The Integration of Humans and Machines in Advanced Batch Manufacturing Systems

by

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September 1990

A thesis submitted for the degree of Doctor of Philosophy of the University of London and for the Diploma of Membership of the Imperial College

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Abstract

A growing literature is documenting the failure of many firms to realize the expected benefits from the application of advanced manufacturing technology (AMT). Many of the "human" problems increasingly associated with the implementation of AMT can be attributed to the predominant "technology-centred" approach to the design of man-machine systems, whereby system designers concentrate on the efficiency of fixed capital and tend to ignore human aspects until the technology has been implemented.

This thesis describes the author's contribution to the development and application of an alternative "human-centred" approach to the design of AMT. This is a parallel design method whereby technical and human aspects are considered together from the beginning of the system design process.

The thesis is divided into two parts: Part I, based largely on the findings of a study tour of leading European AMT users and vendors, investigates the impact of computers in batch manufacturing. A brief analysis of the nature and problems of batch production is followed by a description of the various ways in which computer-controlled equipment is presently applied to solve these problems and the role played by humans in operating and managing this technology. A discussion of the difficulties experienced by many users and an analysis of their causes exposes the inherent flaws in the "technology-centred" approach and, accordingly, indicates the need for a holistic approach to the design of computer-aided technology and work.

Part II details the author's work within SERC/ACME and ESPRIT funded projects, both aimed at the further development and application of a "human-centred" approach to AMT. A discussion of the limitations of past efforts to guide the design and implementation of new technologies and so "humanize" work, precedes the presentation of a framework of design guidelines for human-centred AMT. There is then a detailed description of how this framework, and associated design procedure, have been applied to the design and implementation of a flexible human-centred turning cell. Particular attention is given to the design of the software for the turning cell computer, intended to assist the cell personnel in their operation and management of the cell. The thesis is concluded by an assessment of the potential of human-centred AMT for widespread adoption, in which both obstacles to, and emerging support for, this new approach are considered.

In an Appendix the author's initial efforts to apply a human-centred approach in an industrial setting are described and lessons from this experience for future research are outlined.
I would like to express my sincere thanks to the following people for their guidance and support during the project described in this thesis.

My supervisors Professor Colin Besant, Department of Mechanical Engineering, and Ms. Dorothy Griffiths, Management School, for their endless patience.

Professor Tom Husband, Head of the Department of Mechanical Engineering, for many fruitful discussions.

Mr. Reinhard Ernst, Managing Director, Harmonic Drive Antriebstechnik GmbH. and Mr. David Wheeler, Managing Director, Harmonic Drive Ltd. for sponsorship received during the research.

Mrs. Junko Okuyama and Mr. Graham Thomas of the School of Oriental and African Studies, London for constant encouragement.

My colleagues in the Manufacturing Technology and Nuclear Power research groups in the Department of Mechanical Engineering, Ihab Olama, Leon Hatzikonstantis, Mohammad Sahrad, Tania Hancke, Hans-Peter Weidlich, Christof Barth, Nelson Stratta-Santucci and Ioannis Leon, for their ideas and constructive criticism at various stages in the research.

Last but not least Sue, Bernadette, Chrissie, Lena, Brian and George for moral support and Claudia, Andrea and Connie for their assistance in the preparation of the manuscript.
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References
1. Introduction

In recent years Information Technology has been increasingly portrayed as a vehicle by which to automate batch production. Implementations of Information Technology in batch manufacture, commonly grouped under the term "Advanced Manufacturing Technology" have been widely promoted as the means by which to derive the low unit cost benefits of mass production in a batch manufacturing environment and, therefore, as essential to the competitiveness of companies engaged in this form of production [ACARD, 83] [NEDO, 85:1].

There has been a corresponding avalanche of information, in both media and academic circles, about the various forms of AMT, such as Computer-Aided Design (CAD) and Computer-Aided Manufacture (CAM). Latterly though, AMT has been largely superseded as a "buzzword" by Computer-Integrated Manufacturing (CIM) which, broadly speaking, describes the plant-wide integration of a variety of computer-aided functions and processes such as CAD and CAM, and which has been hailed as a vehicle for "revolutionizing" batch manufacturing.

Importantly, CIM and its various constituent technologies have been widely perceived, particularly in the public eye, as the vanguard of the workerless, paperless "Factory of the Future." CIM technologies are frequently promoted as a means by which to remove the human element from manufacturing systems because it is "unpredictable" and "inefficient;" integrated systems are certainly very rarely viewed from the sense of integrating people and machines, and for many both AMT and CIM have become synonymous with an objective of achieving total automation in an unmanned factory.

Yet, while great benefits have been claimed for different forms of AMT, such as reduced lead times, reduced work-in-progress, increased stock turnover and reduced labour costs, surveys giving the actual figures for the diffusion of AMT indicate "evolutionary" rather than "revolutionary" growth in the use of Information Technology in manufacturing. For example, in the United Kingdom, just 7% of the overall machine tool population is computer-controlled [Metalworking Production, 88:15], and less than 1 factory in 40 possesses a robot [Northcott et al, 86:2], whilst world-wide there is estimated to be just 150 to 200 Flexible Manufacturing Systems (FMS) [Bessant & Haywood, 85:18]. Nevertheless, rapid growth is still expected and it is not unusual to see forecasts of exponential growth for the different forms of AMT.

Various supply-side and user-side constraints that have slowed diffusion have been identified, not least the considerable cost of many forms of AMT and the particular difficulty of successfully integrating hardware, software and organizational systems. In the case of FMS, of particular interest from the point of view of the author's research, the key factor restricting wide spread adoption has been the limited applicability of the current generation of systems in terms of product flexibility. Moreover, it would appear that the benefits frequently claimed could present a biased picture in that failures are seldom admitted and hardly ever publicly reported. A survey by Ingersoll Engineers of 48 FMSs found that an uncomfortably high number had failed to realize the expectations of their purchasers [Holz, 84:22], an experience that other studies indicate is representative for other major forms of AMT, such as CAD/CAM [Marsden, 86].
Many of the problems experienced are the result of new technology being implemented without careful integration into the company's business plan, that is, there is a lack of strategic planning with respect to AMT. The introduction of AMT in sophisticated "high tech" companies has been described as unduly "technology-driven," whilst the development of AMT in less sophisticated companies is characterised by a process of "muddling through" [Clegg, 88:26]. Human operators are typically viewed as sources of unpredictability and error, such that wherever possible system functions are allocated to machines rather than humans. Studies indicate that regardless whether technology-driven or designed by "muddling through", little attention is paid to the human or organizational aspects of AMT until the technology has been designed and often not until it is implemented.

It should therefore be no surprise that there is increasing evidence that unforeseen human and managerial problems with AMT often prove more difficult to deal with than technical problems, which although formidable, are more often anticipated [Meredith, 87]. The lack of attention to the human and organizational aspects of AMT is responsible for a 'lack of fit' between the demands made by technology and the needs, skills and procedures of the human support system on which it still, ultimately depends [Blumberg & Gerwin, 84:114]. There is growing recognition of a need for both technology and organizational structure to be constituted so as to facilitate the co-ordinated and controlled pursuit of strategic objectives [Child, 87:107]. Indeed, it is increasingly clear that organizational integration, by reducing organizational complexity and, thereby, substantial "non-value-added" costs, is a pre-requisite if the full benefits of integrated technologies such as CAD/CAM or FMS are to be realized [Stark, 88:3].

However, as indicated above, there is significant evidence that most companies adopt what can be termed a "technology-centred" approach to system design and implementation, whereby human and organizational aspects of the technology receive scant attention, that is, are taken for granted [Clegg & Corbett, 87:176]. This is particularly problematic in the case of shop-floor applications of AMT, which therefore are the focal point for the author's research.

In the case of FMS, the "shop-floor" end of CIM where, arguably, technological integration has progressed furthest, the typical practical situation revealed by surveys of FMSs in the USA and UK is characterized by inflexible and polarised "pre-FMS" organizational structures, whereby the machine operators "lost control" of what was being done at their machine, the bulk of preparatory work being taken on by other personnel, such as programmers and machine setters [Jones, 86]. Accordingly, work in the FMSs studied did not provide enough autonomy, task identity, responsibility or feedback, leading to the conclusion that work in an FMS has little potential for motivating people, is not very satisfying and is stressful [Blumberg & Gerwin, 84].

This is despite the fact that there is considerable "choice" in the organization of work around AMT. For example, stand alone computer-numerically-controlled (CNC) machine tools are "compliant" in the sense that they can be programmed either at the machine or from an office and, moreover, can allow modifications of work organization to take place after the machines have been installed. However, for more integrated systems, such as FMS, the situation is quite different. Here the impact that the system will have on managers and workers at all levels of the organization becomes more pre-determined and the shape of the organization and individual skills and
responsibilities may be constrained by the design of the system. This can mean that it becomes more difficult for an organization to adopt to changing circumstances and evolve over time [Burnes & Fitter, 87:85].

Thus, Information Technology in manufacturing must be regarded as both a constraint and opportunity for providing organizational change [Gough & Stiller, 83:9]. The potential of AMT as a vehicle for organizational change has been recognized by some companies who have used technologies such as FMS as a catalyst to instigate organizational changes to achieve "Japanese-style" labour flexibility with multi-skilled shop-floor workers [Besant & Haywood 85]. But most companies studied have not been so enlightened, choosing instead "default" options, such that jobs and local organizational structures are left as they were with old technologies, with minimum levels of skill and responsibility and with highly differentiated structures respectively.

A curious paradox thus arises in many highly automated machine shops. Many tasks are limited to menial machine minding activities, yet the operators are still expected to intervene, and if possible correct, in the event of malfunction, this task requiring a high level of information processing and decision-making in an FMS. This latter point is substantiated by the tendency of firms to prefer highly-skilled personnel to man such systems [Scott, 85:121], but, as pointed out by Corbett [85] any system that does not provide the experience out of which operating skills can develop, will be vulnerable in those circumstances where human intervention becomes necessary. Given the need for continual remedial activity in many existing systems [Jones, 86], and the major effect that humans can have on system performance, by the manner in which they respond to operating and maintenance faults, it would seem imperative that the motivation and job satisfaction of operating and maintenance personnel should be considered carefully to avoid such apparent contradictions.

The "technology-centred" approach has a further critical, dysfunctional effect from the point of view of the user company's strategic objectives. Not only does system productivity depend directly on the skill of the operators, but the human element in AMT is also responsible for vital flexibility. Current market characteristics of increased part variety, demands for shorter delivery times and decreasing product life cycles, place great premium on the added flexibility offered by human involvement in the manufacturing process. There is thus the potential for a further paradox whereby a company can own exemplary highly automated factories and still lose its competitiveness, because the high capital investments already undertaken are in fact restricting the strategic flexibility of the company [Warnecke, 88:10].

It is therefore apparent that for an implementation of AMT to be completely successful there is a need for a holistic approach to the design or selection of AMT and its subsequent implementation whereby the technology is shaped by human and organizational considerations, with the objectives of ensuring the psychological well-being of the system operators as well as maximum organizational effectiveness. As indicated by the title of this thesis, it is this need for a new approach to the design and implementation of AMT, whereby both human and technical aspects are taken into account from the start of the design process, that has provided the key source of motivation for the research described herein.
Introduction

Many of the human problems of work design associated with FMS, as described above, are similar to those identified in the past in highly structured manufacturing environments, such as mass production flow-lines. In both cases jobs often involve low levels of control over work methods and pace and high levels of attentional and cognitive demand, resulting, in turn, in high levels of stress and low levels of job satisfaction and motivation. There is a substantial knowledge-base documenting the past efforts of psychologists, ergonomists and sociologists to "humanize" work of this nature, but much of this research suffers from fundamental limitations when considered with regard to the design and implementation of AMT. First, as implied above, most of the work has been concentrated on mass production environments, with little attention to the special features of batch production. Secondly, and most importantly, the bulk of the previous work in this area has been retrospective and has therefore not dealt with the design of the technology, which has been taken as "given". As has already been pointed out, this "determinist" line of thought does not apply to AMT, where there is a degree of choice as to how work is organized around the technology and how functions are allocated between machines and humans, although as has also been indicated, system design can also constrain work organization and job design options.

Various alternatives to the "technology centred" approach have been offered, of which the most notable is the so-called "human-centred" approach, pioneered in the UK by Rosenbrock and Cooley. To date the discussion relating to this new approach has been largely "philosophical" with few practical applications to enable a valid assessment of its applicability and practical benefits.

Largely in order to change this situation the author helped initiate a project in the Department of Mechanical Engineering of Imperial College, entitled "The Operation and Management of Flexible Human-Centred Turning Cells." This project, funded by the ACME Directorate (Application of Computers in Manufacturing Engineering) of the Science and Engineering Research Council and involving industrial partners from the machine tool, computer and control system industries, commenced in December 1986 and has a planned duration of 3 years. A demonstrator turning cell is being constructed as part of this project so that hardware and software designed using a "human-centred" approach can be evaluated and the effects of different task allocations between the cell operators and the various machines and computers can be tested.

The "human-centred" approach to the design and implementation of man-machine systems (which is, after all, what all implementations of AMT are) focuses on how humans are complemented by machines and vice versa. In essence, the system is designed in such a way that the operators deal with the qualitative, subjective judgements, that is, use creative discretionary skill peculiar to the human-while the computer, which is fast, precise, reliable but totally uncreative, deals with the primarily quantative elements. The human controls the machine rather the reverse, as is often effectively the case in existing FMSs, and the overall system is positively structured to build upon and enhance the operators intelligence and skills respectively. Thus in the demonstrator turning cell, the skilled cell operators manage all activities; they are not merely trouble shooters or machine loaders simply required to make the system work. It is assumed that the technology is not "given", but can be shaped by a framework of human-centred socio-technical design guidelines.
Introduction

The project at Imperial College complements ESPRIT Project 1217 (1199) entitled "Human-Centred CIM Systems." This project, which commenced in May 1986 and also has a planned duration of three years, involves partners in three countries. A West German group is developing a factory information system for production planning and control, whilst a Danish group is developing a human-centred CAD system. The British group, to which the author was seconded, is developing prototype turning cells, incorporating human-centred CNC lathes and associated automated workhandling equipment, to be installed at user sites for industrial trials.

The overall objective of the project is to develop a CIM solution for European industry, that is, for the small-and-medium-sized firms undertaking small batch work that make up the bulk of the metalworking industry. This solution must be readily applicable to companies that presently have a predominance of manually-operated machines and processes as they proceed from stand-alone applications of AMT to integrated systems. It must thus be suited to progressive implementation over an extended period in established factories as well as to the installation of new factories at green-field sites.

This thesis is a collation of the author's research as carried out within both the projects described above. The remainder of the thesis is divided into two parts. Part 1, consisting of Chapters 2 to 5, establishes the need for a new approach to the design and implementation of AMT, by describing the background to, and providing a more detailed analysis of, the paradoxes currently associated with the use of AMT. Such a discussion is necessary, since cogent arguments supporting a human centred approach feature only infrequently in the literature, and are then often characterised by esoteric discussions with little clear relevance for practising production and manufacturing system engineers.

Chapter 2 provides the context for the research by means of a description of the application of AMT, with particular attention to shop-floor applications in batch manufacturing, the form of production for which AMT is perceived to be particularly appropriate. The history of the application of computers in manufacturing is traced briefly before a description of the "state of the art" of AMT, as revealed by a study tour of over 30 leading European users and vendors of AMT, carried out by the author on behalf of the British Robot Association [Slatter, 87].

In Chapter 3 the disparity between "theory" of AMT, as outlined in Chapter 2, and "practice," as revealed by the aforementioned study tour and relevant literature, is discussed. The degree to which expected benefits are generally realized is examined, as are the problems experienced with the current generation of AMT, in particular human and managerial problems.

Chapter 4 comprises an investigation of the extent to which companies recognize and acknowledge the human aspects of AMT, that is, the implications of AMT for work organization and job design.

Chapter 5 concludes Part I with a discussion of the fundamental flaws in the "technology-centred" approach and the corresponding need for an alternative. As such, the continuing importance of the human element for the productivity and flexibility of shop-floor applications of
AMT is established and the negative consequences arising from not recognizing this fact are discussed.

Part II of the thesis, comprising Chapters 6 to 10, describes the development of a "human-centred" approach to the design and implementation of AMT and discusses its practical applications.

Chapter 6 commences with a brief analysis of past social science research into job design and work organization aimed at the "humanization" of work and discusses the fundamental limitations of much of this research when considered with regard to AMT. Various alternative approaches to the design and implementation of new technology are examined before the introduction of the concept of "human-centred AMT" and a brief description of previous and current research initiatives.

Chapter 7 describes a design framework for human-centred AMT, as constructed for use within the project at Imperial College. Mindful of the author's view that the human-centred approach should be regarded as a design and implementation "philosophy," rather than a set of rigid rules, a collection of broad design guidelines has been collated from recent work by the social science community in particular from the areas of socio-technical systems design, ergonomics and participative systems design. Particular effort has been made to make the framework "accessible" to, and hence applicable by, manufacturing and systems engineers. Also in this chapter a "parallel" design procedure for AMT, whereby human factors considerations are taken into account from the start of the design process is presented.

