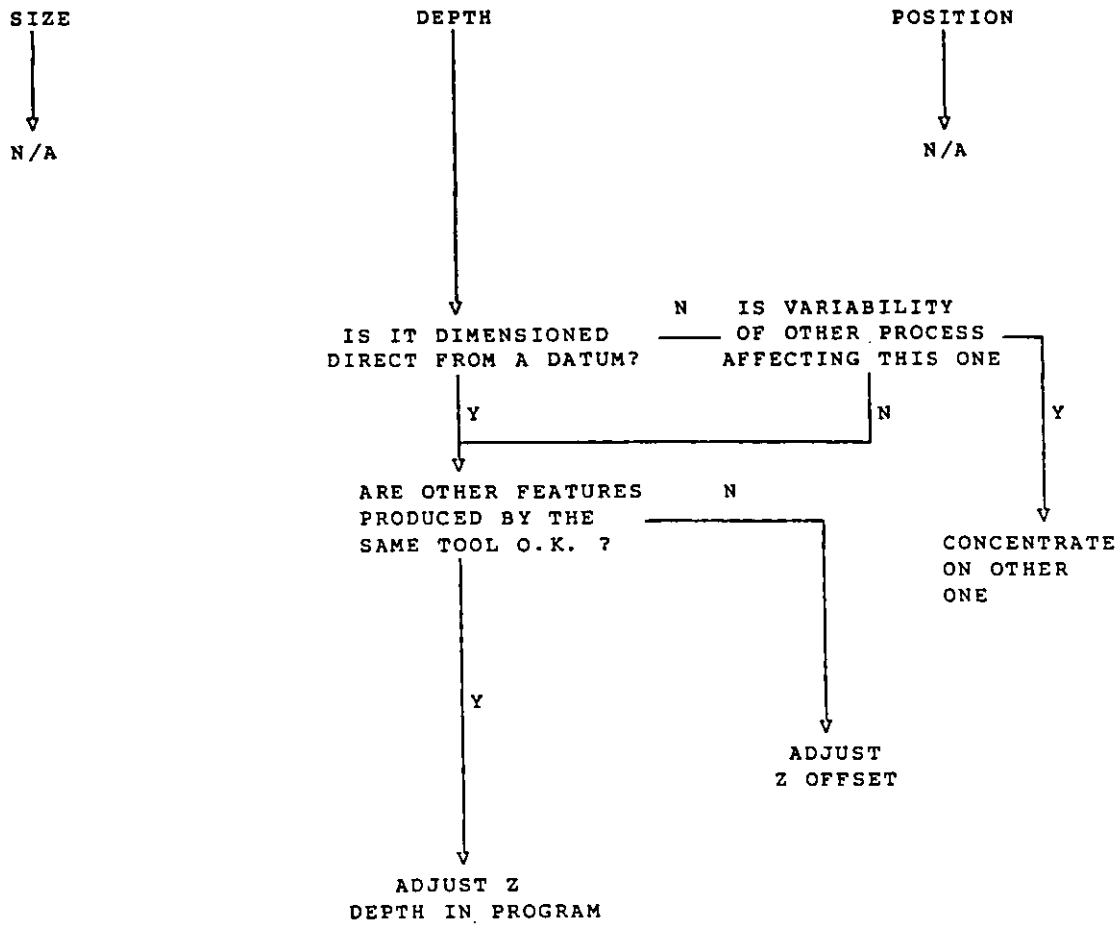


FACE PRODUCED BY FACE MILL OR END MILL.

SHEET 161.



FACE PRODUCED BY BORING BAR. SHEET 162.



RADIUS.

SHEET 18.

END MILL ? — Y → SEE SHEET 104

N

BORING BAR? — Y → SEE SHEET 103

FORM TOOL ? — Y → SEE SHEET 105

SEE SUPERVISOR

PROFILE.

SHEET 20.

END MILL ? —Y— SEE SHEET 104

N

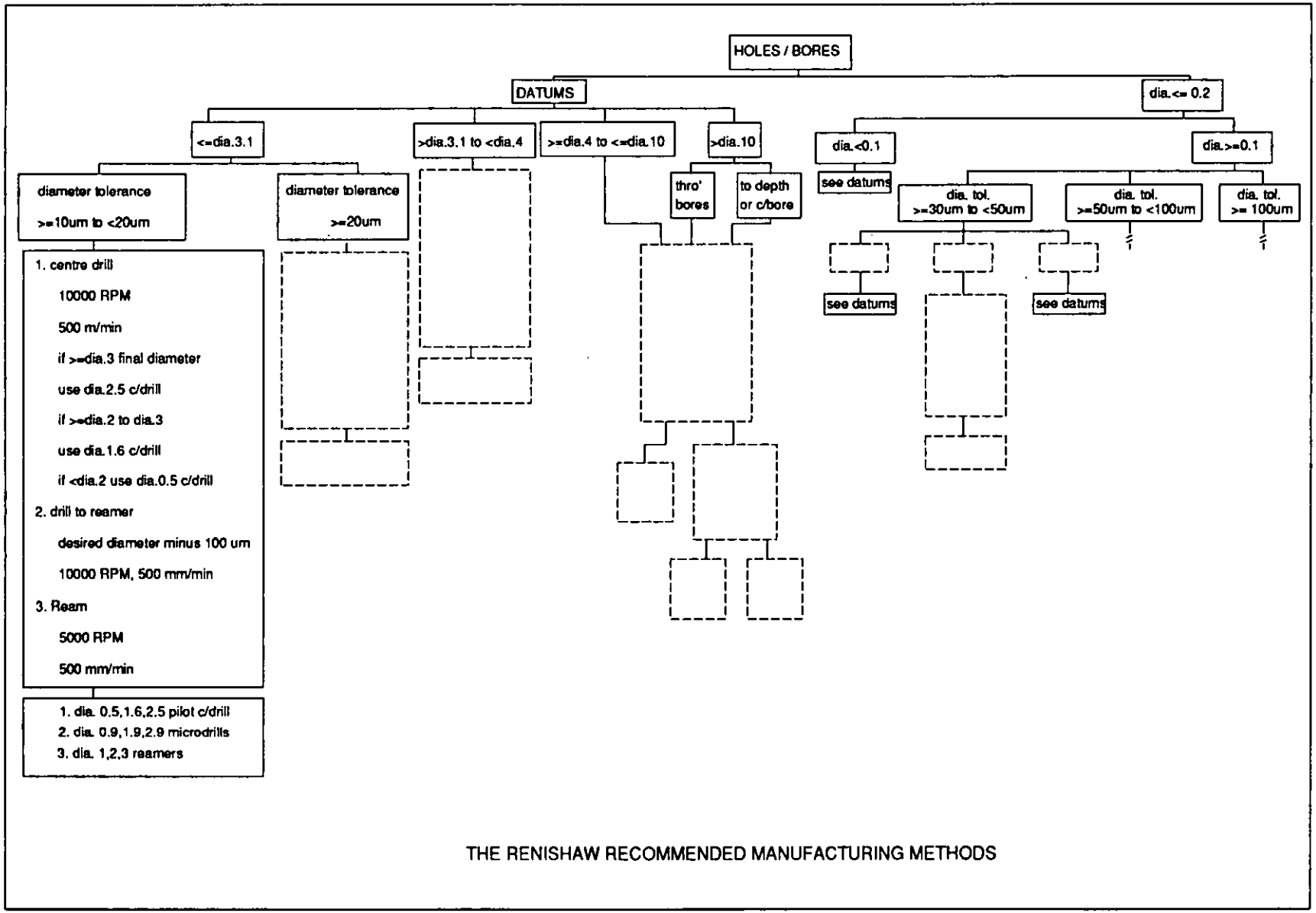
BORING BAR? —Y— SEE SHEET 103

N

FORM TOOL ? —Y— SEE SHEET 105

N

SEE SUPERVISOR



THE RENISHAW RECOMMENDED MANUFACTURING METHODS

APPENDIX 3D.