In Chapter 8 the practical application of this human-centred approach to design and implementation of a flexible turning cell is described. This turning cell is the shop-floor element of a human-centred CIM system currently under development at Imperial College. The broad design of this system is also examined in this chapter.

Whilst Chapter 8 concentrates primarily on the design of the jobs of the cell operators and the turning cell's mechanical hardware, Chapter 9 focuses on the design of the software for the turning cell computer, intended to assist the cell operators in their management of the cell. The author has developed an integrated software suite for process planning, part program management and cell production planning and control, all designed with the intention of facilitating the re-integration of planning, executive and monitoring tasks for the cell operators.

The thesis is concluded by Chapter 10 with an assessment of the potential of the human-centred approach for widespread adoption. Likely obstacles to the approach from both vendor- and user-side are considered, as is the growing evidence that the unjustified euphoria with respect to technological "panaceas" is being displaced by a more common-sense approach, in which the importance of the human aspects of AMT, and, accordingly, the need for an appropriate approach to design and implementation is increasingly recognized.

In an Appendix, the author's initial efforts to apply a human-centred approach in an industrial setting are described and lessons from this experience for future research are outlined.
2. Advanced Manufacturing Technology -
The Application of Information Technology
in Batch Manufacturing

In describing the technological context for the author's research, the objectives of this chapter are two-fold; first, to provide a brief historical review of the application of information technology in batch manufacturing and, secondly, to describe the current stage of development of so-called "Advanced Manufacturing Technology." (AMT)

To this end, the need for new technological solutions, such as AMT, is established by means of a description of the nature of batch production and associated problems in the light of current market imperatives. To clarify the meaning of the term AMT, the history of the application of computers in manufacturing is outlined, this showing clearly the trend towards increasing integration of both manufacturing functions and data. The "state of the art" of AMT is then described, with particular attention on shop-floor applications of AMT, so reflecting the key area of interest from the point of view of the research to be described in subsequent chapters.

2.1 The Nature and Problems of Batch Production

Brödner [86(c):2] describes the key change underway in the markets for consumer goods and, consequently, for capital goods, as a shift away from steady expansion to "stagnation." The comparatively low growth rate of the dominant markets for high value-added goods, that is, the USA, Japan and Western Europe, is causing a change in the nature of competition in many industries with strategies based on price competition and market share optimization being increasingly replaced by strategies focusing on the displacement of competitors.

Under the new market conditions of increased competition by displacement, customers have greater power to demand products adapted to their specific needs, which is leading to an increasing variety of product types and shorter product life cycles. Accordingly, the ability to adapt products to match customer requirements, as well as the guarantee of short delivery times, are joining price and quality as key order-winning criteria in the metalworking industry [New, 85].

Importantly, much of this market-induced pressure is being transmitted by larger companies, competing in international markets, on to their suppliers and sub-contractors. A notable contemporary example is the attempt by major producers in the European automotive industry to achieve Japanese-style "Just-in-time" or "stockless" production by "encouraging" their suppliers to deliver smaller batches more frequently, at reduced cost with improved quality [Slatter, 84].

Clearly, the effects of the changing market on a particular company will vary from one industrial sector to another, and from country to country, and the measures taken to deal with these effects may be very different. It is possible, however, to identify some typical objectives set for the production function in order for it to meet new performance requirements in terms of cost, quality, delivery and responsiveness, as shown in Figure 2.1 [Bessant & Haywood, 85] [Ingersoll, 85:21].
Achieving a combination of such objectives poses a particular problem for those companies engaged in batch production, the most common form of production in the European metalworking industry and responsible for no less than 70% of output from the engineering sector in the UK [Gallagher, 80].
As highlighted by Warnecke [84] Lockyer [84] and Bessant & Haywood [85], batch production is typically associated with a number of significant problems and difficulties;

- Machine utilisation is often very low. Non-operative time may be as much as 90%, with parts waiting to be loaded onto different machines or waiting for a particular machine to finish the batch it is working on.

- Manning levels are often high, because of the need for indirect labour engaged in the handling and transport of materials and in the monitoring of work-in-progress (WIP) etc.

- The queuing problem of parts waiting to be machined means that there is a high level of WIP inventory, which can tie up a significant proportion of a company's working capital on the shop-floor.

- The queuing problem means further that the overall manufacturing lead time is long, which has an adverse effect on the company's delivery performance.

- To support the high part variety/long lead time production pattern, a high level of raw materials stock must be carried.

- This production pattern also means that firms will often try to economise by running longer batches than required to meet orders, this "production for stock" serving to tie up yet more working capital in finished goods stock.

- The overall complexity of the production control task, caused by having to track each job through each machining stage, presents data collection and processing problems that are often so great that the control task is abandoned and all action is taken on a "fire-fighting" basis.

A brief comparison of the above list with the typical objectives for the production function, as shown in Figure 2.1, provides ample indication as to why companies employing "traditional" techniques in batch production are likely to experience particular difficulty in responding to new market requirements.

Given the immense importance of batch production, the need is apparent for new technologies and techniques that can improve its efficiency. However, unlike flow-line production, where the manufacture of large volumes of a standard product allows and justifies the extensive use of automation, such as transfer- lines in car assembly and engine plants, the flexibility demanded by the wide part variety and low production volumes characteristic of batch production has, until comparatively recently, prohibited the widespread use of automated equipment. Another reason why small batch manufacturing has been largely "left behind" in the application of automation is the lack of commercial and technical influence of the small, less unified companies typically engaged in batch manufacture when compared to, say, larger companies in the automotive sector. Such companies have been able to dictate, to a great extent, the type of
equipment developed by the machine tool industry, which is then designed for quite different production requirements than those typical in a small batch manufacturing company.

Most of the difficulties of batch production and, in particular, of the associated functional factory layout, where equipment is grouped together accordingly to the function it carries out, have long been recognized [Gallagher, 80]. The most widely-known means for dealing with some of these problems has been the application of Group Technology (GT). Group Technology is an approach aimed at rationalizing small-to medium-batch production by capitalizing on the similarities that exist between (primarily) component parts.

The essential feature of GT, as applied to component parts, is the formation of part families on the basis of design and/or manufacturing similarities [Gallagher & Knight, 86]. These part families can then be used to improve efficiency in product design, production engineering and cellular manufacturing [Opitz & Wiendahl, 71], [Allen, 73], [Burbidge, 75].

As can be seen from Figure 2.2, in a cellular manufacturing system the production equipment is physically divided into manufacturing cells, each designed to produce a particular part family or range of part families. In comparison to the functional layout, it can be seen that the material flow is greatly simplified, with obvious opportunity cost savings due to reduced delays [Lockyer, 84:169].
In addition to benefits such as reduced set-up times and reduced materials handling costs, increased job satisfaction has also been used as a factor in the promotion of GT [Williamson, 72]. This is because in a number of practical applications of cellular manufacturing it has been possible to increase the autonomy of shop-floor personnel by devolving certain planning activities to the cell operators [Craven, 74].

However, neither the technical nor human case has been without criticism [Leonard & Rathmill, 77]. Nevertheless, despite the apparent limitations and limited adoption [Hyer, 84], GT has recently undergone something of a renaissance due to its close association with new "flexible" automation technologies which, it is hoped, will improve the efficiency of batch production [Black, 83] [Shunk, 85].

As implied earlier, past efforts to improve manufacturing efficiency via technological or organizational means have been concentrated on the high volume, low variety end of the production spectrum, primarily in the automotive industry. Here, the combination of the technology of dedicated transfer-lines and the organizational concepts of Taylor, Ford and Sloan have led to dramatic improvements with respect to costs, plant utilization etc. However, such automation involves a very high capital investment which can usually only be justified in mass production. Furthermore, transfer lines are "inflexible" in the sense that they cannot tolerate significant variations in part design. It is always difficult and expensive - if at all possible - to reconfigure a "hard" automated system to cater for another product.

The nature of small-and medium-volume, high variety batch production is such that the volume of work is not sufficient, and the part variety too great, to make automation in the form of transfer-lines a cost-effective option, yet the volume is often too big to be handled by stand-alone machine tools in a functional layout without encountering the problems described earlier.

But it is now believed that manufacturing technology has advanced to a point where the efficient automation of batch production is now possible [Kaplinsky, 84:70]. New "flexible" manufacturing technologies, commonly grouped under the umbrella term Advanced Manufacturing Technology, or AMT, are portrayed as "combining the low unit cost benefits of mass production plant with the flexibility of small batch, general purpose machinery" [NEDO, 85].

In a later section the "state of the art" of AMT will be described in some detail, but it is instructive to first trace the recent development of manufacturing automation, to identify the trends that have led to this apparent breakthrough and that may yet guide the path of future development.

2.2 Towards Integrated Manufacture

In analysing the development of manufacturing automation the discussion will be limited to the application of electronics-based technologies, since it is the convergence of control, data processing and data communications capabilities within electronics technology that has provided the foundation for the accelerating diffusion of automation technologies in recent years. AMT is thus defined here as the application of Information Technology (IT), that is, technology involving the electronic processing of information, to batch manufacturing activities.
Arguably the key single innovation in the post-war development of manufacturing automation was the introduction of numerical control (NC). The origins of NC lay in the problems experienced, particularly in the aerospace industry, in the manual machining of complex contours to increasingly demanding quality and consistency requirements. Research began in the USA in the mid-1940s to develop an automatic control system to achieve greater product consistency by replacing human control with a system that would always "operate" the machine tool in exactly the same way. After the demonstration of the first NC milling machine in 1952 the initial diffusion was very slow, primarily due to problems with control system reliability and due to time consuming and complex process of producing paper tapes, the medium used to carry and store part programs. In practice the preparation of tapes required specialist office-based programmers and the heavy data requirements of complex programming systems necessitated the uses of costly mainframe computers. This limited the more general use of NC technology, particularly in manufacturing settings where precision was less at a premium than in the aerospace industry [Wall & Kemp, 87].

During the 1960s and 70s the development of NC followed that of electronics and data processing technology in general, with improving performance and reliability and decreasing hardware cost and size. These developments made possible the replacement of 'hard wired' NC controllers with the computer-based control systems of computer-numerically-controlled (CNC) machine tools. This effective decentralization of computing capacity, by integrating a powerful computer with the machine tool, served to increasingly simplify the part programs fed into the machine controller and allowed for a range of programs to be stored and edited rapidly at the machine. This facility for making program changes at the machine greatly accelerated the process of "tape proving" and program optimization. Furthermore, the 1970s saw microcomputers replacing minicomputers as the basis for the low-cost CNC systems, which helped bring down the price of CNC machine tools and, accordingly, extended the market for such machine tools to small-and medium-sized companies.

The fundamental "breakthrough" afforded by NC/CNC, was the use of a computer in place of an operator for direct control of manufacturing equipment. In the words of Kaplinsky [84:63], Information Technology, in the form of NC, served to "reduce the actions of machines to a common currency."

Initially, NC and CNC were only applied to the control of machining processes, but, as will be seen later, computer control has since been applied to a wide variety of manufacture activities, for the control of materials handling, transportation and storage equipment etc. All such applications of IT in manufacturing can be described as examples of direct applications, where the information storage, manipulation and retrieval capabilities of IT are used to distribute information for the control of other equipment which physically transforms or transports material [Wall & Kemp, 87:4]. Notably, it is the programmability of the equipment, and corresponding ability to deal with throughput variety and low changeover costs relative to hard automation that leads to its description as flexible automation. It is supposed that AMT will overcome the efficiency-flexibility "trade-off" that has made it impossible for many batch producers to capitalize on the low costs of production offered by hard, that it, "inflexible" automation. The hoped-for capability of AMT to satisfy hitherto conflicting requirements for increasing productivity and increasing flexibility, gives rise to the concept of economies of scope. As outlined by Bessant & Haywood [85:53], the
essence of this idea is that the flexibility of AMT undermines the traditional advantages of economies of scale, so allowing a greater variety of products to be manufactured at the same cost, or a given variety at reduced cost.

Accordingly, AMT is widely regarded as making automation feasible in a batch production environment and may yet lead to a re-orientation of mass production industry towards customized products and more frequent design changes [Roobeek & Abbing, 88].

Another essential feature of computer control is that it enables communication with other computers and computer-based control devices, so opening up the possibility for the integration of various machines into multi-machine production systems. An example is direct numerical control (DNC), a term that has come to be used to describe the use of a computer to automatically download and upload part programs to/from the CNC controls of a group of machine tools. DNC is often portrayed as a "first step" towards a so-called flexible manufacturing systems (FMS) [Greenwood, 88:104]. An FMS is typically defined as consisting of a number of computer-controlled machine tools connected to a DNC computer, with integrated materials handling and transportation devices, such as robots or automated guided vehicles (AGVs), the activities of the complete system being co-ordinated by centralized computer control. The machining stations are capable of processing a variety of parts within a given family, without significant human intervention being needed to reconfigure the machines to the different component operation requirements. This enables a number of parts to be processed on different stations simultaneously rather than in batches. The integration of processing and handling activities and thereby the absence of batching and handling delays is expected to give lead times appreciably lower than typically possible in batch production using "traditional" techniques, with associated reductions in work-in-progress etc. FMS is a focus of particular interest in this thesis, since it is regarded by many as a "microcosm of a portion, at least, of the future computer-automated, optimized and integrated factory" [Merchant, 85:93].

Not only does the "core" of information technology allow direct applications to be integrated in the form of, say, FMS, but it also enables the integration of direct and indirect applications, where IT is used to store, manipulate and analyse data to support the management of production. These applications include the typically office-based activities of computer-aided design (CAD) and computer-aided production planning and control (PPC), where the main contribution of computers is in information handling, as distinct from machine control. This level of integration is commonly referred to as computer integrated manufacturing (CIM). Kaplinsky [84] views CIM as the "ultimate prize" of what he identifies as the trend towards the gradual automation and integration of discrete activities within what he terms the design, manufacturing and co-ordinating "spheres". This trend is shown diagramatically in Figure 2.2 overleaf.

IT can help integration in a number of different ways, for example, by enabling the integration of different machining operations on one piece of equipment, by enabling machining and materials handling activities to be integrated in, say, an FMS, or by enabling the integration of direct and indirect applications of AMT through linking, say, CAD and NC part program generation.
Nevertheless, current progress towards CIM is limited, as discovered by Ingersoll Engineers [85], who found that few companies had achieved any worthwhile integration to this extent. This reflects the fact that achieving the degree of automation expressed by CIM is an enormous and difficult task and for most companies CIM represents a goal to be attained rather than a reality.

A term commonly associated with the present stage of development is that of "islands of automation," which describes a situation similar to that shown in Figure 2.2 (c). The problems associated with the current situation are well expressed by Dempsey [84:71], with respect to FMS;

"FMS is likely to be the leading edge of manufacturing modernisation and will take its place in the factory amongst much plodding and mundane machinery. Its capabilities - fast response, low work-in-progress, variety of products so highly acclaimed, may well be an embarrassment. Supplies may not arrive fast enough, products may swamp outlets, information demands may not be met. It could become a racehorse broken in spirit by placing it in a field of old nags."

In other words, whilst AMT to date, as exemplified by FMS, has improved the performance of small, self-contained areas within enterprises, the overall effect on company performance has been less than could have been achieved had a strategic, company-wide approach been adopted [Ingersoll Engineers, 85: 34].

Figure 2.3 Different Stages of Automation (Kaplinsky, 84:27)
It is widely perceived that the latest developments in IT, particularly in the field of data communications, will provide the means by which to overcome such problems, by integrating the flow of information to aid the overall control of the manufacturing process. This perception has precipitated the current avalanche of information relating to CIM, which, in turn has led to a profusion of definitions and interpretations as to the scope of CIM. The great majority of definitions focus on the integration of computers and machines, with the result that "integrated" systems are very rarely viewed from the sense of integrating people and machines [Boaden & Dale, 86]. As Alic [84] warns;

"an integrated production system implies integrating design and manufacturing. It also implies, or should imply, integrating people more effectively into manufacturing organizations. Both aspects - successful integration of design and manufacturing, successful integration of people and machine - affect the competitiveness of firms and industries .....(but) computer-integrated manufacturing has become the catch-phrase, sometime seeming to imply getting the people out of the system because they are sloppy, unpredictable, inefficient".

It is a sad fact that CIM and its constituent technologies are widely associated with the total automation of the unmanned factory. The misguided nature of this viewpoint will become apparent in subsequent chapters, though it should be pointed out that many authoritative commentators are already much more circumspect in their analysis of the path to integrated manufacture and the associated role of computers. Ingersoll Engineers [85] and Warnecke [88] stress the "philosophy" or "strategy" of integrated manufacture respectively, where computers are recognized as an enabling technology and the importance of organizational change to accompany technological change is emphasised. This reflects the belief in some quarters that the key benefits of computers derive from the use of their integrative capabilities to facilitate organizational integration, that is, a belief that the system building potential of AMT is considerably more important than the qualities of its physical hardware [Child, 87:107].

The importance of organizational integration, in helping to reduce organizational complexity and so reduce the cost of "non value-added" activities, is highlighted by [Parnaby 87:1]. The ad-hoc development and resultant complexity of understanding and controlling the manufacturing process, typical of all but the smallest of firms, tends to result in these non value-added activities, such as the use of progress-chasing staff to gather up-to-date information to guide production control decisions in the absence of adequate planning and control systems, or the need for excessive layers of indirect labour and service overhead staff, simply for information processing and transmission. This is a particular problem in batch production, where perhaps half or more of costs go towards simply managing the flow of production. Here, the use of computers to provide, for example, accurate and timely information on the state of production can help obviate the need for extensive and expensive clerical staffs. The significant contribution to company performance that can be made by organizational changes alone is shown by those companies that have derived substantial benefits from correcting organizational inefficiencies highlighted by AMT feasibility studies without needing to subsequently implement the technology [Bessant & Haywood, 85:50].
Nevertheless, the "philosophy" of integrated manufacture and the supporting role of computers as an enabling technology is all too often lost sight of, and CIM is frequently presented as an end in itself. Clegg [88:27] notes the common assumption that "all roads lead to CIM as if according to some evolutionary imperative," an attitude that is reflected in the technical press by the use of terms such as "automate or liquidate" or "sink or CIM?" This is a good point at which to step back from such speculation and consider the current "state of the art" of AMT to develop a clearer understanding of the different ways in which information technology is applied in manufacturing, to so indicate the degree to which CIM is currently realizable.

2.3 Advanced Manufacturing Technology - "The State of the Art"

For an assessment of the current state of development of the various forms of AMT, a useful conceptual framework is provided by a "CIM" model, such as that developed by Scheer [87], which is shown in Figure 2.3. This model, chosen for its particular clarity, is divided into two distinct halves. The right-hand side of the model comprises the applications of AMT that can be grouped under the broad definition of computer-aided design and manufacturing (CAD/CAM), that is, those applications associated with the creation and manipulation of data relating to a product, and the subsequent use of this data in the manufacturing of this product. The left-hand side of the model shows the applications of AMT that can be grouped under the definition of computer-aided production planning and control (PPC), that is, those applications relating to the planning and control of the flow of production.
2.3.1 Computer-Aided Design (CAD)

As shown by Figure 2.5 below, current CAD systems can be used in four distinct phases of the design process.

Figure 2.5 The Design Process Using CAD  (Adapted from [Groover, 87:712])

<table>
<thead>
<tr>
<th>The Design Process</th>
<th>Computer-Aided Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recognition of Need</td>
<td>Software Functions</td>
</tr>
<tr>
<td>Problem Definition</td>
<td>Geometric Modelling</td>
</tr>
<tr>
<td>Synthesis</td>
<td>Engineering Analysis</td>
</tr>
<tr>
<td>Analysis &amp; Optimization</td>
<td>Design Review &amp; Analysis</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Automated Draughting</td>
</tr>
<tr>
<td>Presentation</td>
<td></td>
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<tr>
<td></td>
<td>Hardware (Typical Configuration)</td>
</tr>
<tr>
<td></td>
<td>CPU</td>
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<tr>
<td></td>
<td>Secondary Storage</td>
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<tr>
<td></td>
<td>Workstation</td>
</tr>
<tr>
<td></td>
<td>Output Devices</td>
</tr>
</tbody>
</table>

**Geometric modelling** describes the use of a CAD system to develop a mathematical description of the geometry of an object, so allowing the user to display an image of the model on a graphics terminal and then to perform certain graphics operations on this model, such as magnifying a particular feature. Different types of geometric models feature in current CAD systems. Two-dimensional (2D) models are adequate for, and primarily associated with, automated draughting systems, whilst more complex three-dimensional (3D) models allow a wider range of operations to be carried out on the model, including a variety of genuine design activities.

After the geometric modelling of a particular design alternative, some form of engineering analysis, such as finite element analysis or model analysis, can be carried out using a CAD system [Besant & Lui, 86: 180-212]. Importantly, the software used to carry out such activities, often
grouped under the term computer-aided engineering (CAE), greatly simplifies time consuming and complex activities, which would otherwise often be over-simplified or even omitted from the design procedure [Groover, 87:714].

Following engineering analysis, the CAD system can be used in various design evaluation and review procedures, such as automatic dimensioning or kinematics routines for analysing mechanisms.

The final area where CAD is currently used in the design process is for automated draughting, where the CAD system can produce highly accurate and consistent drawings very quickly. It is typically claimed that a CAD system can increase productivity in the draughting function by five-fold when compared to manual draughting [Groover, 87:716]. Not surprisingly, CAD systems are usually justified on the basis of drawing office efficiency, though, as discovered by Leonard [88:15] users subsequently regard the major benefits as arising from improved quality of design, faster quotations and improved parts lists, that is, benefits from data processing capability rather than from draughting efficiency.

Most CAD software vendors offer the facility for so-called CAD/CAM, where CAD is extended to incorporate NC part program generation (which is then, confusingly, termed computer-aided manufacture (CAM)). This is promoted on the basis of increasing the speed of program generation and reducing errors by permitting the direct uses of CAD geometry in the programming procedure.

A variety of different hardware configurations for CAD systems are encountered in practice. Figure 2.4 shows a minicomputer based workstation, which is increasingly the preferred hardware for more powerful 2D and 3D systems, although there has been rapid growth recently in the availability of low-cost 2D draughting packages running on PC-type microcomputers [Grausemeier, 87] [Groover, 87:718].

### 2.3.2 Computer-Aided Process Planning (CAPP)

Broadly speaking, the process planning procedure translates product design requirements into technical manufacturing requirements and the typical procedure and data required are shown in Figure 2.6. As noted by Parnaby [87:139] it has been estimated that in conventional manual process planning up to 85% of the time required to produce a plan is spent looking up data, cross referencing, calculating and carrying out essentially clerical activities, such as preparing standards documents and tables. Accordingly, there is considerable scope for computer assistance in accelerating this data retrieval and processing exercise.

The particular functions carried out with computer assistance in the process planning procedure depends on which planning approach is adopted;

(a) Retrieval (variant) process planning, or
(b) Generative process planning.
**Retrieval** - type CAPP systems are based on the principles of Group Technology and parts classification and coding, as described briefly earlier. Once a range of parts has been properly classified and coded, a standard process plan is created for each part family and then stored on the computer, ready for retrieval for the process planning of a new part within this family. If the manufacturing requirements of a new part differ slightly from those listed for the part family then the user edits the standard plan accordingly. This capacity to alter existing process plans leads such systems to be often described as variant CAPP systems [Gallagher & Knight, 86:189].

Despite the fact that most commercially-available CAPP packages are based on a retrieval procedure, the variant method is perceived to suffer from a number of significant problems, the most important being the need for a potentially massive database to accommodate stored plans, and the difficulty of maintaining consistent editing practices.

This has led to increasing efforts to develop *generative* process planning packages which, instead of retrieving and editing an existing plan contained in a database, create a process plan by use of logical procedures similar to those used by a human process planner. Various attempts
have been made in the field of Artificial Intelligence to develop Expert Systems for generative process planning, where process plans are to be created without significant human involvement and without a stored set of predefined standard plans [Srinivasam & Liu, 84:179-193].

CAPP packages are typically justified on the basis of increased productivity of process planners, as the result of more rapid data retrieval and documentation, though generative process planning systems are often promoted with dubious arguments about the shortage of competent human planners [Groover, 87:725]. The author's own experience indicates that the most significant benefits result from the increased consistency and legibility of plans, together with faster quotations resulting from the integration of CAPP software with other software, such as for estimating.

By the definition implicit in Figure 2.4, CAPP includes the preparation of part programs for computer-controlled machine tools or handling devices. Such part programs can be generated by a variety of methods which will be investigated in detail later in the thesis.

2.3.3 Computer-Aided Production Planning and Control (PPC)

Expressed in simple terms, the key objective of the production planning and control function is "the efficient and economical execution of customer orders" and is therefore concerned with:

- knowing at all times what delivery dates can be realistically offered, taking account of existing commitments,
- planning future capacity to meet sales opportunities,
- ensuring the right materials are ordered
- ensuring that work-in-progress proceeds through the manufacturing stages in the right sequence,
- providing flexibility to meet changing customer requirements or priorities without incurring excessive inventory [Corke, 85:1].

Various models have been offered for the different activities involved in the above functions of production planning and control, notably by Groover [87:731], Parnaby [87:131] and Scheer [84:138]. Figure 2.7 overleaf is a composite of the principal functions featured in these models, as appropriate to a company engaged in batch production.

Clearly a wide range of activities are involved in a complex process, and many of the activities are, in themselves complex. When all are operated manually, the overall success of the system is dependent on the co-ordination of the work of many people, typically in different locations. As pointed out earlier this task has proven beyond the capability of management in many companies, resulting in a combination of plant capacity problems, sub-optimal production scheduling, long
manufacturing lead times, inefficient stock control and low work-centre utilization [Groover, 87:729].

The use of computers in a PPC system offers two key benefits. First, individual activities may be performed more effectively through, for example, more rapid data retrieval, or faster production of documentation. Secondly, the use of computers compels a clear definition of how each activity is to be carried out, which makes it easier for management to understand the operation of the different functions and the system as a whole. This, in turn, makes it easier to ensure that the different functions are operated consistently. In practice, a wide variety of different configurations of PPC system are found, with only some or all of the activities described above being executed with computer assistance.

The most widely publicised application of computers is in Materials Requirements Planning, or MRP. MRP is the means by which future requirements of material, whether made in-house or bought in, are calculated for each stage of manufacture. In essence, the product quantities in the master schedule are multiplied by the unit quantities of each material and component, as listed in bills of material, product specifications etc. to give the gross material requirements to make the products. Existing stock and quantities already on order are then deducted to give net
requirements which provide the basis for raising orders on the factory and outside suppliers. Clearly this activity is very demanding in terms of data processing requirements, which explains why MRP is synonymous with the use of computers in production planning and control.

Recently there has been a rapid increase in the availability of "standard" PPC software packages, usually in modular form, that can be implemented in phases and can be configured readily to suit a particular company's specific needs. Despite the fact that a prospective user can usually see a "standard" package in use in other companies before deciding to buy, some companies still prefer turnkey systems or, in some cases, to develop their own software.

There is a similarly wide range of current options for hardware, ranging from mainframe-based systems, through minicomputer-based systems to increasingly popular installations utilising low-cost PC-type computers [Corke, 85].

**2.3.4 Computer-Aided Manufacture (CAM)**

As has been pointed out above, the acronym CAM is often used to refer simply to part program generation. In this section, however, the broader definition implicit in Figure 2.4 will be adopted, where CAM also includes the computer control of manufacturing equipment such as machine tools or robots.

Mindful of the "traditional" problems of companies engaged in batch production, and of the current market requirements in the metalworking industry, a variety of basic objectives for the implementation of new manufacturing technology present themselves -

- improved machine utilisation - reduced materials handling time and costs,
- reduced work-in-progress levels,
- reduced raw materials and finished goods stocks,
- reduced lead times,
- reduced direct and indirect labour costs.

Experience has shown that there are a number of different ways of configuring a manufacturing system in order to achieve one or more of the above objectives, by combining different elements and technological options to suit particular purposes. The appropriate use of technology depends on the "flexibility" required of the system.

As shown by Figure 2.8 (a) overleaf, the term "flexibility" has a variety of different possible interpretations each of which, in turn, is influenced by a number of different factors. The most widely-used definition relates to the ability of the manufacturing system to deal with a variety of different parts or products, that is, *product flexibility*. 
Further definitions include *production flexibility* which is a measure of the extent to which the equipment comprising a particular system can be reconfigured for the production of completely new parts or products; *routing flexibility*, which refers to the ability to produce a given set of parts by various different routes, so providing a measure of the system's performance in the event of, say a machine breakdown; and *volume flexibility*, which relates to the ability to operate a system profitably at different production volumes [Browne et al, 84:114-117] [Slack, 88].

Figure 2.9 below shows the different areas of application for various forms and structures of programmable manufacturing automation classified according to their relative productivity and product flexibility. Figure 2.10 shows how increasing productivity is typically associated with an increasing integration of functions and decreasing scope for human intervention.

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**Figure 2.8 a) Factors Determining the Required Flexibility of a Manufacturing System**

<table>
<thead>
<tr>
<th>Key Parameters in the Planning Process</th>
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<tbody>
<tr>
<td>- Product life cycle</td>
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<tr>
<td>- Product variety &amp; volumes</td>
</tr>
<tr>
<td>- Seasonal demand variations</td>
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<tr>
<td>- Workpiece size range</td>
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<td>- Predictability of machining processes</td>
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<th>Flexibility</th>
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<tr>
<td>Product flexibility</td>
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<tr>
<td>Production flexibility</td>
</tr>
<tr>
<td>Volume flexibility</td>
</tr>
<tr>
<td>Routing flexibility</td>
</tr>
</tbody>
</table>

- Current Products
  - Product life cycle
  - Product variety & volumes
  - Seasonal demand variations
  - Workpiece size range
  - Predictability of machining processes

- Future Products
  - Product life cycle
  - Product variety & volumes
  - Seasonal demand variations
  - Workpiece size range
  - Predictability of machining processes

- Planning information with high degree of uncertainty
- Planning information with low degree of uncertainty
- Exact planning information
Figure 2.8  b) Manufacturing System Features Determining System Flexibility

Figure 2.9 Different Choices of Manufacturing Technology (Adapted from [Kief, 86:5.1])

- Number of Different Parts
- Transfer Lines
- Special-purpose Machines
- Dedicated Manufacturing Systems
- Flexible Transfer Line
- FMS
- FMC
- Flexible Manufacturing Systems
- Machining Centre
- Machining Centre
- FMC
- Flexible Manufacturing Systems
- Machining Centre
- Machining Centre
- FMC
- Flexible Manufacturing Systems
- Machining Centre
- Machining Centre
- FMC
- Flexible Manufacturing Systems
- Machining Centre
- Machining Centre
- FMC
- Flexible Manufacturing Systems
- Machining Centre
- Machining Centre
- FMC
- Flexible Manufacturing Systems
The CNC Machine Tool is the basic building block of any modern "flexible" manufacturing system and computer-controlled machines are now available for a wide variety of machining processes in the manufacture of prismatic, rotational and sheet-metal components. An important development has been that of machining centres, which are machine tools capable of carrying out a number of different machining operations, typically milling and drilling, at a single workpiece set-up. The provision of automatic tool changing provides the capability for machining for extended periods without a need for continuous human intervention. A more recent development has been that of turning centres. That is, lathes with driven tooling for milling and drilling operations, so that second operation machining can be carried out on turned parts without having to remove the component from the machine. As with machining centres the integration of operations can improve quality by reducing the number of set ups for a particular component, which also reduces lead-times, and can simplify material flow and production control by reducing the number of machines on which a particular part has to be processed.

A Flexible Machining Cell (FMC) is generally understood to be a general-purpose CNC machine tool, such as a machining centre, interfaced with automated materials handling equipment. The provision of the latter, by extending the period for which the FMC can operate autonomously, enables an FMC to achieve higher levels of utilisation than a stand-alone machine.
Figure 2.11 Flexible Machining Cells

a) For Prismatic Parts

b) For Rotational Parts
There are a number of different opinions as to what constitutes a Flexible Machining (or Manufacturing) System (FMS), but a typical definition is that of "several general-and special-purpose machine tools and/or flexible machining cells, interlinked by an automated materials handling system in a way that enables the simultaneous machining of different workpieces, which pass through the system along different routes under real-time computer control." As such, FMS represents the most complex type of manufacturing system regarded as suited to batch production, and the relationship between its constituent elements is shown schematically in Figure 2.12.

Figure 2.12 Basic Elements of an FMS
Usually workpieces are loaded and unloaded "off-line" at a central location within the FMS. In the case of an FMS for the machining of prismatic parts, the workpieces are typically transferred between the machining centres on pallets, which can be carried on a pallet conveyor or, as is increasingly the case, by wheeled carts. A number of different types of cart are in use in existing FMSs, as shown in Figure 2.13 below.

Once a part is loaded into the materials handling system, it is automatically routed to the particular workstations required in its processing. Not only may the routing be different for each different workpiece type, but the operations and tooling required at each workstation may also differ. To be fully productive, the FMS must have sufficient workpieces available in advance of their being required at a workstation. In the case of a pallet-based materials handling system, the required storage can take a number of forms, such as pallet carousels for each machine, or pallet pools, as shown in Figures 2.11 (a) and 2.13 (a), or a centralized automatic storage and retrieval system (AS/RS) as shown in Figure 2.13 (b).