THE DATA OUTPUT

Appendix 3D :
The Case Study Data Output

3D.1 FAULT-FINDING SOLUTION
(FEATURE OF HOLE/BORE USING DRILL, REAMER AND BORING BAR ARE ILLUSTRATED)

```
        Fault-Finding Solution:
menu header : What is the feature?
  menu elements :
    Hole/Bore:
      menu header : How is the feature produced?
        menu elements :




          Drill:
            menu header : What is the feature attribute?
              menu elements :
                Size:
                  menu header : What is the size?
                    menu elements :
                      Oversize:
                        menu header : Check Run-out
                          menu elements :
                            Run-out is not within limit:
                              menu header : Problem is due to
                                menu elements :

                                    collet size ==
                                      FAULT:
                                      fault description : "wrong collet size"

                            Run-out is within limit:
                              menu header : Confirm check with micrometer
                                menu elements :

                                    drill diameter(too large) ==
                                      FAULT:
                                      fault description : "wrong drill diameter"

                      Undersize:
                        menu header : Confirm check with micrometer
                          menu elements :

                              drill diameter(small) ==
                                FAULT:
                                fault description : "wrong drill diameter used"


                Depth:
                  menu header : Are all features using this tool out?
                    menu elements :
```

```
        length offset/design spec ==
          FAULT:
          fault description :  "depth dimension is out of specification"


    Position:
     menu header :  How is it dimensioned?
       menu elements :
         From a Datum:
          menu header :  Check actual xy position of spot drill with programs
            menu elements :
              Not Influenced by Mean:
               menu header :  Not Influenced by Mean
                 menu elements :

                     positioning of spot/centre drill ==
                      FAULT:
                      fault description :  "position of spot/centre drill is out of tolerance"

              Influenced by Mean:
               menu header :  Influenced by Mean
                 menu elements :

                     position of feature ==
                      FAULT:
                      fault description :  "position of feature is out of tol"

         Not from a Datum:
          menu header :  Check position and capability of feature it is dimensioned from
            menu elements :

                position of feature ==
                 FAULT:
                 fault description :  "position of feature is out of tol"



Reamer:
 menu header :  What is the feature attribute?
   menu elements :
     Size:
      menu header :  What is the reamer's size
        menu elements :
          Oversize:
           menu header :  Check Run-out
             menu elements :
               Run-out is not within limit:
                menu header :  Problem is due to
                  menu elements :

                      collet size ==
                       FAULT:
                       fault description :  "wrong collet size"

               Run-out is within limit:
                menu header :  Confirm check with micrometer
                  menu elements :
```

```
                reamer diameter(too large) ==
                 FAULT:
                 fault description :  "wrong reamer diameter"

        Undersize:
         menu header : Confirm check with micrometer
           menu elements :

              reamer diameter(small) ==
               FAULT:
               fault description :  "wrong reamer diameter used"


    Depth:
     menu header : Are all features using this tool out?
       menu elements :

          length offset/design spec ==
           FAULT:
           fault description :  "depth dimension is out of specification"


    Position:
     menu header : How is it dimensioned?
       menu elements :
         From a Datum:
          menu header : Is it influenced by Mean?
            menu elements :
              Not Influenced by Mean:
               menu header : Dimension is not influenced by Mean
                 menu elements :

                    position of reamer ==
                     FAULT:
                     fault description :  "position of reamer with respect to spot/csntre and drill"

              Influenced by Mean:
               menu header : Dimension is Influenced by Mean
                 menu elements :

                    position of feature ==
                     FAULT:
                     fault description :  "position of feature is out of tol"

         Not from a Datum:
          menu header : Check position and capability of feature it is dimensioned from
            menu elements :

               position of feature ==
                FAULT:
                fault description :  "position of feature is out of tol"


Boring Bar:
 menu header : What is the feature attribute?
   menu elements :
```

```
Size:
 menu header : What is the size?
   menu elements :

       local position of boring bar ==
        FAULT:
        fault desscription :  "The boring bar is out of position locally"


Depth:
 menu header : Are all features using this tool out and influenced by means?
   menu elements :
     Not Influenced by mean:
      menu header : Not Influenced by mean
        menu elements :

            length offset/design spec ==
             FAULT:
             fault description :  "depth dimension is out of specification"

     Influenced by Mean:
      menu header : Influenced by Mean
        menu elements :

            position of feature ==
             FAULT:
             fault description :  "position of feature is out of tol"


Position:
 menu header : How is it dimensioned?
   menu elements :
     From a Datum:
      menu header : Check that all tools (spot,drill) use the same xy position
        menu elements :

            position of boring bar ==
             FAULT:
             fault description :  "position of boring bar is out of tolerance"

     Not from a Datum:
      menu header : Check position and capability of feature it is dimensioned from
        menu elements :

            position of feature ==
             FAULT:
             fault description :  "position of feature is out of tol"
```

3D.2 MANUFACTURING METHOD SELECTION (FEATURE HOLE/BORE AS DATUM IS ILLUSTRATED)

```
As Datum:
menu header : What is the diameter range for hole used as Datum
 menu elements :
   diameter is le 3.1mm:
    menu header : What is the tolerance range for diameter le 3.1mm
      menu elements :
        tolerance is ge 10 micrometer to lt 20 micrometer:
         menu header : The manufacturing method recommended for
ge 0.010mm tol is
           menu elements :

              B/dia le 3.1/tol ge 0.010 to lt 0.020 == ...

        tolerance is ge 20 micrometer:
         menu header : The manufacturing method recommended for
ge 0.020mm tol is
           menu elements :
              B/dia le 3.1mm/tol ge 0.020mm == ...


   diameter is gt 3.1mm to lt 4.0mm:
    menu header : The manufacturing method recommended fro gt 3.1mm
to lt 4.0mm dia is
      menu elements :

         B/dia gt 3.1 to lt 4.0 == ...


   diameter is ge 4.0mm to le 10.0mm:
    menu header : The manufacturing method recommended for ge 4.0mm
to le 10.0mm dia is
      menu elements :

         B/dia ge 4.0 to le 10 and gt 10.0mm == ...

         B/dia ge 4.0 to le 10.0 == ...


   diameter is ge 10.0mm:
    menu header : What is the hole types?
      menu elements :
        Through bores:
         menu header : The manufacturing method recommended for
through bores is
           menu elements :

              B/dia ge 4.0 to le 10 and gt 10.0mm == ...

              B/dia dia ge 10.0/Boring == ...

              B/dia gt 10.0/0.8 rad == ...

        To depth or c/bore:
```

menu header : The manufacturing method recommended for
To depth or c/bore is
menu elements :
B/dia ge 4.0 to le 10 and gt 10.0mm == ...

B/dia dia ge 10.0/Boring == ...

B/dia gt 10.0/0 rad == ...