Figure 2.13
a) FMS Utilizing a Rail Cart (prismatic parts)
c) FMS Utilizing Robots and a Conveyor (rotational Parts) [Greenwood, 88:26]
The machine tools in an FMS are typically programmed via a DNC computer, which is responsible for downloading and uploading part programs as required. This computer is also typically used to collate status and performance information for the individual machine tools and passes this on to the computer used for overall control of the FMS.

The position of FMS and its computer control system within a hypothetical "CIM" architecture, is shown in Figure 2.14 below. This diagram shows the physical network configuration necessary to connect the various computer-aided functions and computer-controlled devices described so far. The actual information flow between the different elements is shown in simplified form in Figure 2.15.

---

**Figure 2.14 Model CIM Architecture**

![CIM Architecture Diagram](image)

**Key:**
- LAN - Local Area Network
- MIU - Machine Interface Unit
- PC - Personal Computer
- CNC - Computer-Numerically Controlled
- PLC - Programmable Logic Controller

---
The distributed computer system shown in Figure 2.14 reflects the trend towards such a structure, where the various system components are linked by means of Local Area Networks (LANs). However, the task of integrating a large number of computers and computer-controlled programmable devices in this fashion is a formidable exercise in data communications, as will become apparent from the next section.

### 2.3.5 Data Communications

The computer control system and corresponding communications network are arguably the two most important and also the most complex technical aspects of any highly automated manufacturing system [Greenwood, 88:158]. Certainly it is recent developments in the general area of data communications that have both enabled and precipitated the current debate about CIM.

For many of the connections between computers or computer-controlled devices serial communications links are still the most widely used and understood. This is especially the case at the lower levels of a manufacturing control system for, say, communication between a cell
computer and the cell's machine tool controllers. Serial communications links are viable when there is a limited number of devices that need to be connected, but when there are many computers or machines to connect, then point-to-point communications of this nature rapidly becomes unmanageable. *Local Area Networks*, have emerged as the preferred means of connecting a large number of computers and machines together, as is typically the case in a highly automated manufacturing system. The resulting communications network typically features one of the three common network topologies shown in Figure 2.16.

As pointed out by Groover [87:768-769] the bus network is widely perceived as the most appropriate for a factory LAN for various reasons. First, the main transmission line of the network can be laid out in a way that corresponds closely to the layout of the machinery in the factory, thus simplifying installations of the communications system. Secondly, new devices can be connected to the network without major disruptions to the other devices, and, thirdly, the bus network is generally easier to repair and maintain than the other structures shown above.

However, a major difficulty presents itself in the implementation of a LAN in manufacturing surroundings, namely that the various computers and computer-controlled devices are not always compatible in terms of their ability to communicate with one another, that is, they often obey different communication protocols.
Accordingly, substantial efforts have been made to develop protocol standards to enable equipment from different vendors to communicate reliably and efficiently, notably in the form of the Manufacturing Automation Protocol (MAP) and Technical and Office Protocol (TOP), both of which are based on the International Standards Organization's, Open System Interconnection (OSI) reference model [Da Silva, 86:123].

An essential point that must be made before concluding this section is that while such developments in data communications enable the linking of various computers and computer-controlled machines, integration, in the true sense of the word, is not yet possible [Leonard, 88:18]. That is, whilst a link between, say a computer-aided design system and a production planning and control system may allow the transmission of a parts list in a predetermined format, it is not yet possible for the users of such systems to interact with each other, such that the user of one system can access, interrogate and alter data on another. As pointed out by [Harrison et al [86] this is unlikely to be possible in the foreseeable future due to incompatibility of databases, database management systems etc.

Accordingly, it is a somewhat liberal use of terminology by which the architecture shown in Figure 2.14 can be described as a computer integrated manufacturing system.

2.3.6 Visions of the Future

In common with their popularity in the technical press, CIM enabling technologies are the subject of considerable research. A focus for particular interest is Artificial Intelligence (AI), an enabling technology widely expected to have a significant long term impact on the development of manufacturing automation.

The key notion underpinning AI, namely that of enabling computers to carry out a measure of intelligent problem solving, has led to the concept of intelligent or knowledge-based manufacturing systems, in which "intelligent" machines carry out ever more complex manufacturing, assembly and inspection tasks. To date, however, the most widespread use of AI techniques has been in so-called Expert Systems, which can be defined as;

"a computer system reflecting the decision-making process of a human specialist by embodying organised knowledge, factual and heuristic, concerning a specific area of expertise, and frequently operating as a skillful, cost-effective consultant." [Milner, 85:15]

This definition points to the expected benefits of Expert Systems in that they do not suffer any of the "problems" of human experts with respect to experience, relocation or tragedy. Expert systems are portrayed as consistent, reliable, not requiring payment, and a means by which to make expensive expertise available to less skilled individuals. As documented by Kempl [85] and Rogers & Williams [88], Expert Systems have been applied in a wide variety of uses, including process planning, job shop scheduling and operations sequencing in machining cells.
Despite the research nature and limited success of many such applications, major UK and European projects have been initiated, aimed at the increased applications of AI techniques in manufacturing [Burrows 84] [Meyer et al, 88].

Importantly, the apparent potential of AI, and thereby, intelligent CIM, for bringing about a paperless, workerless factory (free of direct production and assembly workers, that is) has contributed to a widespread belief that the unmanned factory is an entirely reasonable possibility [Merchant, 85: 98]. Whilst the majority of practitioners are far more circumspect in their predictions, drawing back from the prospect of the "automatic factory," it is the science-fiction accounts that are transmitted to a wider audience, as exemplified by the following quote [The Economist, 87]

"Imagine, if you will, an engineer sitting at a computer terminal punching in data for the design of a new product and sketching freely with a light-pen on the screen before him. Happy with the design he presses a button and the details are passed electronically to another computer running software that checks to see whether the design's stresses and strains are within prescribed limits. The information then zips along to a third computer which generates instructions that command the tools in the workshop to machine, assemble and store the engineer's product ready for distribution - all done automatically, without hassle delay or hefty manhandling, and all before the mornings coffee break. One more satisfied customer. Welcome to the "factory of the Future." For the first time in three quarters of a century the factory is being reinvented from scratch. Long, narrow production lines with men crawling all over them - a feature of manufacturing everywhere since the early days of the car-making dynasties - are being ripped apart and replaced with clusters of all-purpose machines (sic) huddled in cells run by computers and served by nimble-fingered robots. The whole shape of the industrial landscape is changing in the process."

Despite the frequency with which such "visions of the future" appear in the media, it will become clear in subsequent chapters, when looking at the role of humans in advanced manufacturing systems, that the "Factory of Today" needs people, and will do so for the foreseeable future. Indeed, it will become apparent that whilst the number of people engaged in shop-floor activities will, in all probability, decrease over time, the significance of the remaining shop-floor personnel will increase markedly. The deleterious effects of a failure to recognize this fact are already becoming apparent.
3. Advanced Manufacturing Technology - Theory versus Practice

In the preceding chapter the "state of the art" of AMT was described and the benefits expected from its implementation discussed. The key objective of this chapter is to compare this "theory" with "practice" by analysing the extent to which these benefits have been realised by the use of AMT to date, in particular shop-floor AMT.

3.1 Revolution or Evolution?

The potential of AMT to improve the competitive ability of firms has been extensively documented in the literature. Significant improvements resulting from the implementation of these technologies have been reported frequently; in stock levels, quality and its costs, space requirements, lead and cycle times, scrap and yield rates and a number of other measures. In some cases the benefits reported are truly impressive, as shown by the selection of benefits claimed for FMS in Table 3.1 below.

Table 3.1 Benefits of FMS

a) Survey by Bessant & Haywood [85] (Sample: 60 UK Companies)
   - Manufacturing Lead Times \( \downarrow 74\% \)
   - Work-in-Progress Inventories \( \downarrow 68\% \)
   - Stock Turnover \( \uparrow 3.5\times \)
   - Machine Utilisation \( \uparrow 63\% \)

b) Survey by United Nations Economic Commission for Europe [Kochan, 86]
   - Labour Costs \( \downarrow 30\%+ \)
   - Material Costs \( \downarrow 15\%+ \)
   - Stock and WIP \( \downarrow 50\%+ \)
   - Manufacturing Lead Time \( \downarrow 40\%+ \)
   - Machine Utilisation \( \uparrow 30\%+ \)
   - Floor Space Requirements \( \downarrow 50\%+ \)
   - Total Production Costs \( \downarrow 14\%-27\% \)
   - Operating Projects \( \uparrow 112\%-310\% \)

Considering the magnitude of some of the improvements claimed, it is not surprising that there should be a widely-held perception that a "revolution" is underway in manufacturing (exemplified by the quote at the end of the preceding chapter).
This perception has, in turn, led to predictions of rapid growth in the implementation of most forms of AMT. For example, a market growth rate per year of 30% has been forecast for industrial robots, whilst a growth rate of 40% per year has been predicted for CAD/CAM systems [Wall et al, 87:8]. Figure 3.1 below shows the forecast exponential growth in investment in flexible manufacturing technology in Europe, whilst Figure 3.2 shows a similar exponential growth rate as expected for CIM technologies as a whole.

**Figure 3.1 Forecast Investment in Flexible Manufacturing Technology [Kochan, 85:42]**

![Graph showing exponential growth in investment in flexible manufacturing technology.](image)

- All forms of flexible manufacturing equipment
- "Full systems", of which:
  - Machine hardware - 50-55%
  - Control systems - 25-30%
  - Transport systems - 20-25%

**Figure 3.2 Forecast Investment in CIM Technologies [Bullinger, 88:58]**

![Bar chart showing investment in CIM technologies.](image)

- USA
- Japan
- Europe

(All values in $ Thousand Million)

1980 1985 1990

Source: Booz, Allen & Hamilton
Despite such forecasts of exponential growth and the perception of a "revolution" underway in the metalworking industry, actual figures surveyed for the current diffusion of AMT and present growth rates paint quite a different picture. Although such empirical evidence on the diffusion of AMT is less than systematic and comprehensive, those surveys that have been made suggest that penetration into industry is not yet high and is particularly low in the UK in comparison to major industrial competitors.

In surveying "Robots in British Industry," the Policy Studies Institute found that, on average, less than 1 factory in 40 possessed an industrial robot [Northcott et al, 86:2], such that in 1987 the total robot population in the UK was just 4303 [British Robot Association, 88]. Although other countries have larger overall robot populations, in particular Japan, the USA and West Germany, even in these countries the impact of robots outside particular industrial sectors, such as the automotive or consumer electronics industries, has been limited [Slatter, 87:5].

A recent survey of machine tools and production equipment in Britain shows that just over 7% of the machine tool population is computer-controlled, that is, NC or CNC, a percentage roughly similar to that in most other European countries [Metalworking Production, 88:15].

For more integrated technologies, such as FMS, diffusion is even more limited. In compiling the findings from a number of studies Bessant & Haywood [85] suggest that the total world population of flexible manufacturing systems is between 500 and 600, with just 22 systems in the UK. Even these figures may be optimistically high, in that many studies of FIVIS adopt "liberal" definitions of what constitutes a "flexible manufacturing system."

As for CIM, Ingersoll Engineers, in their report on "Integrated Manufacture" [85], found that progress towards computer-integrated manufacturing, as defined in Chapter 2, is very limited indeed.

It would thus appear that there is little support for the notion of an "information technology revolution" in manufacturing, rather than an "evolutionary" process is underway, characterised by modest growth rates and the "piecemeal" introduction and application of AMT [Wall et al, 87:8] [Buchanan and Boddy, 83:240].

Not only is the rate of change to AMT much less rapid than typically portrayed, when looked at from the point of view of the metalworking industry as a whole, but more detailed consideration of the findings of recent surveys of the diffusion of FMS reveals a variety of disparities between "theory" and "practice" with respect to both benefits and areas of application of shop-floor AMT.

Arguably the most significant point revealed by the various surveys of the implementation of FMS and FMCs is that these systems are "flexible" only in a very limited sense. Bessant & Haywood [85:10] found that just 22% of the systems surveyed could cope with more than 100 different part types, whilst Edgehill & Davies [85:42] found that the average part variety for the systems they studied was between just 7 and 12 parts. This reflects the fact that while many
current systems do exhibit volume flexibility, that is, they are capable of producing parts efficiently in small- to medium-batch quantities, and product mix flexibility, that is, when the necessary parts, tools, part programs and fixtures are immediately available, parts can be processed in a random sequence, they often lack product flexibility, that is, they can only handle a very limited variety of different part types [Willenborg & Krabbendam, 87:1686].

It is apparent from the surveys that most current FMSs are used in the machining of prismatic components of high value with comparatively long machining times. Edgehill & Davies [85:45] found that from an overall sample of 107 FMS/FMC, just 16 were used in the production of rotational, that is, turned parts, despite the fact that in general engineering some 70% of machined components have at least one turning operation [Von Zeppelin, 85:3]. They also found that current installations are concentrated in companies with a particular type of product, typically machine tool parts, transmission system components and engine castings, with relatively small families of parts and machining of only one material.

Importantly, the cost of current systems is very high, the average cost of the FMS/FMCs surveyed by Bessant & Haywood being £2.4 million! This high investment requirement means that flexible manufacturing technology, as it stands at present, is largely limited to big companies; small-and medium-sized enterprises have been virtually untouched by the technology. The high system cost demands high utilisation which is reflected by the fact that most of the systems installed to date are operated in multiple shifts [Willenborg & Krabbendam 87:1686]. Furthermore, not only have most FMSs been installed in large companies, but in many cases in companies engaged in medium-to high-volume production [Hoffmann & Höhmünn, 83].

A further salient point is that there is little evidence of significant manpower reduction or of "unmanned shifts," with the current generation of FMS. Bessant & Haywood [86:37] found that in the UK, labour force reductions directly attributable to FMS had been relatively small and that while many companies had aspired to "unmanned production," difficulties experienced in attempting to realize this objective meant that operators were still required to monitor the system. Hirt [88:78-86], in his study of 95 FMCs in West Germany, found that of those cells based on machining centres just one-fifth had been operated in "unmanned" shifts, whilst for those cells based on lathes or turning centres none had been run without an operator for a complete shift.

It is clear from the above analysis that the practical realization of FMS/FMC often differs from the concept of FMS as it is most widely portrayed, that is, as a manufacturing solution for small-to medium-batch production of a wide variety of parts.

A closer look at the results of the above-mentioned surveys indicates the need to exhibit caution with respect to the validity of many of the claims made for the benefits of FMS/FMC [Meredith, 87:1493]. First, as already noted, the parts usually selected for processing by an FMS are typically high value, critical components which would receive special attention in any conventional system, and are likely to show a greater return from improved production methods. However, these parts are typically only a small portion of a company's overall part spectrum, with the result that the benefits of FMS often only represent improvements at the operating level that are not reflected at the company level [Boddy & Buchanan, 84:234].
Secondly, FMS/FMCs have often been implemented by machine tool companies in their own plants as demonstrations of their own products and technical capabilities, which means that some of the more impressive claims made by such companies must be treated with caution [D'Iribarne & Lutz, 83:130].

A third point relates to the need to make the systems look successful, both from the point of view of the individual(s) with overall responsibility for system implementation and the company as a whole [Holz, 84] [Haywood & Bessant, 87:31]. As pointed out by Haywood & Bessant, this need tends to result in "post-hoc rationalization" of the system in question. The author's own study tour revealed that few of the companies visited had carried out any form of post-audit to check whether expectations of system performance and improvements were actually being fulfilled [Slatter, 87].

Despite the need to analyse claimed benefits carefully, it is clear that many companies do enjoy substantial benefits from the implementation of AMT. This then begs the question as to why the rate of diffusion of these technologies should be so comparatively slow? Various constraints on diffusion have been identified, on both the supply-and user-side.

The most obvious constraint with its origin on the supply side relates to the applicability or "appropriateness" of the technology on offer. " Appropriateness" can be defined in different ways, but two key factors are the high cost of most forms of AMT and the fact that in many manufacturing applications computer-controlled machines or systems have not yet proved more effective than "earlier" technology, or are simply not yet available.

In the case of FMS the high system cost has already been mentioned earlier in this chapter, whilst an example of the second factor is the limited availability of highly integrated systems for dealing with turned components. Arguably, automated systems are easier to develop for cubic, or prismatic components. A variety of factors, including work-handling requirements, variety of blank and work-shapes, workhandling and tooling, all contribute to make the automation of high variety small-batch production of turned components appreciably more difficult than for prismatic components [Craven, 86:169] [Looney, 85].

The very high cost of an FMS/FMC and the limited product flexibility of many current systems conspire to make such technology inapplicable in many small-and medium-sized companies engaged in high variety small-batch production. Vendor companies have also, to a great extent, been "driven" by the requirements of companies in particular industrial sectors, notably the automotive and aerospace sectors which, in turn, have tended to "impose" certain forms of AMT on their sub-contractors and suppliers.