3D.3 FAULTS STORED IN FAULT LIBRARY (SOME EXAMPLES)

drill diameter(small) ==
FAULT:
fault description : "wrong drill diameter used"
causes :
cause description : "The actual drill size used is too small
when confirmed with micrometer"
actions :
action description : "Change drill size (check with
drawing specification)"
probability :
prob : 100.0

drill diameter(too large) ==
FAULT:
fault description : "wrong drill diameter"
causes :
cause description : "The actual size of drill is larger than
specified"
actions :
action description : "change drill diameter, check with
design specification"
probability :
prob : 100.0

length offset/design spec ==
FAULT:
fault description : "depth dimension is out of specification"
causes :
cause description : "All features using this tool is out of tol"
actions :
action description : "adjust length offset"
probability :
prob : 50.0

cause description : "Not all feature using this tool is out"
actions :
action description : "adjust depth"
probability :
prob : 50.0

positioning of spot/centre drill ==
FAULT:
fault description : "position of spot/centre drill is out of tolerance"
causes :
cause description : "actual xy position of spot/centre drill does not ties up in program"
actions :
action description : "adjust spot/centre drill position in program (confirm with specs)"
probability :
prob : 50.0

cause description : "actual xy position of spot/centre drill in program ties up with design spec"
actions :
action description : "move both spot/centre drill and xy position in program"
probability :
prob : 50.0

position of feature ==
FAULT:
fault description : "position of feature is out of tol"
causes :
cause description : "posn capability and spread of feature from datum would influence means"
actions :
action description : "correct posn of this feature, NOT the one in question"
probability :
prob : 100.0

collet size ==
FAULT:
fault description : "wrong collet size"
causes :
cause description : "wrong collet size used causes run-out to be out of tol"
actions :
action description : "change collet size and repeat run-out procedure"
probability :
prob : 100.0

B/dia le 3.1/tol ge 0.010 to lt 0.020 ==
FAULT:
fault description : "The procedure is in sequence"
causes :
cause description : "First use centre drill with 10000rpm and 500mm/min"

actions :
action description : "If dia is ge 3.0, use dia 2.5 centre drill"

action description : "If dia is ge 2.0 to lt 3.0, use dia 1.6 centre drill"

action description : "If dia is lt 2.0, use dia 0.5 centre drill"
probability :
prob : 100.0

cause description : "Second, use drill to reamer with 10000rpm and 500mm/min"
actions :
action description : "If dia is ge 3.0, use dia 2.9 microdrill"

action description : "If dia is ge 2.0 to lt 3.0, use dia 1.9 microdrill"

action description : "If dia is lt 2.0, use 0.9 microdrill"
probability :
prob : 100.0

cause description : "Third, use reamer with 500rpm and 500mm/min"
actions :
action description : "If dia is ge 3.0, use dia 3.0 reamer"

action description : "If dia is ge 2.0 to lt 3.0, use dia 2.0 reamer"

action description : "If dia is lt 2.0, use dia 1.0 reamer"
probability :
prob : 100.0

B/dia dia ge 10.0/Boring ==
FAULT:
fault description : "This follows after drilling"
causes :
cause description : "Use Boring bar PCM 270-25"
actions :
action description : "If finish dia is gt 10.0 to le 16.0, use dia 8.0mm"

action description : "If finish dia is gt 16.0 to le 12.0, use dia 10.0mm"

action description : "If finish dia is gt 22.0 to le 28.0, use dia 16.0mm"

action description : "If finish dia is gt 28.0 to le 34.0, use dia 20.0"

action description : "If finish dia is gt 34.0, use
dia 25.0"
probability :
prob : 100.0

B/dia gt 10.0/0.8 rad ==
FAULT:
fault description : "This follows the process after boring"
causes :
cause description : "Use 2000rpm and 100mm/min"
actions :
action description : "Use 0.8 rad and 55 degree carbide
insert"
probability :
prob : 100.0

B/dia gt 10.0/0 rad ==
FAULT:
fault description : "This follows the process after boring"
causes :
cause description : "Use 2000rpm and 50mm/min"
actions :
action description : "Use 0 rad and 55 degree carbide
insert"
probability :
prob : 100.0

APPENDIX IV.

THE ISS PROJECT - IDEF0 REPRESENTATION

1. Maintain Company Information

Raw data is taken and interpreted to produce information which may be used by other activities. The information may itself be raw data but stored in a retrievable form but it could be more, for example, new data combined with existing information could be used to modify the design of the company model.

2. Design Company Model

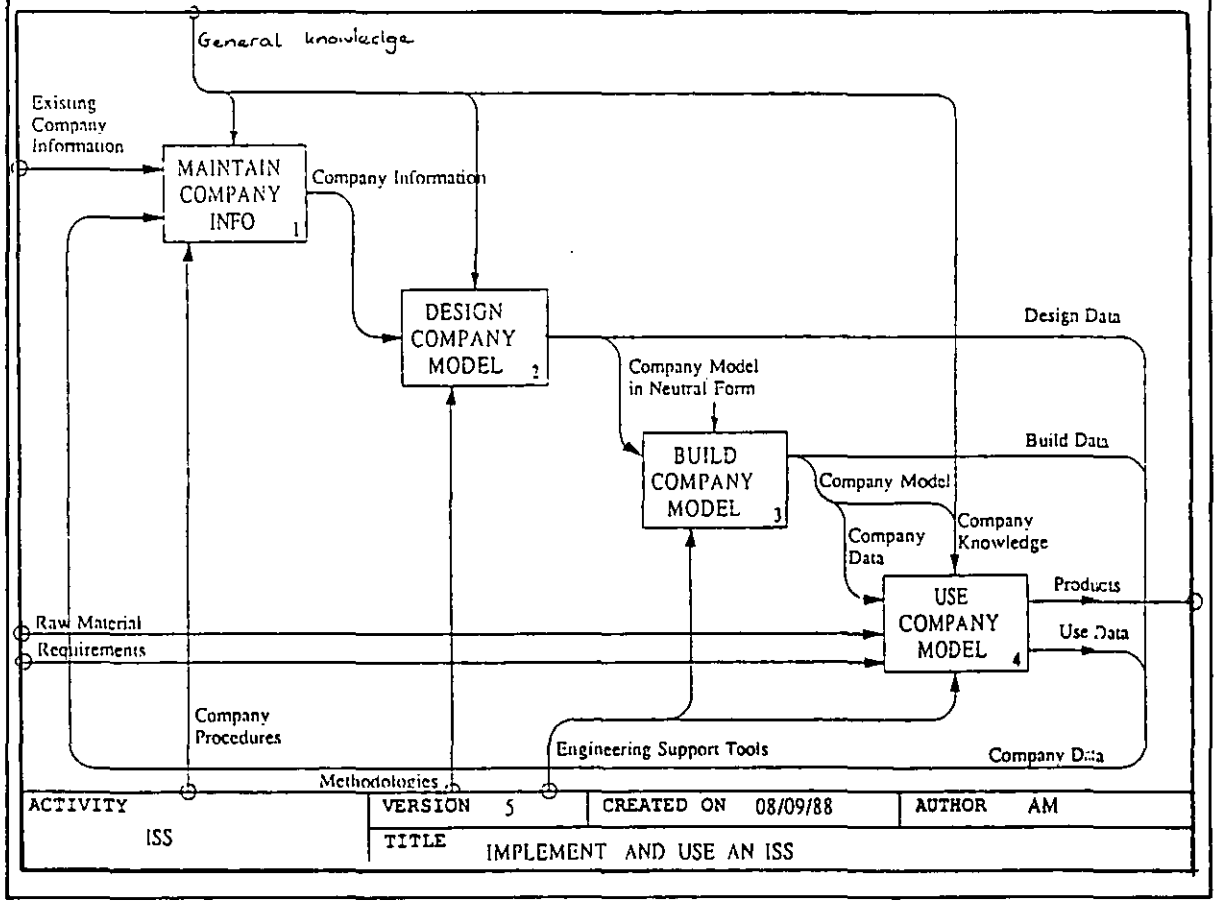
Using all the relevant information about the company a design for a company model will be produced. This design should be independent of the way in which the model will be implemented.

3. Build Company Model

The company model is implemented during this activity.

4. Use Company Model

The company model contains all the data about a company, including product data. Here this data is used to convert raw material into products.



1. Analyse Requirements

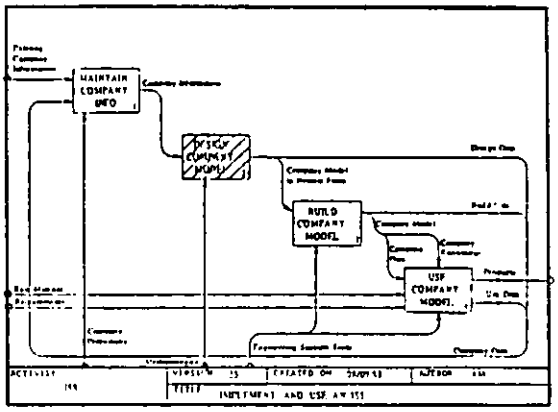
Information about the company will be looked at and a set of requirements for the ISS will be produced.

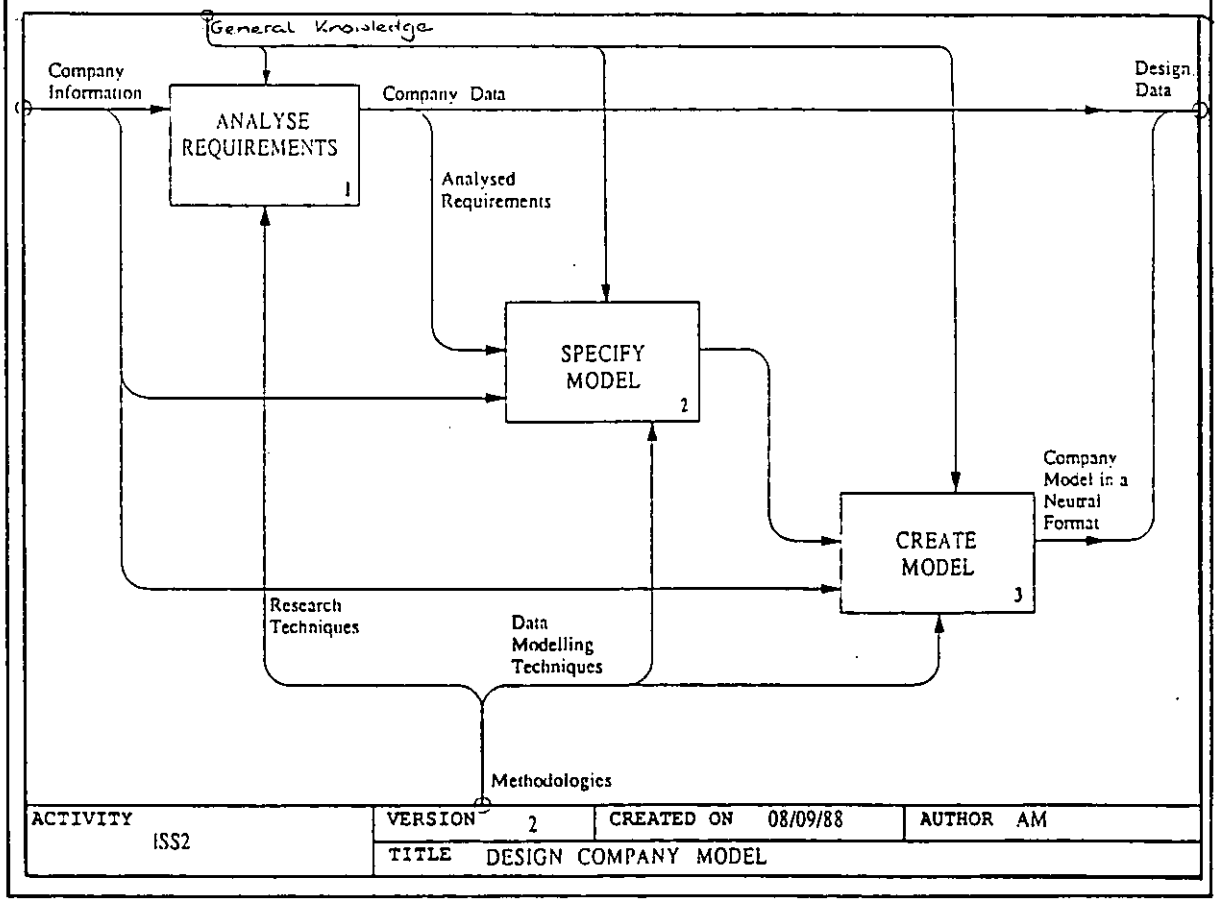
2. Specify Model

The requirements will be taken and a formal specification will be drawn up

3. Create Model

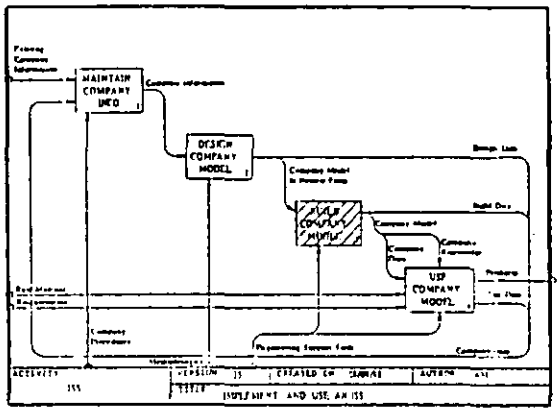
A formal language or method will be used to define a company model which will satisfy the specification.





Describe Static Structures

Static Structures are those structures which are unlikely to change much, for example, SE meta-structures or database schemas. Some are likely to be supplied by the project, for example, those which describe the form of geometric descriptions, and will be used to produce a company specific structure.