However, there are signs that vendor companies are recognizing that flexible manufacturing cells could be a major growth area for those firms that do not have the financial wherewithal, or production needs, to justify a "sophisticated FMS." The market for cells could run into several thousands in the UK alone, whilst the market for more complex and expensive systems is limited to perhaps as few as 40 or 50 companies [Bessant & Haywood, 85:35].
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A significant problem with more sophisticated, integrated systems arises with software and control systems. Although application packages for functions such as part programming or DNC are widely available as standard products, the effort required to integrate suites of software suitable for the control of FMS is immense, in the case of one leading supplier of FMS exceeding 130 man-years in the development of their present generation of software [Bessant & Haywood, 58:29].

This reflects the fact that the language and communications protocol incompatibility described in the previous chapter usually demands custom-written software, which is naturally costly and complex. This problem is often compounded by physical difficulties in linking different hardware elements.

A combination of the above factors of cost and system complexity mean that shop-floor AMT is typically applied to one stage of the overall workflow at a time and often then only carries out a proportion of the operations at that stage. A major drawback of this "gradualist" approach, however, is the danger that unless the user-company has a clear long-to mid-term plan of where the new technology will lead, equipment purchased may be incompatible with previously or subsequently purchased equipment, or may become outdated and unable to meet the requirements of further stages in the development of the manufacturing system.

On the user-side a significant barrier to more widespread diffusion, caused by the high cost of the current generation of flexible manufacturing technology, is the difficulty of financial appraisal and justification. The most significant problem derives not from a shortage of capital, but from the dominant short-term, financially-orientated point of view with respect to the justification of new equipment.

This viewpoint is largely the result of applying "traditional" techniques of financial appraisal, such as payback methods or discounted cash flow (DCF) methods, both of which are inappropriate for assessing technologies with long-term benefits, such as FMS [Slatter, 86:56-60].

Another difficulty derives from the fact that the above-mentioned methods focus on direct savings, in particular labour costs, whilst many of the benefits of FMS are "intangible" and thus less easy to quantify. Various techniques have been proposed for taking such "intangible" benefits into account, to thereby quantify the total effect of AMT on the competitive ability of the company and so improve the chances of projects with long-term benefits being justified [Primrose & Leonard, 85a, 85b; 85c] [Hundy, 84].

However, Senker [84:229] makes the essential point that no appraisal technique can compensate for a lack of appropriate skills to exploit the available technology. In their survey of FMS/FMCs in small-to medium-sized companies in the UK, Haywood & Bessant [87:57-88] found that all of the companies surveyed were experiencing problems in recruiting skilled personnel and that a lack of key skills was a significant barrier to growth. Importantly, the companies studied all stressed the need for more widely skilled people to run systems such as FMS/FMCs efficiently.
This directly contradicts the popular opinion that such technology has the capacity to replace skilled labour by allowing unskilled or semi-skilled workers to run these systems. This particular point of "appropriate" skills and requisite training and re-training is central to the thesis and will be dealt with in more detail in subsequent chapters.

A further problem for potential users of AMT is the prospect of a long learning curve, beyond an already extended planning period, associated with the efficient exploitation of the advantages offered by the technology. Even then, problems such as hard/software compatibility may arise well into the working life of the system.

Interestingly, although the introduction of AMT often calls for a re-structuring of skills and in some cases leads to job losses, the response of the workforce and trade unions in the UK has not been to resist the implementation of the technology. A significant point revealed by the Policy Studies Institute survey of robots in British industry is that while just 2% of robot user companies actually experienced opposition from shop-floor workers or unions, almost one-third of these companies had expected resistance prior to implementation.

Experience would indicate that problems are far more likely from the resistance of middle managers, who may see AMT as a threat to their authority or even to their jobs. The resultant "human inertia" [Meredith, 87: 1507] is shown clearly by the study of Haywood & Bessant [87:45-46], with a substantial minority of managers unprepared to train up to the necessary standards in new technologies and techniques and thereby reluctant to commit themselves to new production methods.

Clearly there is a wide variety of constraints on both supply-and user-sides that serve to slow the diffusion of AMT, but questions are also being asked as to how successful current user companies have been in their exploitation of the technology. It is this concern that provides the subject for the next section.

3.2 Advanced Manufacturing Technology - Promise Fulfilled?

The evidence available to date suggests that for a substantial number of users the answer to the above question is negative, or, at best, non-committal.

In the case of office-based applications of AMT, Waterlow & Monniot [86] reported that of 29 companies studied using computer-aided production management systems, just 12 rated their installation as successful. A particularly well-known case is that of TI-Raleigh, where the change to computer control systems not only failed to produce improvements but caused a serious loss of production efficiency [Bessant & Haywood, 86b, 46]. Experience with MRP in the USA has been similarly dismal, and is amply summarized by the quote that "MRP is a $100 billion mistake, and 90% of MRP users are unhappy" [Aggarwal, 85:9]. Marsden [86] indicates that this poor experience is representative of that with other office-based applications, such as CAD/CAM.
The story is disturbingly similar for shop-floor AMT, such as industrial robots, where Fleck [84] found that nearly half of the companies that he examined had experienced initial problems with robots, and of these around half had subsequently abandoned projects involving robots. In the case of FMS, a survey by Ingersoll Engineers of 48 systems found that an "uncomfortably high" number had failed to realize the expectations of their purchasers [Holz, 84]. Faced with such evidence it is not surprising that the technical media should feature headlines such as "Abysmal success rate of CIM, FMS" [Engineering News, July 1985]. Figure 3.3 shows in graphical form one commentator's appraisal of experience to date with AMT and associated manufacturing techniques.

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<tr>
<th>&quot;High&quot; Technology</th>
<th>Financial success / failure history</th>
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<tr>
<td>CIM</td>
<td>Fully successful</td>
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<tr>
<td>CAD/CAM</td>
<td>Marginally successful or failures</td>
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<td>MRP II</td>
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<td>FMS</td>
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<th>&quot;Medium&quot; Technology</th>
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<td>CAD</td>
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<th>&quot;No&quot; Technology</th>
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<tr>
<td>Product simplification</td>
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<td>Improved layout</td>
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There is also evidence that such problems on the user-side are matched by problems on the supply-side. Rodger [86] reports on the difficulties experienced by a number of vendors of AMT, particularly in the CAD/CAM, robotics and FMS markets, which are characterised by a period of "profitless prosperity." The difficulty in deriving profits from factory automation system is largely a result of the need to develop complex, custom-built, high cost systems to solve customers manufacturing problems by means of say, FMS, which often simply shifts these problems over to the vendor [Bessant & Haywood, 85:28].

Both user and vendor difficulties are reflected in more modest growth rates now being made for shop-floor AMT, for example, 20% p.a. for CNC machine tools [Metalworking Production,
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88:25] and 25% p.a. for FMS [Engineering News, April 88] - figures that are modest indeed considering the currently small installed base in the UK. Similarly, reduced growth rate forecasts are now being made for industrial robots, even for the exceptionally strong West German manufacturing industry [British Robot Association, 88].

Moreover, there is evidence that users and vendors alike are pulling back from more sophisticated technologies such as FMS. Dunn [88:34] reports on the conspicuous absence of flexible manufacturing systems at recent machine tool exhibitions, with a distinct move back to stand-alone machines and flexible manufacturing cells, while the author has discovered that even in Japan, a number of machine tool manufacturers have moved away from the use of FMS in their own factories, finding that such highly integrated systems are not necessarily economically viable.

Certainly there has been a recent trend, exemplified by Ingersoll Engineers [85] and Wamecke [88], for authoritative commentators to preach the wisdom of simplicity, the virtues of returning to basics, and the dangers of automating existing problems. This trend is leading to a degree of scepticism as to the real benefits of AMT and the technical media, sensationalist in its initial praise of new technologies, is now being equally opportunist in its criticism of technologies such as FMS, in failing to fulfill early promise [Mortimer, 87:55].

Hughes [87:81] and Greenwood [88:5] both take the positive view that a period of unjustified euphoria and "technology-hype" is now over, to be replaced by a more "common-sense" approach linking underlying business needs with an appropriate use of technology, rather than pursuing technological excellence for its own sake. However, other commentators, such as Scheer [87:v] perceive the danger that FMS and CIM might follow the example set by "Management Information Systems (MIS) in the 1960s, whereby early overselling and poor design and implementation could lead to essentially sound concepts of flexible, integrated manufacture also being discounted.

But why should experience to date be so poor for so many users? The most obvious reason would appear to be the formidable technical problems associated with the planning and implementation of shop-floor AMT.

The complexity of systems such as FMS leads to significant problems of integration, not only of software, but also of the mechanical hardware of the system, such as the interfacing of materials handling equipment and machine tools. The detailed planning required to avoid problems here is a major contributory factor to the long overall planning period typically required for an FMS. As pointed out by Meredith [87:1503], independent solutions are not possible for more sophisticated systems as they commonly are with conventional, stand-alone equipment. System interdependence typically takes an inordinate amount of extra time to address, time that is often not allowed for in the initial system implementation plan.

Meredith [87:1498] goes on to make the important point that despite the long planning period and long learning curve, technologies such as FMS do not necessarily exhibit highly extended lifetimes. Although the flexibility of the technologies can extend their lifetime beyond
the point where a transfer line, for example might become obsolete due to product changes, the equipment still wears out and loses its capabilities just like conventional equipment. Importantly, problems of software obsolescence, resulting in less vendor support, less compatibility with new software etc., are just as difficult to deal with as problems of hardware obsolescence.

Many problems experienced by FMS user companies reflect the limited product flexibility typical of the present system generation. Great attention has to be paid to specifying the parts spectrum for a given system, since the quantity and variety of different parts to be produced are the factors with the greatest influence on system complexity and cost. The disastrous consequences of not carrying out this task exhaustively are described by Holz [84]. His illuminating practical example concerns a $20 million FIVIS built to produce 12 different components types. When the system was finally delivered it could handle only 2 component types. Instead of carrying out detailed planning and checking, those responsible in the user company assumed the system to be so flexible that it could "flex" to match the changes in component design, production volume and mix that occurred between the system being ordered and ultimate delivery 18 months later.

The effort required in technological planning to avoid problems such as described above, is immense, Senker [84:229] reporting that Yamazaki in Japan invested 100 000 man-hours in the planning of an 18 machine FMS!

It is apparent from experience to date that the limited flexibility of current FMSs places great importance on infrastructural matters such as "design for manufacture," since designers have to be aware that new product designs must fall within the critical limits of the systems capabilities. Design standardization also becomes important to help reduce the number of cutting tools, jigs and fixtures required. Willenborg & Krabbendam [87:1687] note that traditional sequential interdependence between the design and production engineering functions turns into a reciprocal interdependence where designers need feedback on the "manufacturability" of their designs, and production engineers need information on future product lines for the sake of capacity planning.

In general, technologies such as FMS, characterised by high capital intensity and a limited capability for adapting automatically to variations in, say, raw material quality, demand a more carefully planned and prepared machining process. With the current generation of FMS this is leading to process decisions being made increasingly by technical specialists, rather than by system operators, the belief being that improvisations on the shop-floor to compensate for imperfections in the supply of materials or information are too slow and too expensive [Willenborg & Krabbendam,87:1686]. The negative consequences of this shift in decision-making responsibility will be dealt with fully in the next chapter.

This is an apt point at which to reflect that many studies indicate that technological difficulties are by no means the only reason for problems experienced in the implementation of AMT. Problems due to technical complexity are often expected, but many companies are completely unprepared for associated managerial problems [Meredith,86:68].
In the case of CAD/CAM, Stark [88:3] goes so far as to suggest that the main reason for companies failing to report significant gains from its use, is a failure to reassess organisational and human resource issues. Some of the managerial problems associated with the implementation of AMT have already been alluded to, such as the difficulty of financial appraisal, but the most significant problems relate to the "human aspects" of AMT.

Greenhalgh [85] attributes the bulk of these problems to an incompatibility between the technology and the organisational infrastructure into which it is to fit. It is this "lack of fit" that contributes to the "human inertia" described earlier and that leads to poor worker motivation. Not only does this mean that new equipment is often not exploited to its full potential, but also that it becomes difficult to retain or attract the required calibre of staff.

The negative effects of such a "lack of fit" are amply demonstrated by experience with MRP. As pointed out by Aggarwal [85:8], the successful implementation of MRP depends critically on the discipline of those employees feeding updated information into the computer system. However, the increased formality of planning implicit in MRP is often resented by workers accustomed to "informal systems" for getting the job done, with the result that inaccuracies can find their way into important MRP files, so rendering a powerful system ineffective.

It is such problems that are central to this thesis because, in the words of Stark [88:3]

"The characteristics of advanced manufacturing technologies are surprisingly similar. They lead to a higher local production rate (be it of parts or drawings). They call for higher capital investment per employee. They call for greater interdependence between previously separate work activities. Although this leads to a welcome reduction in the number of bureaucratic barriers between activities, it also implies that a malfunction of a previously separate part of the system will now have serious consequences for the whole of the system. There is a trend with the use of AMT to team-oriented work, with the result that fewer employees are involved with a particular product, part or process, but their level of responsibility is higher. Their work is more often dependent on mental rather than physical skills and effort with the result that output may become sensitive to human behaviour rather than to that of machines."

Similar thoughts lead Goodridge [87, 45] to state that

"The biggest single factor which will make the difference over the next decade will not be the technology but the people."

It is also a documented fact that problems in dealing with this lack of fit between technological "hardware" and organisational "software" are leading many companies to "reintroduce" human intervention into their manufacturing systems that is, reverse the trend towards total automation! [Blumberg & Gerwin, 84:126].

Valuable pointers to why this "lack of fit" should occur are provided by Clegg's propositions about the way in which companies introduce new manufacturing technologies [88:26]:

(a) Many new technologies are implemented without careful integration into the company's business plan, that is, there is a lack of strategic thinking and planning for AMT.
(b) In sophisticated, "high tech" companies the development of AMT is often technically
dominated and driven, with the result that general managers and personnel specialists are
usually only involved in system development after the system has been designed and often
only after it has been commissioned.

(c) In less sophisticated companies, the development of AMT typically follows a process of
"muddling through," an approach which is particularly problematic in large, differentiated
organisations.

(d) Often maximising the level of automation is a major objective of company automation plans.
Human operators are viewed as sources of unpredictability and error, and technical feasibility
and financial limits are often the only constraints placed on seeking to allocate functions to
machines rather than humans.

(e) Whether technologically driven, or designed by "muddling through," the human and
organisational aspects of AMT typically receive little, if any, attention. The result is often
that jobs and the local organisational structures associated with preceding technologies are
adopted, with minimum levels of skills and responsibility and highly differentiated structures.

(f) The difficulty of searching for and evaluating "optimum" solutions to manufacturing problems
means that system designers often "satisfice" that is, adopt the first available satisfactory
solution that meet basic requirements.

It would appear that the "human side" of AMT has a central role to play in determining whether
a particular application of AMT will prove successful. Accordingly, the relationship between
technology, work organisation and job design requires more detailed consideration.
4. The Human Side of AMT

As suggested by its title, the objective of this chapter is to analyse the relationship between advanced manufacturing technology and its "human aspects". To this end the various forms of work organization associated with different types of AMT and the skills typically required of operating personnel will be analysed.

The extent to which companies recognize and account for such human aspects in the design and implementation of AMT is also discussed, as are the various organizational features regarded as compatible with the integration and close operational control associated with AMT.

4.1 AMT and Work Organization

To establish the reasons behind some of the "human" problems experienced with the implementation of AMT, it is instructive to summarize the key findings of various studies of the relationship between shop-floor AMT and the organization of work around the technology.

It is important to point out here that it is beyond the scope of the thesis to look beyond the level of the firm, that is, at the broad social effects of the implementation of AMT. For an appraisal the reader is referred to papers by Francis [83], Chisholm [87], Heginbotham [82] and Petrella [84].

For reasons that will become apparent, it is important to separate the discussion of "stand-alone" forms of AMT, such as CNC machine tools, from that of more integrated technologies, such as flexible manufacturing systems.

4.1.1 CNC Machine Tools

Sorge et al [83], in a comparative survey of the use of CNC machine tools in the UK and West Germany, found significant variations in the organization of work in the companies studied. In this survey six companies of differing sizes and producing different batch sizes were studied in each country. Using the schematic of activities involved in the preparation and execution of machining tasks, as shown in Figure 4.1, attention was focused on the degree to which work planning and programming-related activities were devolved to shop-floor personnel.

A wide range of factors was found to influence work organization, but as shown by Figure 4.2, plant size and batch size were identified as the most significant factors deterring the breadth of activities carried out by shop-floor personnel.

It was found that in the smaller plants studied an unbureacratic, simple organization meant that programming and planning-related functions were less concentrated into specialised departments or positions, whilst in larger companies more systematic procedures and a greater
division of labour had the effect of differentiating programming functions away from the shop-floor. An important point raised by the study is that "high technology" by no means necessitated greater bureaucratization since the smaller plants in the study featured a higher proportion of CNC machine tools, yet with weak formal methods of organization [83:148].