Describe Features, Standards, etc

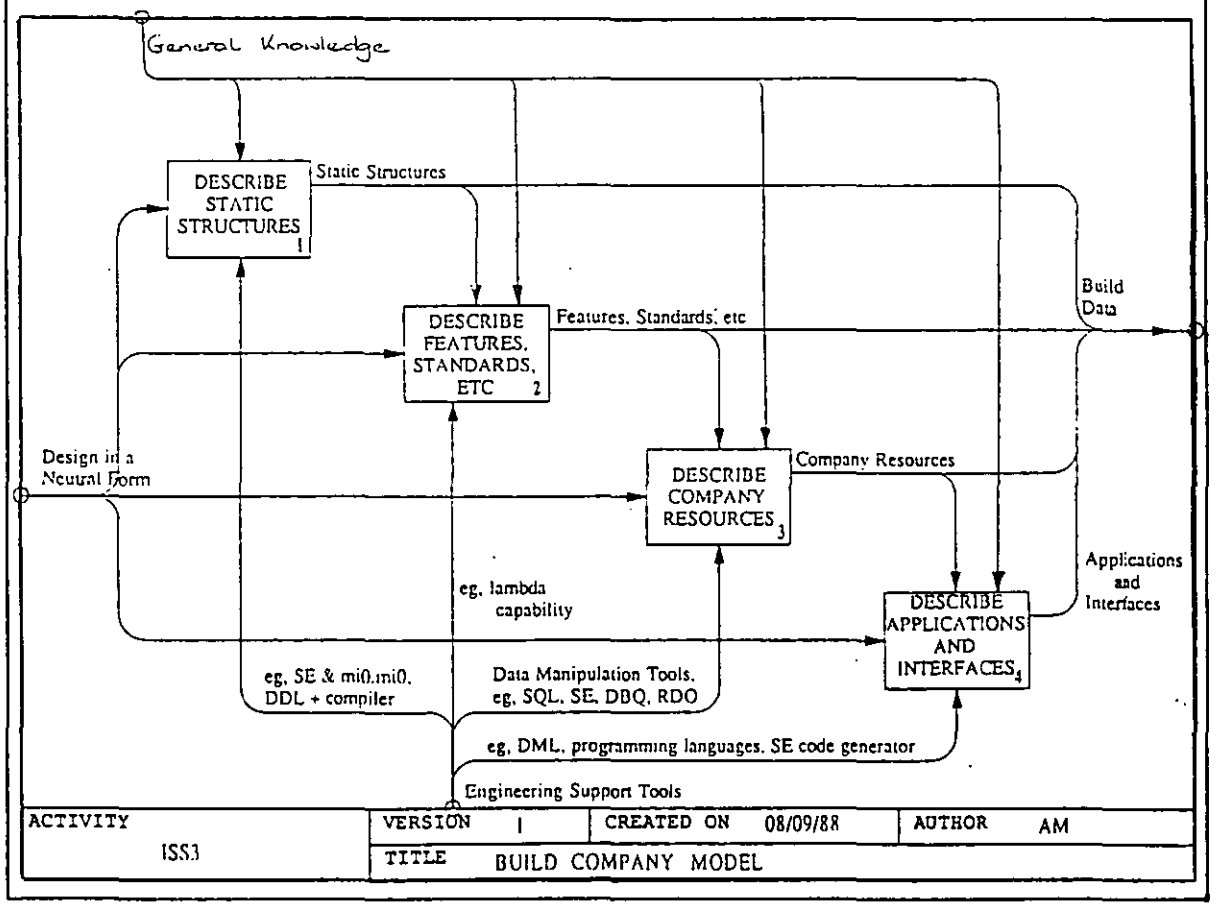
These will be defined in terms of the static structures and will be used by engineers to create designs, process plans and the like. Examples include tables of standard parts, form features, part family templates and other parametrized descriptions which would be defined using lambda expressions in the SE or solid families in NONAME.

Describe Company Resources

These are the facilities, both computer and manufacturing, which are available and used to produce products. They would be instance data in the SE or the contents of a database.

Describe Applications and Interfaces

Here the operations upon the company model which will be needed for the ISS to be useful will be specified. Where the application is outside the ISS an interface will also be specified.



Build Product Structure

Here the relationships between different products, which make up a larger one, will be specified.

Specify, Design and Manufacture Product

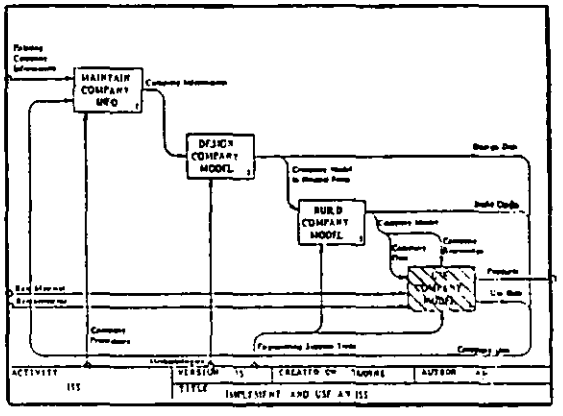
The specification, design and manufacture of a single product.

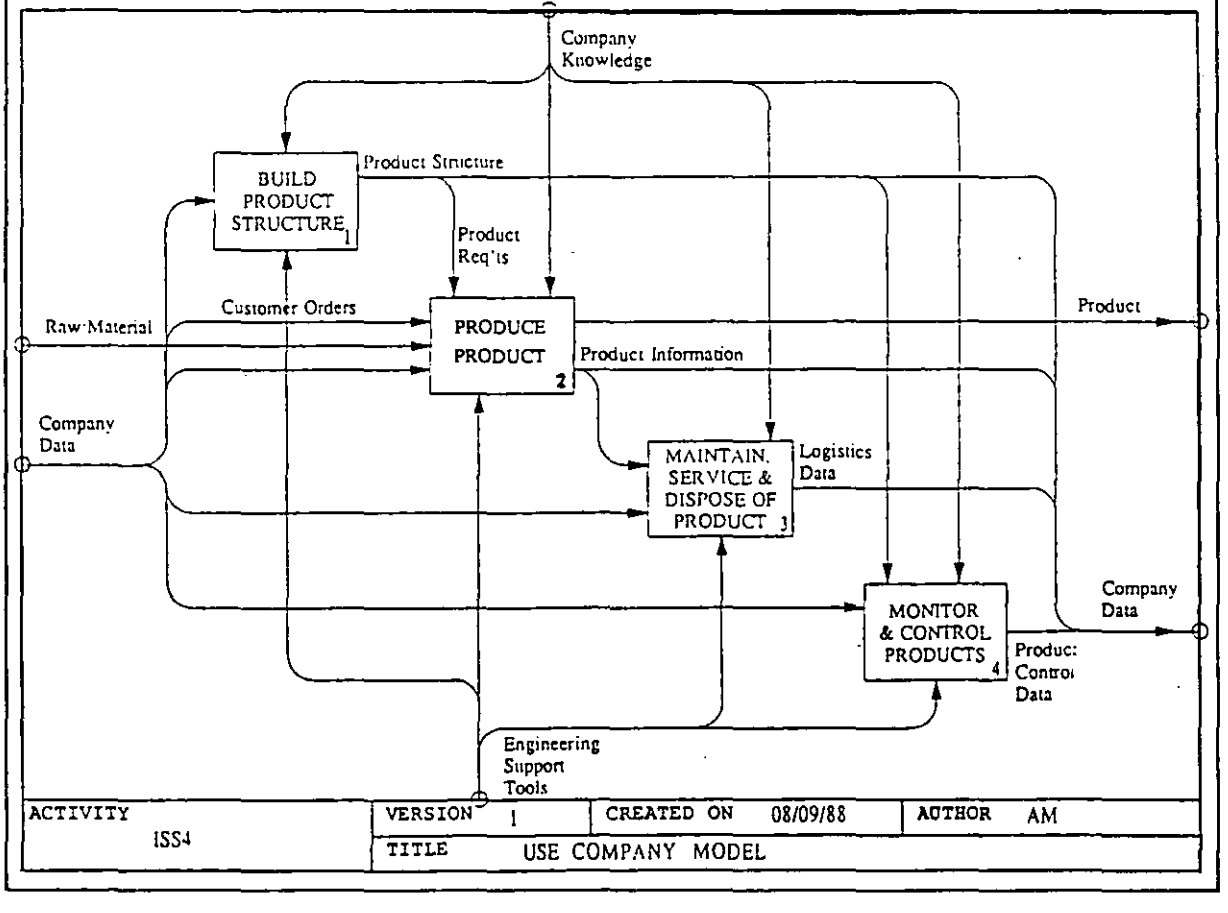
Maintain, Service and Dispose of Product

This activity includes all the processes which are carried out from the finished product's transfer to the other side of the factory gate until the end of its lifecycle. Depending upon the nature of the product this data may be recorded by none or more companies or individuals. For example, data about a plane's life may be stored by the companies which do or have owned it and all those which have been concerned with it from its conception.

Monitor and Control Products

This includes management activities such as version control and management





1. Specify.

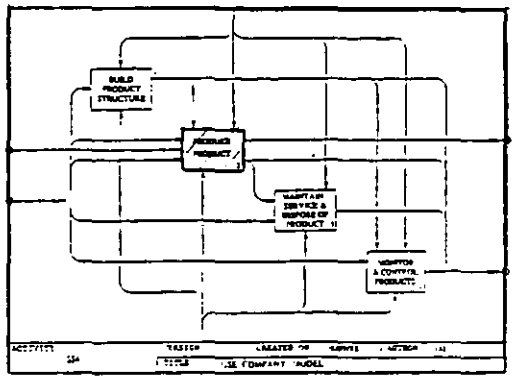
Consider the product's requirements, including market requirments, using company data and knowledge to produce a specification suitable for design consideration.

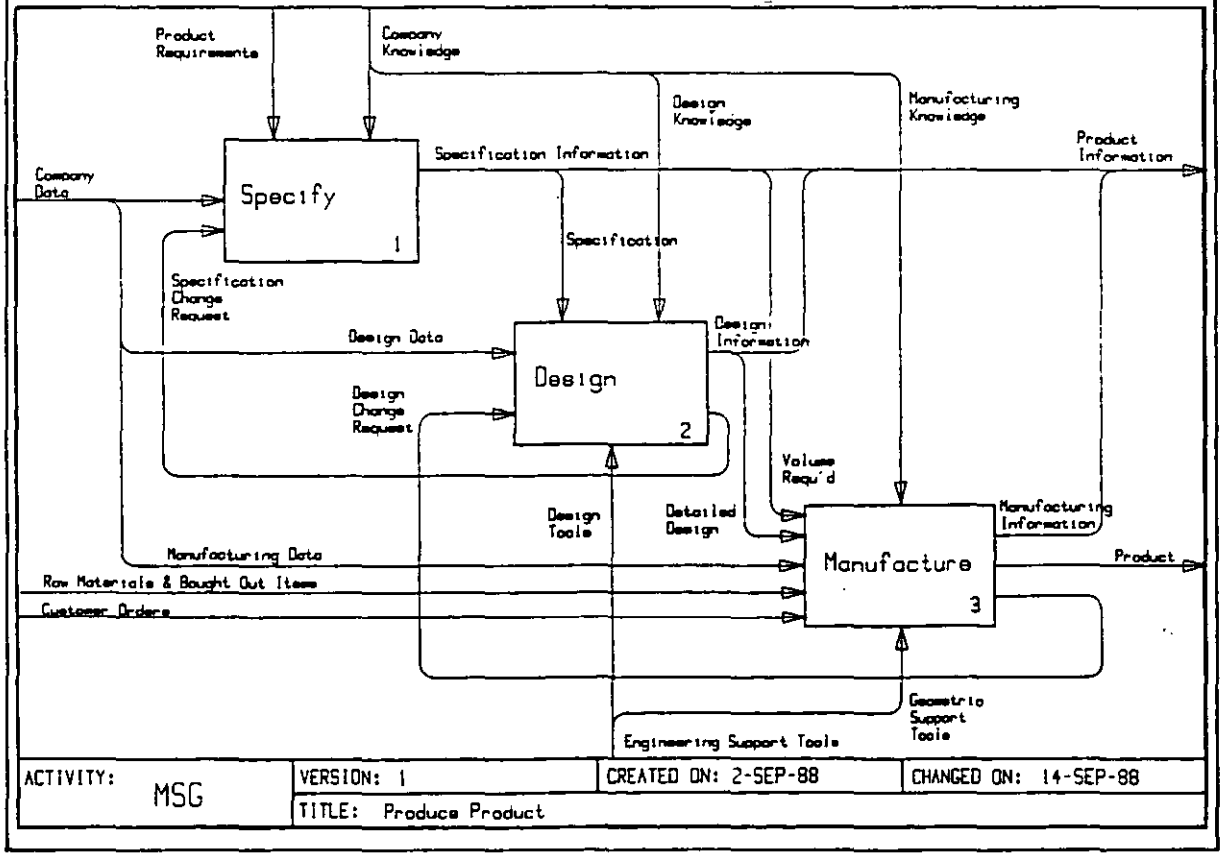
2. Design.

Identify ways of meeting the product specification, producing a detailed design for the chosen method. Make design improvements as further information becomes available.

3. Manufacture.

Plan how to produce the product, identifying costs, times, methods and required equipment. Produce the product to meet customer orders while being aware of other production commitments.





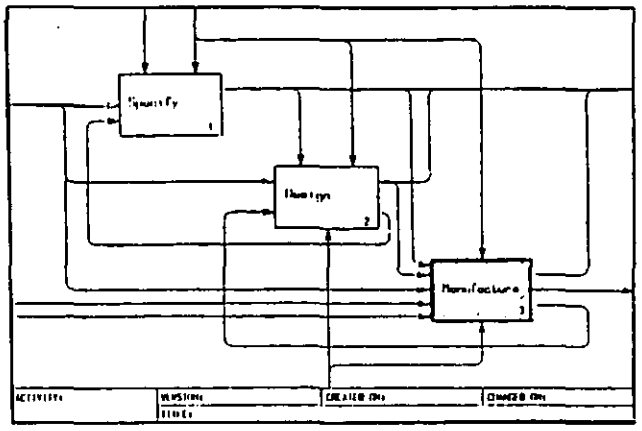
1. Plan for Manufacture. Identifies the way, or ways, in which products are to be made, the equipment and time required.

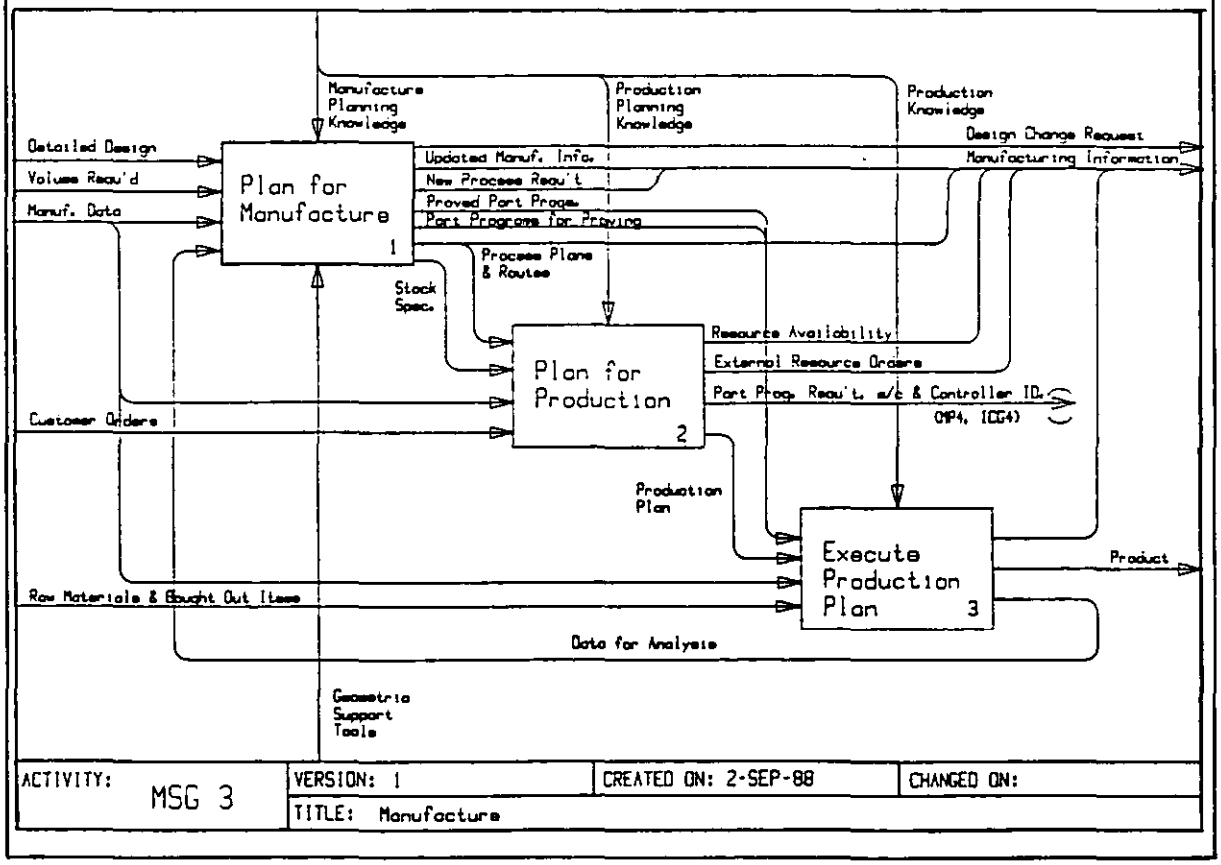
2. Plan for Production.