Increasing batch sizes were found to be associated with increasing differentiation of programming activities away from machine setting activities, though not necessarily into specialised departments. The explanation offered is that the smaller the batch sizes produced, so the greater is the need for frequent resetting of machines with new tooling, fixtures and part programs, and less is the difference between machine setting and operating activities. Larger batch sizes reduce the frequency of machine setting, and since machine setting and programming functions frequently overlap, the elimination of machine setting from the operator's tasks usually results in the differentiation of programming activities away from machine operation [83:148-149].

Figure 4.1 Preparation and Execution of Machining Tasks (adapted from [Sorge et al, 83:46])
However, there is a variety of further factors that can influence the extent to which functions and skills are polarized. One of the most important factors is the time taken to generate part programs, which, in turn, is typically a function of workpiece complexity and machine tool type.

The study found that, generally, the more time taken to generate a part program, so the more is programming differentiated from operating activities so that it can then occur in parallel to maximise machine utilization. This was found to be the case particularly for machining centres, though interestingly, it was found that the operators of such machines were predominantly classified as skilled, primarily because of the responsibility associated with high costs of machine, tools and materials, and the complexity of the machining process.

It should be pointed out that at the time of Sorge et al's study, the feature of "parallel programming", whereby the part program for the next component to be machined can be generated whilst the machine tool is in operation, was in an early stage of development, whereas today this feature is standard on most CNC controllers. Clearly the practicality of parallel programming depends on a number of factors, not least that the operator is relieved of frequent workpiece handling, so that he/she can concentrate on programming. Nevertheless, it makes CNC machine tools much more suitable for shop-floor programming, as does the trend towards "dialogue programming" which greatly facilitates the programming procedure.
It is also important to point out the national differences revealed by the study, which show that work organization is not just a function of plant and batch size, or type of machine tool, but also reflects different societal environments, that is different traditions of work organization, management and training [83:151-152]. It was found that there was a consistently greater use of shop-floor and operator programming in the West German companies studied. Sorge et al related this to the distinctively different qualification structures in West Germany and Britain. In the British companies studied the more frequent separation of programming and operation is closely linked to the increasing differentiation of technician and worker apprenticeships, whilst in Germany technician training is invariably subsequent to a craft apprenticeship and craft experience.

In both countries, however, the perception prevailed that CNC operation is less distinctive for requiring "information technology skills," than for requiring advanced machining "craft" skills. In other words, the various programming aids offered, whether on the machine tool controller, or in the planning department, are seen as "tools" to help facilitate the control of the machining process that is featuring an ever more complex mix of precision, machining speeds, tools, fixtures and materials [Sorge et al, 83:153].

Dodgson [85] in his survey of the use of CNC machine tools in 40 small firms (less than 200 employees) in the UK, found that even in small firms these machine tools are employed in a variety of ways. Dodgson analysed the content of operator tasks, that is, whether the machine operators merely monitored the machine, or carried out further activities, such as machine setting, program proving or part programming. As with the study of Sorge et al, a variety of factors were found to influence the way in which work was organized, as shown below in Figure 4.3.

**Figure 4.3 Major Influences on Work Organization (adapted from [Dodgson, 85:65])**
The Human Side of AMT

Based on his findings Dodgson set up a typology of work organization, shown below in Figure 4.4. Companies with a "polyvalent" work organization were those where the machine operators not only operated the machines, but were also responsible for machine setting and program proving, and in some cases part programming. In companies where the work organization was classified as "fragmented", the operators merely loaded and unloaded parts, whilst in a "mixed" organization the operators had an additional task of either machine setting or program proving. Based on the influences shown in Figure 4.3, it was found that "polyvalent" or "fragmented" firms often shared common characteristics, as summarized below in Table 4.1.

It was found that the majority of operators in the companies studied were described as "skilled": and had attended CNC courses off-the-machine. However, as implicit in the above typology, the range of tasks performed by these skilled men varied considerably. Importantly, as shown by Table 4.1, unpredictable production and small batch sizes were found to be associated with a "polyvalent" work organization, that is, extended task ranges for the machine operators. The explanation offered for this is that the flexibility in work organization offered by extending operator jobs to include setting, program proving and part programming is more important where production features more "new" or "exceptional" cases [Dodgson, 85:96].

Figure 4.4. Work Organization with CNC Machine Tools (adapted from Dodgson [85:66])

<table>
<thead>
<tr>
<th>Company (Sample)</th>
<th>Work Planning</th>
<th>Programming</th>
<th>Program Proving</th>
<th>Tool Setting</th>
<th>Machine Setting</th>
<th>Work Handling</th>
<th>Machine Observation</th>
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<td>C &quot;Fragmented&quot; 1) (2 Operators)</td>
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- "Always involved"  
- "Occasionally involved"  
- "Frequently involved"  
- "Never involved"
Table 4.1. "Polyvalent" vs Fragmented Work Organization [Dodgson, 85:94]

<table>
<thead>
<tr>
<th>&quot;Polyvalent&quot; Work Organization</th>
<th>&quot;Fragmented&quot; Work Organization</th>
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<tbody>
<tr>
<td>Smaller numbers of employees</td>
<td>Greater numbers of employees</td>
</tr>
<tr>
<td>Higher profitability</td>
<td>Lower profitability</td>
</tr>
<tr>
<td>More often family / single person ownership</td>
<td>More often subsidiaries</td>
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<tr>
<td>Major factors in competition include:</td>
<td>Major factors in competition include:</td>
</tr>
<tr>
<td>Quality</td>
<td>Quality</td>
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<tr>
<td>Price</td>
<td></td>
</tr>
<tr>
<td>Delivery Times</td>
<td>Predictable and regular production</td>
</tr>
<tr>
<td>Unpredictable and irregular production</td>
<td>Formal industrial relations structures</td>
</tr>
<tr>
<td>Few formal industrial relations structures</td>
<td></td>
</tr>
<tr>
<td>Owners sympathetic to skilled use of CNC for operating and social reasons</td>
<td></td>
</tr>
<tr>
<td>Managerial &quot;high trust&quot; ethos</td>
<td>Managerial &quot;low trust&quot; ethos</td>
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</table>

It was also found that where social relations within the firm were good, as reflected in low labour turnover and absenteeism, there appeared to be less concern to restrict operator autonomy and discretion. In return, extending job definitions to include more complex, computer-related, tasks, led the operators concerned to be more committed to the success of the firm, have greater job satisfaction, and to be more likely to solve complex problems through the continued development of their craft skills. Dodgson described this feature of companies with "polyvalent" work organization as an "ethos of co-operativeness" [85:97].

Importantly, this "high trust" relationship was reflected by a higher annual turnover per employee in "polyvalent" companies than in "fragmented" companies, and led to the conclusion that, "The ability to produce quality goods quickly and at competitive prices is enhanced when CNC machine tools are used with a skilled workforce capable of performing a wide range of tasks." [Dodgson, 85:98].

An important point revealed by the above studies and reaffirmed by Bullinger & Lentes [82] relates to fundamental differences between the organization of work possible with CNC machine tools when compared to earlier NC technology (see Section 2.2). The limited capabilities of early
The Human Side of AMT

NC controllers effectively dictated the use of office-based programming by specialists using expensive, centralized programming systems. Moreover, in many companies NC machine tools were implemented to overcome a perceived shortage of skilled labour, since it was assumed that NC machines only required semi-skilled or even unskilled operators [Noble, 79]. But CNC machine tools, by effectively decentralizing computer power, lend themselves to shop-floor programming and therefore do not necessarily form part of what many studies have portrayed as a progression towards more centralized, polarized forms of work [Sorge et al, 83:7].

This points to a possible explanation for the greater bureaucratisation of programming activities in larger companies. Many such companies will have used NC technology and built up programming departments to suit, which are still used when CNC machines are introduced. Many smaller companies, however, make the step straight from manual to CNC machine tools and thus have no reason for differentiating programming away from the shop-floor.

4.1.2. Flexible Manufacturing Systems

Further studies indicate that not only are there significant differences between the work organization associated with CNC and NC machine tools, but also between "stand-alone" forms of shop-floor AMT and more "integrated" forms, such as flexible manufacturing systems (FMS).

Hannam [85] and Jones [86] in their studies of the manning of FMSs in the USA, and Willenborg & Krabbendam [87] in their study of FMSs in the Dutch and UK metalworking industries all found much greater consistency in the organization of work in an FMS than was revealed for CNC machine tools by the studies described earlier.

Work in most of the systems studied was characterised by a strict division of labour with a complete separation of operating from planning and programming activities. Typically there was a hierarchy of job classifications within FMSs studied, the lowest category being workpiece handling, followed by "FMS operators," tool and maintenance specialists, and at the highest level "system managers" or "system supervisors." FMS operators were mainly responsible for system monitoring, loading and unloading parts, and setting up fixtures, pallets and tools.

In a few systems, operators were also allowed to carry out tool pre-setting and in some companies to make minor program adjustments. In some cases unskilled labour was used for loading/unloading, but more companies adopted a "team" approach, whereby loading and machine monitoring personnel were rotated on a regular basis. The stated logic behind this approach was to give direct system workers an identity with the whole system and to provide a larger source of "system qualified" personnel.

Whether tool maintenance and preparation was carried out by a specialist, or was one of the activities of the FMS "team" was found to depend on machine and tool utilisation. To guarantee immediate machine maintenance when required, it was found in many companies that maintenance personnel were allocated directly to the FMS.
The function of the system manager typically involved production scheduling, supervision of the operators and reaction to unanticipated deviations from normal operations. In some companies an industrial engineer was also allocated to the FMS to carry out system support activities, such as software maintenance and refinement.

The findings of Willenborg & Krabbendam [871, summarized in Figure 4.5 below, are typical in showing that in all of the FMSs surveyed part programming was carried out outside the FMS in specialized programming departments.

Jones [86], reporting on his study of eight FMSs in the USA, found the most important distinctions in job classification to be at the top and the bottom of the "hierarchy," that is, in the separation of workpiece handling from other manual tasks, and in the allocation of responsibility for updating and modifying the computer schedules for the work to be carried out by the FMS.

A variety of reasons were identified for the segregation of loading tasks as a lower status occupation with lower pay, not least the dislike of the FMS operators for carrying out this essentially monotonous activity, and the policies of the plant trade unions, which tended to favour specialized, closely defined jobs [86: 81.

However, it was at the interface between computer scheduling and mechanical operating tasks that Jones found the greatest barriers to "flexible" working practices, which in this case were largely the result of management policies.

Figure 4.5  Job Specification in Flexible Manufacturing Systems
[Willenborg & Krabbendam, 87:1689]

<table>
<thead>
<tr>
<th>Company</th>
<th>NC Programming</th>
<th>Program Adjustment</th>
<th>Tool Pre-setting</th>
<th>Scheduling</th>
<th>Loading / Unloading</th>
<th>Deburring</th>
<th>Quality Control</th>
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- Tasks performed by direct system operators
- Tasks performed by specialists

54
With the current generation of FMS technology there are usually numerous manual interventions required to correct faults or to modify the processing of parts through the system, and consequently a need for frequent minor scheduling and program adjustments and amendments. This requires, in turn, frequent and often intensive communication between the system operators and the system manager. Despite obvious potential time-and effort-saving advantages of permitting the system operators to modify schedules, it was found that in all the systems surveyed bar one, management sought to prohibit operators from carrying out this task. One reason offered by the managers interviewed were the constraints of the labour relations system, that dictated that scheduling jobs be preserved as non-production roles due to the management content of the job. A second reason given was that workers trained in craft-type machining work could not be trusted not to “interfere” with the complex computer technology on which the central controlling function of the FMS relied [Jones, 86:9].

Despite the fact that the overall quantity of tasks performed by direct system operators in an FMS is often less than associated with operation of a manual or stand-alone CNC machine tool, Hwang et al [84:841] make the important point that the level of decision-making and information processing increases markedly. This is a function of variety of factors, not least the technical complexity of an FMS which, given current technology tends to result in a need for continual remedial activity to keep the system operating (despite claims of trouble-free running!), and a need for system operators to make rapid decisions to deal with unforeseen disturbances, such as tool breakages or machine breakdowns [Jones 86:4]. [Hwang et al, 84:844].

Despite this increase in the amount and speed of information processing demanded of direct system operators, it is clear from the above studies of work organization in FMSs that system operator tasks feature few degrees of freedom with respect to planning and programming activities. A variety of reasons for this shift in planning decision-making from shop-floor personnel to specialists in the case of FMS were given in the preceding chapter, and it is also not unreasonable to extrapolate from some of the findings of Sorge et al with respect to CNC machine tools. As shown in Section 3.1 most FMSs are implemented by large companies, and a sizeable proportion of current systems are used in mid-to-high-volume production, that is, in environments associated with increased bureaucratization of programming and polarization of skills respectively.

A polarized and hierarchical work organization appears to be a feature of FMS regardless of national setting, as shown by the broadly similar findings of Bessant and Haywood [85] in Britain, Bullinger et al [86] in West Germany, Kuisma et al [86] in Finland, and the studies described above in the USA and the Netherlands.

The effects on individuals and the organization as a whole of such polarized work organization are described in detail by Blumberg & Alber [82] and Blumberg & Gerwin [84]. In this extended study in a US company, supervisor and worker reactions to FMS were surveyed by means of a questionnaire measuring factors reflecting employee performance, motivation, satisfaction, attendance and retention. The questionnaire results were then compared with the responses of a normative sample of employees in the metalworking industry and a more general sample of employed adults. These comparisons showed that the FMS operators felt that they had little control over their jobs, that is, it was felt that the work in the FMS did not offer enough autonomy
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(freedom in determining procedures), responsibility or task identity (degree to which the job requires completion of a "whole" piece of work). Moreover, the direct workers felt that there was too little participation in work-place decisions although, conversely, first-line supervisors felt that direct worker had too much say. The predictable results of these contradictory perceptions was that job satisfaction was generally low.

The survey showed further that the work in the FMS was comparatively stressful, particularly with respect to an inability to exercise valued skills. The lack of intrinsic motivation inherent in the work in the FMS was reflected by dissatisfaction with pay, health and safety factors [Blumberg & Gerwin, 84:121-124]. This, in turn, made the job of first-line supervisors more difficult. Motivation of the direct workers was an important task of the supervisors, since the quality and cost of production was greatly influenced by the manner in which the direct FMS operators responded to operating and maintenance faults. However, the lack of intrinsically satisfying job characteristics made this task very difficult, particularly in the case of the workers engaged in more routine work, such as workpiece handling. The situation was not improved by the difficulty in devising adequate pay incentive schemes, because it was difficult to relate increased production rates to the increased effort of individual workers [84:125].

4.1.3 Summary

Seeking now to summarize the key points emerging from the above studies, it is immediately apparent that AMT is not necessarily "deterministic," in other words, the technology itself does not shape its associated work organization. Rather, there is clearly a degree of managerial choice in the way that work is organized around the new technology. This is particularly apparent for "stand-alone" forms of AMT where it is evident from the findings of Dodgson and Sorge et al, that there is no general impact of CNC and that its effects will vary from company to company, depending on particular circumstances. The critical point is that decisions made by management, when specifying or designing AMT, can substantially determine the shape of the organization and form of the individual jobs that result from the change of technology. This means that CNC machine tools are compliant, in the sense that they can be implemented in such a way as to produce one effect, that is, the further development of the skills of the machine operators, or to produce the opposite effect, that is, the degrading of these skills. Thus, simplistic generalized statements that CNC is polarizing because it does not do away with separate programming and planning, or that it is depolarizing, because it allows programming at the machine, are little more than platitudes. From his research on the point on the impact of CNC machine tools Wilkinson [82:40] reached the following conclusion, which amply summarizes the above points:

"There is no inherent logic in microelectronics which demands that tasks become ever more mundane, nor does the technology demand that skills be increased and work become more interesting and fulfilling. The way in which work is organized, and thus the quality of working life of the shop-floor worker, is a responsibility which managers cannot shirk by reference to the notion that everybody has simply to adapt to technology's demands."

One body of opinion, exemplified by Child [87:125] and Bessant & Senker [87:169-70] is that AMT increases the "degrees of freedom" available for organizational design. Supporting
arguments for this viewpoint are provided by Warnecke [88], who suggests that the use of IT tends to "simplify" individual manufacturing activities, by enabling human manual and cognitive skills to be incorporated into machines, so making task integration more easy, and Rauner [86], who makes the interesting point that the use of IT on the shop-floor is tending to make the "user-interfaces" of manufacturing equipment more homogeneous, which can also assist task integration. Child [87:129-30] goes on to point out that the information network of computer-integrated systems allows for choice in the siting of, say, terminals etc, thereby providing flexibility with regard to the spatial location of groups and the centralization/decentralization of activities. A change in technology can thus act as a catalyst for organizational change by making available new organizational options [Burnes, 86:57].

However, the earlier discussion would also tend to indicate that there is a significant difference in the degree of choice available, dependent on the form of AMT concerned. Certainly the studies show that a greater variety in work organization is encountered with "stand-alone" forms of AMT than with more "integrated" forms. It will become apparent in subsequent chapters that the choice is still there for integrated systems, but that there are additional factors that influence the decisions taken by management when specifying or designing more complex manufacturing systems.