Plan the usage of the company's manufacturing resources to meet customer orders against company planning requirements.

3. Execute Production Plan.

Operate the company's manufacturing resources to meet the production plan.





1. Plan Processes.

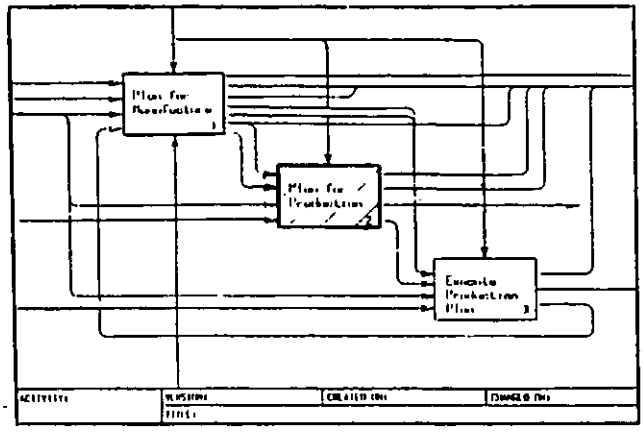
The component required is assessed against volume required, available equipment and the company's expertise to decide on process plans and routes. Specific Machine Planners are called to provide detailed information as necessary.

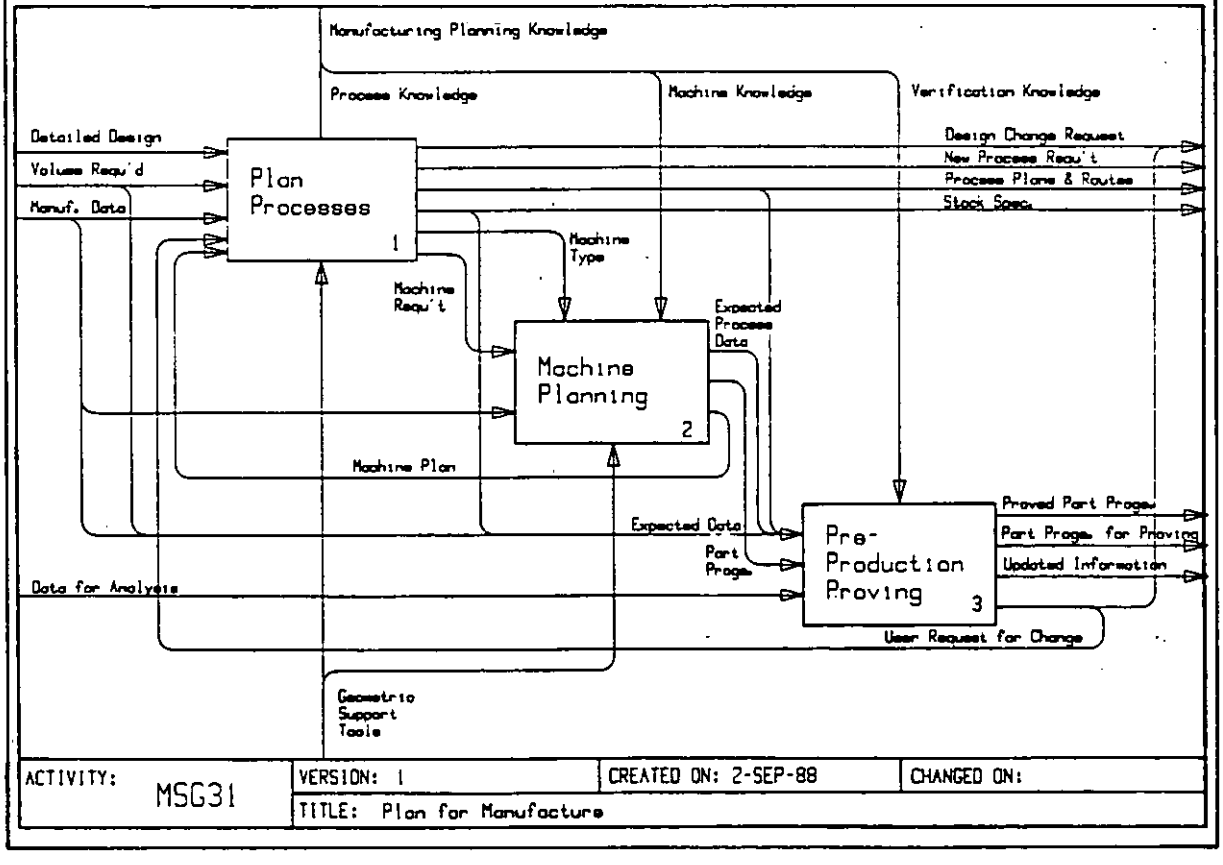
2. Machine Planning.

Data is supplied to Planning Processes about how to achieve what is be required of a specific machine type. Test part programs are produced if required.

3. Pre-Production Proving.

Ensure that all data pertinent to producing a workpiece is available and verified before production may commence.





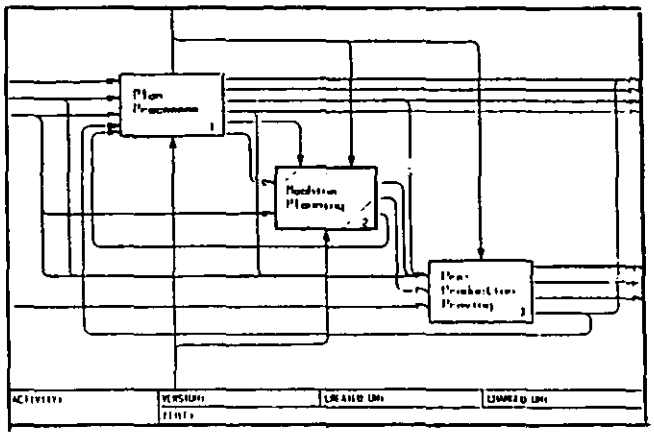
1. **Machine Planning for Metal Removal.** Detail planning information for metal removal processes is generated. Part programs are produced as required.

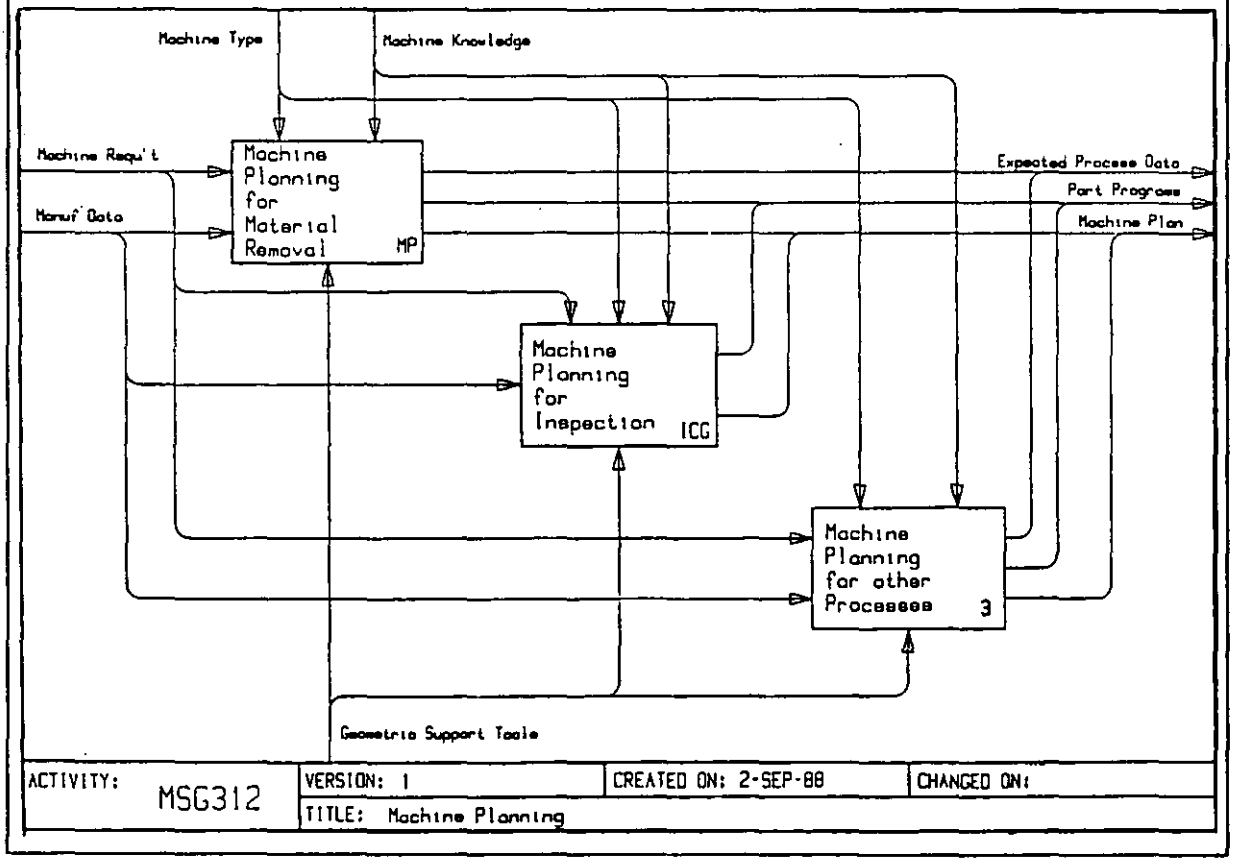
2. **Machine Planning for Inspection.**

Detail planning information for inspection is generated. Part programs are produced as required.

3. **Machine Planning for other Processes.**

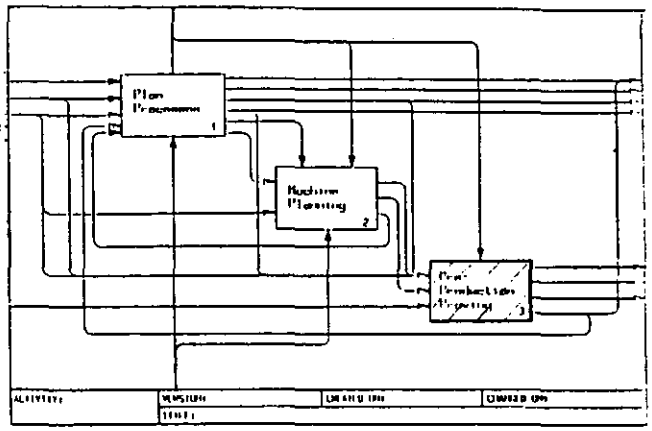
Detail planning information for processes other than metal removal or inspection is generated. Part programs are produced as required.

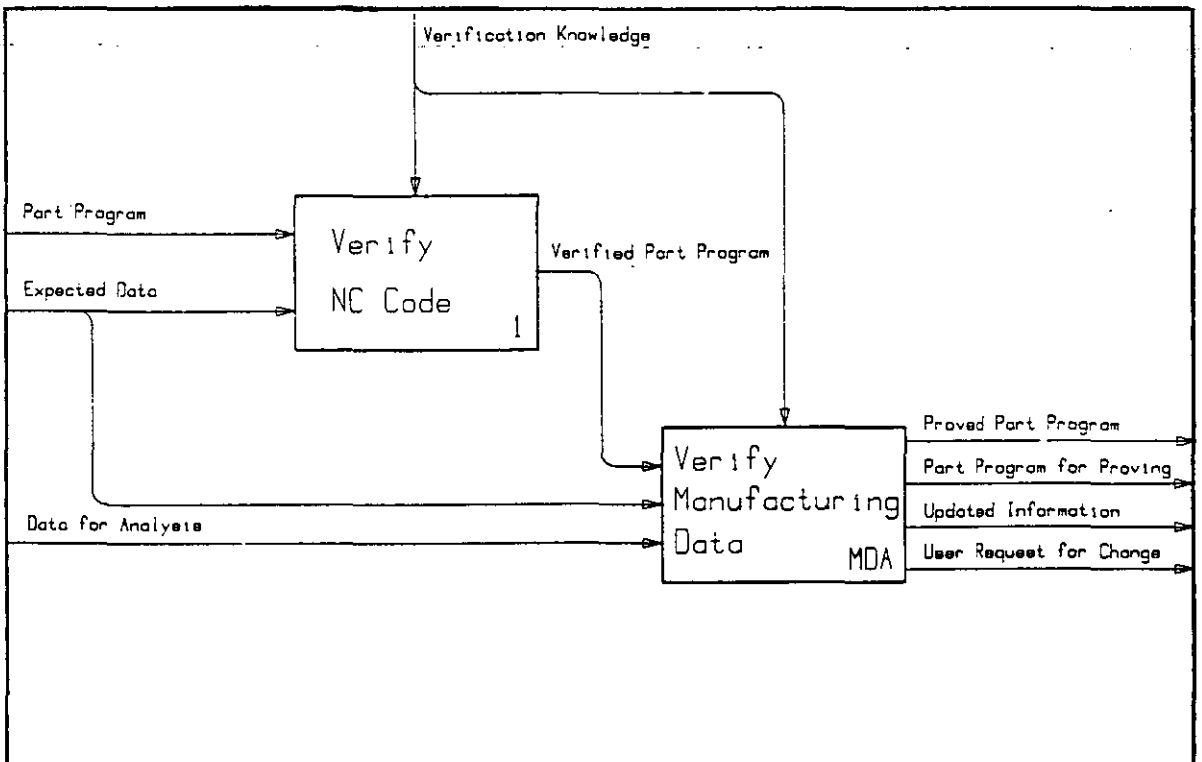




1. **Verify NC Code**
Geometrical Errors are detected by simulating the tool paths in the latest part program.

2. **Verify Manufacturing Data**
The part program is further verified for technological errors before production may commence.





ACTIVITY: MSG313	VERSION: 1	CREATED ON: 7-SEP-88	CHANGED ON:
	TITLE: Pre-Production Proving		