A key factor distinguishing "stand-alone" and "integrated" systems can be described by the term pre-determination. This term can be interpreted in two ways: The first interpretation refers to work content and describes the fact that in more highly automated systems there is more likely to be a separation of planning tasks from operating tasks such that the system operators have no control over the pace or sequence of work. This division of task is usually justified on the basis of improving the utilisation of these more capital-intensive systems. The second interpretation relates to the long gestation period associated with the implementation and commissioning of complex manufacturing systems. The complexity of the systems means that decisions made at an early stage in the system specification and design process effectively "fix" the shape of the associated work organization and individual responsibilities and skills.

In the case of stand-alone CNC machine tools, the very fact that the machines are not usually linked to other machines or computers means that the choice as to how such machines are to be used is not overly constrained by how this choice will affect other parts of the overall manufacturing "system." Not only does this allow greater flexibility in the design of shop-floor jobs, but it also allows modifications of work organization to take place after the machines have been installed.

The situation is quite different for a flexible manufacturing system. As Information Technology enables the integration of more functions within a manufacturing system, so the interdependency of the constituent elements of the system increases. No longer can one element be changed without significant effects on other elements. This both limits flexibility in the design of shop-floor jobs and also places restrictions on the adaption of the work organization after system implementation. Importantly, this fact, combined with the long planning period required for FMS, means that work organization and the skills that can be employed by individual operators are
largely "pre-programmed" by those with the responsibility for determining the criteria for selection or design of the new manufacturing technology [Burnes & Fitter, 87:85]. The suggestion that greater integration implies more "pre-determination" has obvious implications for even more highly integrated systems, such as CIM.

Evidence of the important relationship between information system design and work organization is provided by the research conducted by Clegg & Fitter [78], who found that the existing information system in the factory studied limited the possibility for increasing the autonomy and responsibility of shop-floor personnel. In effect, organizational control systems and information flows had been designed with fragmented, low responsibility jobs in mind. Thus if the design of an information system does not make the appropriate information for planning or programming activities available to the shop-floor, then it is difficult, if at all possible to substantially increase the degree of planning responsibility enjoyed by shop-floor personnel. This can also mean that changes to jobs and organizational structure may become "trapped" by past decisions [Buchanan & Boddy, 83:255].

As outlined earlier in this section, in the case of many current FMSs, the combination of a highly complex manufacturing system with an apparent lack of concern for organizational issues often results in operator jobs that are characterised by low levels of control over work methods and pace, yet with high levels of attentional and cognitive demand - a job profile that is often associated with high levels of stress [Corbett, 88:35]. This is not to say that it is not possible for FMS to offer the opportunity for skill enhancement, all-round job descriptions and task rotation of the kind promoted by human relations and job enrichment proponents for many years - various efforts to redesign work roles in FMS will be discussed in a later chapter, and indeed, part II of this thesis is testimony to this possibility.

However, it is clear that in practice, dependent on managerial choices, Information Technology, as embodied in AMT, can act as both opportunity and constraint from the point of view of the design of work organization and individual jobs. This key point is well summarized by the following quote from Buchanan & Boddy [83:255].

"The capabilities of the technology are enabling, rather than determining. They facilitate the pursuit of particular goals in particular ways, but determine neither the ends nor the means. Ends and means are ultimately determined by the decisions of those in positions to direct the use of the technology, and design jobs and organizational structures around it."

This, too, is a critical point because a general finding of studies of work organization for AMT is that companies pay precious little attention to organizational issues when selecting or designing manufacturing systems, or perhaps more accurately, fail to recognise the need for organizational change to accompany major technical change, despite ample realization that operating the new technologies would require learning new skills. This impression is supported by a variety of studies that show that frequently AMT is used with the previously existing work organization, or indeed is designed or specified so as to reinforce the existing work organization [Bengtsson & Berggren,66:101] [Stark, 88:5]. Importantly, this problem of companies failing to recognize the need for, or opportunities provided by, work redesign, appears to be independent of the type of
AMT being installed, also being revealed by studies of the implementations of CAD or industrial robots [Cummings & Blumberg, 87:49-55].

The findings of Blumberg & Gerwin, described earlier, make it clear that a lack of attention to human aspects runs the risk of leading to a mismatch between the technology and its organizational infrastructure;

"Too much attention has been paid to technical innovation and not enough to the adjustments needed in organizations to accommodate the new technology. This has produced a lack of fit between the demands made by the technology and the needs, skills, procedures, structures and equipment embodied in the social and technical structure of companies. The result is that the new technology raises both cognitive and motivational problems with which managers, staff specialists and workers have great difficulty in coping." [Blumberg & Gerwin, 84:114].

As already noted in the preceding chapter there is an increasing recognition, in the literature at least, of the need to match new technology and its corresponding organizational infrastructure to avoid such problems. A growing array of influential commentators, including Skinner [85:30-31], Meredith [86:68-73] and Hill [85:158-200], are drawing attention to this need. This emerging line of thought is typified by the following quote:

"Experience shows that it is only in small areas of the company that a purely technological solution is suitable. At the individual level in small teams and in factory cells, pure technology can produce apparently significant gains at the local level. However, when looked at from the company level, these gains appear less significant. Pure technology is not sufficient to make significant changes at the company level. Organizational issues must also be addressed and the roles and responsibilities of people must be reassessed." [Stark, 88:3].

The emergence of this point of view begs the question as to why so few companies recognize the need to match technological and organizational change? It is conceivable that whilst the problem has been recognized there is still too little practical guidance available to enable such a parallel development to be adequately planned. The aim of the next section is to investigate what theoretical guidelines are available to companies to help them avoid any "lack of fit" between new manufacturing technology and its work organization.

4.2 Flexible Organization for Flexible Technology?

As discovered by Child [87:103] there have been precious few analyses of the relationship between AMT and organizational design, beyond those studies already referred to above. The natural consequence is that there are, indeed, few well-defined theories of organizational design for AMT.

However, guidance is available and one of the more detailed theoretical frameworks so far presented, namely that offered by Cummings & Blumberg [87] will be described in some detail in
Chapter 7. Here the discussion will be more general, focusing on the key current influences on
the choice of technology and associated organizational design, and the broad options available to
companies when seeking to undertake organizational change.

Immediately apparent in the relevant literature is the surprising consensus as to the desirable
features of work organization in the "Factory of the future," as summarized in Figure 4.6 below

[Willenborg & Krabbendam, 87:1689], [Bessant and Senker, 87:162], [Warnecke, 88],
[Thorsrud, 80:101, [Goodridge, 86].

![Figure 4.6 "Flexible Organization" for Flexible Technology?](image)

<table>
<thead>
<tr>
<th>&quot;Traditional&quot; Organization</th>
<th>&quot;Flexible&quot; Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>High division of labour</td>
<td>Organizational Integration</td>
</tr>
<tr>
<td>- Fragmented tasks/differentiation</td>
<td>- Tasks varying in complexity</td>
</tr>
<tr>
<td>- Single skills</td>
<td>- &quot;Whole jobs&quot;; Team work</td>
</tr>
<tr>
<td>- Demarcation</td>
<td>- Multiple skills</td>
</tr>
<tr>
<td>- Rigid working practices</td>
<td>- Overlapping jobs</td>
</tr>
<tr>
<td>- High ratio of indirect to direct workers</td>
<td>- Flexible working practices</td>
</tr>
<tr>
<td>- Low work value/motivation</td>
<td>- Low ratio of indirect to direct workers</td>
</tr>
<tr>
<td>- Instrumental orientation (wage)</td>
<td>- High work value/motivation</td>
</tr>
<tr>
<td>- Low priority for training</td>
<td>- Content orientation (work)</td>
</tr>
<tr>
<td>- Primarily &quot;on the job&quot;</td>
<td>- Training and organizational development given high priority</td>
</tr>
<tr>
<td>- &quot;Trial and error&quot;</td>
<td>- Comprehensive training</td>
</tr>
<tr>
<td>- Low training costs</td>
<td>- Increased theoretical content</td>
</tr>
<tr>
<td>- Centralized planning and decision making</td>
<td>- High training costs</td>
</tr>
<tr>
<td>- &quot;Tall&quot; organizational structure</td>
<td>- Decentralized planning and decision making</td>
</tr>
<tr>
<td>- Low local authority</td>
<td>- &quot;Flat&quot; organizational structure</td>
</tr>
<tr>
<td>- Limited &quot;risk taking&quot;</td>
<td>- High local authority/ devolved responsibility</td>
</tr>
<tr>
<td>- Low local problem solving capability and authority</td>
<td>- Increased innovation and &quot;risk taking&quot;</td>
</tr>
<tr>
<td>- Technology taken as &quot;given&quot;</td>
<td>- Increased local problem solving capability and authority</td>
</tr>
<tr>
<td>- Systems designed with man as &quot;exchangeable part&quot;</td>
<td>- Technology shaped to meet organizational needs</td>
</tr>
<tr>
<td>- Employees and organization learning to take on new functions</td>
<td></td>
</tr>
</tbody>
</table>

60
There is a tendency in the literature to portray a dichotomy between the currently predominant "traditional" or polarized, and future "flexible" organization of work. Frequently the desirable "flexible" features are presented without clear reasoning, as if their advantages were obvious, but Child [87: 101-133] is a notable exception, seeking to substantiate reasons for, and benefits to be expected from, the organizational features listed above.

As apparent from Section 4.1, a great variety of factors can influence the organization of work around AMT, and as explained in Chapter 3, there is great variety in the different forms that AMT can take, in terms of the different functions that can be executed under computer control or with computer assistance.

Child classifies the various strategic influences on the choice of AMT and associated organizational design as general contingencies, which are macro-economic and affect most companies in common, or specific contingencies, which are peculiar to a particular enterprise [87:107]. The key general strategic contingencies have already been discussed in Chapter 2, but it is nevertheless instructive to briefly re-iterate some of the most important points.

It was argued earlier that the markets of metalworking companies are characterised by a trend towards increasing product differentiation, reflected in increasing product variety and falling batch sizes. In order to be able to absorb market uncertainties through a flexible response and to be able to concentrate on the manufacture of products with high value-added, the recommended strategic response is one of "flexible specialization," based on flexible multi-use equipment, a skilled adaptable workforce and competition through innovation [Piore & Sabel, 84].

It is widely felt that increasing product variety and ever decreasing product life cycles will render obsolete the rigid "traditional" organization based on a hierarchy and strict division of labour, to be replaced by "flexible firms" employing new manpower strategies aimed at increasing flexibility in terms of workforce deployment [Child, 87:108].

It is the pursuit of a flexible manufacturing strategy, which can be broadly defined as a capacity to innovate to meet new demands and raise product sophistication, the consequent offering of more product variants, and a ability to produce small batches economically, that is encouraging integration between what have been hitherto separate departments or roles. This in turn is providing the driving force behind the use of information technology to achieve computer-integrated manufacturing.

However, the choice between specific types of AMT and the details of organizational design are determined by specific strategic contingencies. As discussed in Chapter 2, two of the key factors determining the choice of appropriate technology for shop-floor automation are production volume and product variety. These factors also play an important role in determining an appropriate organizational design, though it is important to add here a third factor, namely variability, which, for example, can have an important effect on operating conditions due to the uncertainty and planning difficulties caused by high production variability.
In high volume "standardized" production there is relatively little and infrequent change in the requirements placed on the production system, and rapid unanticipated shifts in contingencies are not expected. Accordingly, the level of uncertainty which management has to deal with is low and the conditions of decision-making and information processing are of a correspondingly routine nature. In such a situation a company would probably find it adequate to integrate production programmes with marketing plans and design and development plans on the basis of a long-term forward plan. The company can function adequately with a mechanistic structure characterised by a high level of functional differentiation and centralized planning and co-ordination. Integration is formalized and impersonal and administered by a large staff component [Child, 87:113].

The implications for organizational design of producing a greater variety of parts depends greatly on production variability, that is the predictability of demand and therefore production requirements for the different products. If the product mix and production requirements can be forecast well in advance then increased product variety merely presents problems of processing more information than in the high volume, low variety situation. This high variety, low variability case places great importance on devising production plant and methods that permit fast and cheap changeovers from one batch to another. From the point of view of organization, if production variability is sufficiently low, then it may still be possible for the company to function along relatively mechanistic lines with integration largely realized by means of forward planning.

The situation is quite different in a high variety, high variability context. Here the company might be operating in a market where variety in product specification is important in a competitive context, or where a premium is placed on innovation. The pattern of orders that can be secured will not be predictable and unplanned adjustments in production volume will need to be made accordingly. Furthermore the products themselves will have a continually changing technical specification requiring continuous design changes and alterations to the method of manufacture. This context of "non-routine manufacturing" [Perrow, 70:83] characterizes the direction of the trend in manufacturing strategy dictated by the general contingencies described earlier, and provides the most difficult challenge both in the use of AMT and in organizational design. A number of features are essential if a company is to function successfully in a high variety, high variability environment, namely, devolution of initiative, rapid mutual adjustment to new circumstances, and a high level of integration between groups and levels within the organization, since co-ordination between and within departments and groups in the company will be through feedback rather than through advance planning [Child, 87:113-114].

Child summarizes the types of AMT and approaches to organizational design that are regarded as appropriate for different continuations of production volume and production variability as shown below in Figure 4.7.

Whilst being arguably the most important factors, production volume and variability are by no means the only specific contingencies, as shown by the studies of Sorge et al and Dodgson described earlier. A company will have a variety of inherited characteristics that will also affect its ability to change its organization so as to adapt strategically and employ AMT to that end.
Company size plays an important role as shown by the findings of Sorge et al, where larger companies tended to separate programming of CNC machine-tools away from their operation, that is, larger scale was associated with greater specialization and formalization. It is thus to be expected that larger organizations will experience more difficulty in modifying their modes of organization to suit strategic requirements for a more flexible and integrated mode of production.

The study by Sorge et al showed too, the importance of a company's stock of available competence and skills as a contingency for the use of AMT and the organization of jobs and work around the technology. For example, the national differences found between West Germany and UK can be interpreted as showing that it is easier to add the programming of CNC machine tools to an operator's activities if the person concerned has been more highly trained.

Dodgson's study showed the importance of the operating tradition and state of social relations in a company. In the companies surveyed where social relations were good there was greater evidence of shop-floor workers enjoying "responsible autonomy" [Friedman, 77], where there is greater reliance on the informed discretion of workers, whose roles are enlarged in scope accordingly.
The Human Side of AMT

With such a wide range of factors influencing managerial choice it is clear that there can be no "one best way" with respect to the matching of technology and organizational infrastructure. It is thus instructive to now discuss organizational arrangements regarded as consistent with a flexible manufacturing strategy, that is, compatible with integration and close operational control.

It is important to reflect that "integration" has two dimensions. First, the physical dimension whereby the attempt is made to integrate machining operations on one machine, or to integrate the handling and machining of parts in an effort to approach a continuous flow. This aspect of integration was dealt with in detail in Chapter 2. The second dimension, the informational or managerial dimension, is the focus of attention here and refers to the effort to achieve a high level of co-ordination between marketing, design and production functions in order to offer a flexible and economic response to market opportunities (Such integration is essential if, say, a "just-in-time" (JIT) production system is to be supported).

The key problems associated with "traditional" functionally specialized organizational structures relate primarily to the inevitably complex information flow. Poorly defined interfaces between different functions lead to long lead times and corruption of data, with the result that there are often high overhead costs associated with simply managing the flow of information. The consequent growth in administrative staff employment only serves to extend the managerial hierarchy and further exacerbate problems of co-ordination [Hill, 85:158-200].

In attempting to remedy some of these problems by means of cross-functional integration, two methods are available to the organizational designer: first, convergence within the same role of tasks previously performed within separate roles and, secondly, through a closer coupling or overlapping of different roles [Child, 87:118].

Considering role convergence first, one important example that has already been touched upon is the extension of the role of machine operators to include programming, thereby reducing the need for functionally specialised programming-departments. This development has been enabled by the ever-increasing power and capabilities of CNC controllers, which have made the task of programming at the machine increasingly straightforward [Besant & Lui,86:233]. The incorporation of diagnostic software on such modern CNC controllers is also raising the possibility of integrating traditionally separate maintenance tasks within the role of machine operators, and some controllers even offer the means for carrying out quality control activities at the machine tool.

Thus the integrative properties of AMT provide the means for developing what we might term "flexible craftsmen" or "computer-aided craftsmen", capable of carrying out a combination of hitherto separate roles. The reassignment of planning and evaluating activities, typically completed by support functions, to those responsible for executive tasks in production, can have a variety of benefits. Not only does it enable support specialists to concentrate on activities within the scope of their specialism, but can also increase job interest for shop-floor personnel and, as intended, remove communication problems at the line management/specialist interface. The principle of role convergence as described here is shown schematically in Figure 4.8 below.
Figure 4.8 Role Convergence - The Reintegration of Planning, Evaluating and Executive Tasks
(adapted from [Hill, 85:169-175])

Phase 1
With the introduction of specialist functions, sets of similar responsibilities are realigned.

Phase 2
Over time, the specialist functions develop their own 'independent' reporting structures.

Phase 3
The integrative properties of AMT now allow the "re-integration" of planning, doing and evaluative tasks.

Other forms of AMT also "enable" role convergence as described by Voss [84] and Stark [88] in the case of CAD/CAM, which can enable integration of tasks in design, draughting and production engineering.

In addition to the benefits described above role convergence can also raise labour productivity because employees now carry out more tasks, though the new technology reduces the effort required for some. Apart from constraints due to say, demarcation problems, which will be discussed in a later chapter, the main limit on this development is likely to lie in the capabilities of the individuals concerned to cope with enlarged jobs. This has obvious implications for policy on selection, training and reward systems, that is, work context modifications that will also be dealt with later.
The second means for achieving cross-functional integration involves the coupling of different roles or groups more closely together. Various means are now available for achieving this end. If the need for close integration is only needed on occasion, or can be foreseen well in advance, then little more is necessary than to ensure that the personnel concerned are in regular contact and that responsibility for this contact is clearly understood [Child, 87:120].

A useful measure here is the implementation of agreed procedures, as described for use with a CAD/CAM system by Stark [88]. Should the need for integration be more intense, for example where new product designs or manufacturing methods need to be finalised quickly, then a correspondingly closer and more flexible form of integration between the functions concerned is required. In this situation, which is typical of the high variety, high variability context which is the main one of interest in this thesis, it is necessary to establish teams or project groups. A number of examples or practical experience with project teams have been collated by Child [87:120-121].

A number of factors will influence the decision whether to attempt cross-functional integration through convergence within roles or between roles. It may be thought necessary to retain some specialist roles intact either because specialist formal qualifications are required legally, or because the level of knowledge and ability required for a particular function may be such that the role cannot be divided readily. Company size will also influence the decision since, as already seen above, larger firms are likely to exhibit greater internal resistance to role convergence because it will normally have a well-established and rigid departmental structure. A further factor is possible political resistance to efforts to converge hitherto distinct roles and groups into single entities.

Turning to control issues, it is interesting to note how the literature is divided as to the effect of AMT. The dominant view is that the introduction of AMT will lead to greater centralization of control, that is more bureaucratic structures with less discretion for those at the lower end of the organization, but a considerable number of authors adopt the converse view, that is, that computerization will aid decentralization and the delegation of authority [Burnes & Fitter, 87:89]. Certainly Information Technology can extend the possibility for managerial control. First, it can provide faster, more comprehensive, and more accurate knowledge of operations, particularly if relevant data is captured directly by sensors or monitoring devices. Secondly, the capture of data combined with the use of decision support and other analytical systems can reduce the influence of employees on whom management may have previously been dependent for evaluative feedback. Thirdly, IT offers the means by which to unify previously separate control systems, which can enable a more comprehensive and balanced assessment of performance [Child, 87:123].

With its core of IT, AMT and ultimately CIM would appear to lend themselves to a centralization of managerial control by reducing the importance of the monitoring role of middle-level functional departments and junior line management. This proposition seems to be backed up by the findings of Wild [85] who, in a study of thirteen companies, found an increasing centralization of decisions on production scheduling and control combined with a greater dependency upon computer-based control procedures.
The Human Side of AMT

But is a centralization of planning and control with computer assistance necessarily the best strategic choice? In a classic study Lawrence & Lorsch [67] examined the effects of uncertainty in technology and markets on the structure and performance of a variety of organizations and discovered that where uncertainty was high, that is, where the situation was increasingly unpredictable, decision-making was forced downwards within the organization to where the requisite expertise for short-term decision making was to be found. Accordingly, in an uncertain environment influence and authority became more evenly distributed. Thus the co-ordination through mutual adjustment characteristic of non-routine manufacturing requires a high level of organized integration, but at a decentralized level close to the workflow itself. In a manufacturing system this could mean that production control activities are devolved to machining cells or islands where IT permits such delegation to co-exist with periodic central monitoring of performance.

In summing up, there is an obvious disparity between the "theory" with respect to organizational design compatible with a flexible manufacturing strategy, and the "practice" as revealed by the studies described in Section 4.1. This is not altogether surprising considering the scant regard paid to work redesign in most of the companies studied. Further evidence of this lack of attention to the human side of AMT is provided by Clegg & Kemp [86], who reported on the predominance of "Sequential design" processes, in which the technical aspects of systems such as FMS are specified or designed first, with human aspects considered too little and too late in the day. They suggest that it is not uncommon for organizations to devote at least 90% of allocated resources (financial and time) to the technical side of AMT, such that any choices made about human aspects tend to get made "by default," rather than on a planned basis according to some explicit strategy. Even when companies do recognise that there is a human and organizational dimension to AMT, such considerations can be very limited - for example, showing people a model of the proposed system, or giving operators on-the-job training once the technology is in place. Whilst both these activities are worthwhile, they clearly represent a very limited view of what the human aspects involve.

With such an approach the opportunities and benefits that can arise from appropriate organizational change to match new manufacturing technology are missed, despite the fact that there is a growing literature documenting the benefits of such changes [Hughes,87] [Meredith,86]. For example, Bessant & Haywood [85] studied a company employing conventional technology that achieved a 60% reduction in stock held and a 30% increase in output simply by adopting "good management and methodological practices". These practices were adopted as the consequence of an FMS feasibility study alone, which would indicate that many of the benefits of FMS come from applying a philosophy of flexible manufacture rather than necessarily from the technology itself. This point is very important, since it shifts the emphasis away from what technology is used to how it is used.

Quite apart from the missed opportunities to improve overall company performance are the negative consequences that can result when organizations fail to redesign work and modify the work context to accommodate AMT. As described above there can be considerable employee dissatisfaction with pay, as well as stress associated with the learning of new skills and performing of new tasks.
In the FMS studied the employees felt that the technology had not sufficiently enriched their jobs, and work motivation and job satisfaction were generally low. The direct system workers felt that there was too little participation in decision-making, and that in the future they would like work having more variety and responsibility.

Why should there be this disparity between "theory" and "practice"? Is there some reasoning behind this apparent inattention on behalf of management to the human aspects of AMT and does the technology itself contribute to the disparity? These issues provide the focus for the next chapter.
5. A New Approach to the Design and Implementation of Advanced Manufacturing Technology

The discussion in the preceding chapters has shown that the human and organizational aspects of AMT are often ignored in practice, even though they are wide-ranging and important.

Clegg & Corbett [87:179], suggest two possible reasons for this. The first is that those responsible for system specification or design believe that human aspects will cease to be so important as advanced manufacturing systems become more fully 'automated', that is, the human factor will become irrelevant as AMT evolves.

The second reason could be that whilst human aspects are and will remain important, this message has failed to get across. This view will be dealt with in section 5.2, but the next section focuses on the first of the above reasons.

5.1 "The Legacy of Technocentrism"

The first explanation for the apparent lack of regard for human aspects relates closely to the popular vision of the workerless, paperless "factory of the future". Although most practitioners draw back from this view (no doubt mindful of the problems encountered to date in trying to achieve such "unmanned" manufacturing), it is difficult to refute this view directly, due to the unpredictability of the evolution and diffusion of AMT. In the next section an effort will be made to predict the likely nature of the change, based on current trends, but here the discussion will concentrate on contemporary problems caused by the approach to the design and implementation of AMT that is encouraged by this scenario.

Many of the problems encountered with technologies such as FMS are identifiably the result of inadequate technological planning [Holz, 84] [Steinhilper, 84] [Bessant & Haywood, 85]. However, it is the author's contention that an equal if not greater source of problems is the design and implementation approach adopted for AMT, which grossly undervalues the contribution and importance of the human factor.

The "sequential" design process described by Clegg & Kemp [86] is indicative of what Broedner [85] describes as the dominant "technocentric" approach to the design of man-machine systems and their associated work organization. He defines this approach as one where;

"man-machine systems are analysed and designed on the basis of functional requirements to be realized with respect to the actual technological state of the art, where man has to take over those functions that are technically not yet solved. The systems are evaluated only by criteria of technical functionality, feasibility and economic rentability, while man is regarded as being reduced to functions he can carry out better compared to the machine"
A New Approach to the Design and Implementation of AMT

This approach is thus characterised by systems designers concentrating on the efficiency of fixed capital and largely ignoring human factors considerations until the technology has been implemented. As a result, the allocation of functions within the manufacturing system is such that operators are usually left to carry out, by default, tasks that cannot yet be executed by computers or machines. In Jones' view [86:9], this leads management to view manual operating staff; "As incidental and temporary actors, because the show is really about squeezing human costs out of the system; perhaps entirely in the long run."

As has been seen, this means that in many companies where CNC machine tools or flexible manufacturing systems have been implemented, operator tasks are limited to menial activities, such as part loading/unloading, tool changing, swarf clearance etc. Yet in a machine monitoring role, operators are still expected to intervene, and if possible correct, in the event of a system malfunction, this task requiring a high level of information processing and decision-making, particularly in complex systems such as FMS.

The "technocentric" approach, or "task and technology-centred" approach, as it has been termed by Blackler & Brown [86] (henceforth referred to as the "technology-centred" approach), is thus an extension of the principles of "Scientific Management", as developed by F.W.Taylor [Buchanan & Huczynski,85:225-260]. These principles of the division and organization of work based on rationalization, specialization and subdivision of tasks, and the minimization and standardization of skills, were originally developed as a specific approach to managing the technical, economic and social problems in American companies at the turn of the century.

Despite this origin, Scientific Management has had a lasting impact on organizational practice, particularly in companies engaged in mass production. Numerous studies have shown that assumptions implicit in Scientific Management still influence the design and organization of jobs and work today, even in companies engaged in batch manufacturing [Bailey,83:7-10]. It is not surprising that there has been such a long and persistent trend in operative job design towards specialization and the reduction of discretion, bearing in mind the advantages for the employer that have been claimed for this approach in terms of reduced costs and increased control over workplace practices [Child,84:30].

Davis [71:67] describes Scientific Management as the "machine theory of organization", because;
- Man is regarded as an extension of the machine, useful only for doing things that the machine cannot do.
- Job fragmentation is a way of reducing the costs of carrying on the work by reducing the skill contribution of the individual who performs it. Man is simply an extension of the machine, and by machine-theory logic, the more the machine is simplified (whether it is a living or non-living part), the more costs are lowered.
- Attention to the primacy of technological requirements provides an optimal outcome; conversely, satisfying the requirements of inter-related social systems merely increases costs.
A New Approach to the Design and Implementation of AMT

The view that new manufacturing technology can act as a "Trojan Horse" by providing further means for extending the principles of Scientific Management [Cooley, 87:38], provides the basis for many of the "classical" sociological theories with respect to the impact of such new technology. As summarized by Sorge et al [83:6-7], the studies of Friedman [50], Lutz [69], Kern & Schumann [71] and Braverman [74] are largely unanimous in prophesying that the introduction of new technology in manufacturing leads to more rigid bureaucratic structures with less discretion for workers at the "lower" end of the organization. Various reasons for such a development are given, for example, it is proposed that the use of computers to co-ordinate functions previously co-ordinated by supervisory staff and line managers will lead naturally to greater centralization of decision-making by fewer people. Another theory is that computerization leads to greater formalization of practices and procedures, resulting in more rigid and centralized organizations and a reduction in individual autonomy. It is argued further that there is a tendency for senior management to select and implement new technology in such a way that it supports and extends their decision-making power.

Whilst the empirical evidence presented in the previous chapter does not support these theories unequivocally, they are nonetheless useful for predicting some of the deleterious effects of the technology-centred approach. These negative consequences can be grouped into three categories: First, for the system operators; secondly, for the robustness of the manufacturing system itself; and thirdly, for management control. These consequences can be collectively termed "the Legacy of Technocentrism" [Corbett, 85].

Considering the consequences for the system operators, the studies summarized in the last chapter showed that in many companies implementing shop-floor AMT the work-structure is still based on traditional job classifications and hierarchical leadership. Thus "inflexible" and polarized organizational structures have been applied to the manning of new manufacturing technology, with the result that machine operators suffer from a loss of control over their work [Blumberg & Gerwin, 84:128]. Accordingly, local organization often remains in a "pre-AMT" form, that is, as it was with older technologies, with limited levels of skill and responsibility and highly differentiated structures. In many of the companies surveyed implementing CNC machine tools and in most companies implementing FMS, the bulk of preparatory and evaluative work for machining tasks was taken on by personnel off the shop-floor, such as programmers. This is symptomatic of a transference of decision-making further up the organizational hierarchy, that is, centralization of control, associated with the introduction of computerized equipment on the shop-floor. In the previous chapter it was found that the resultant work has little potential for motivating shop-floor workers, is not very satisfying and is stressful. According to Ingersoll Engineers [83:49]:

"The role of people in an environment which is to an increasing extent determined by computer systems which are outside their control will demand careful study by industrial management. The unsocial hours and the heavy work may well be left behind, but what takes their place could be, in its own way, even less pleasant."

Apart from this consequence it is important to reflect on the apparent policy of the technology-centred approach, that is, to replace the tasks of skilled workers wherever possible with machine functions, leaving perhaps some unskilled work to be done by people, then, in turn, to displace those doing the unskilled work entirely. This corresponds closely to Braverman's
"polarization" thesis [74]. Braverman argued that microelectronics would lead to the majority of the workforce being deskilled, whilst a few, at the top end of the organizational hierarchy, would be highly skilled and rewarded, and would have the responsibility and discretion to control the work of the majority. However, what is clear from empirical evidence is that most companies find that a high level of skill is required of direct operators if AMT is to be utilised effectively, regardless whether of a "stand-alone" or "integrated" nature.

The study of Sorge et al [83] showed that with the introduction of CNC machine tools traditional engineering craft skills, far from being rendered unnecessary by the transition to more advanced methods of small batch production, still have a vital role to play in the effective utilisation of such equipment. Furthermore, Scott [85:121-129], in his study of the manning of FMS in various British companies, reaffirmed the continued importance of craft skills, finding that machinists' traditional skills and discretion were still crucial to the continuity of production and the avoidance of downtime. Importantly, Scott found also that the selection and recruitment policies for operators of such systems showed that more highly skilled personnel were preferred by the companies studied [85:127-128]. This evidence stands in stark contrast to the assumption that shop-floor AMT can be used effectively by less-skilled labour.

However, skill-level is not necessarily a valid indicator of job content, that is, there is often a significant difference between the skills possessed by people carrying out a particular task and the skills actually used in the everyday execution of the allotted job. Clearly the skill content of a particular job is a direct function of the organization of work around a particular form of AMT [Willenborg & Krabbendam, 87:1687]. Bessant & Haywood [85:45-46] noted that many companies now give a high priority to the development of multi-skilled/disciplinary shop-floor personnel. Indeed, some specific examples of measures undertaken to encourage this development will be investigated in a later chapter. However, in a subsequent study Haywood & Bessant [87:42-44] found that in most cases skills are only integrated "horizontally" rather than "vertically". In other words, whilst many companies successfully increase the mobility of workers between jobs at similar skill levels, very few enrich jobs vertically to include planning and programming activities.

Turning to consequences for the manufacturing system itself, the most significant negative effects relate to system robustness. In all practical systems there will be some unforeseen or unalterable failures in hardware or software, which can be dealt with in three ways [Corbett,85];

i) Remove at source,

ii) Predict all disturbances and develop means of dealing with them automatically, and/or,

iii) Utilise a skilled operator to drive the system to its goal despite unforeseen disturbances.

The technology-centred approach concentrates on the first two methods, but the reluctance of companies to run even stand-alone CNC machine tools in an "unmanned" environment is indicative of the difficulty of forming computer "models" of manufacturing tasks adequate to allow such autonomous operation. Therefore, since expense and complexity would otherwise put the technology completely beyond the reach of small and medium-sized companies, most practical systems fall back on an untidy combination of all three methods.
A New Approach to the Design and Implementation of AMT

If a system's robustness is defined as its capability to withstand external disturbances and to cope with uncertainties and discontinuities, then it is clear that the availability of a skilled human to cope with such variability will be a great advantage [Corbett, 85]. Problems arise when those with the responsibility for designing or selecting AMT make choices that fragment operators' jobs and remove large parts of their skilled control of the system, yet still rely on them to deal with all unforeseen disturbances. Buchanan & Boddy [83] describe this situation, as one in which operators have "distanced roles", typical of work in "nearly automated" systems, where the effort has been made to replace traditional skills with new technology, but where experience of the remaining work equips the operators with neither the capabilities nor motivation to carry out residual, but key, functions effectively. As Corbett [85] points out;

"Clearly a technical system that does not provide the experience out of which operating skills can develop will be vulnerable in those circumstances where human intervention becomes necessary."

Given the need for continual remedial activity in complex manufacturing systems, and the significant effect that humans therefore have on system performance, particularly utilization, it would seem imperative that the training, motivation and job satisfaction of operating and maintenance personnel be given adequate priority. This is particularly important when it is considered that problems revealed in earlier sections, with respect to system reliability etc., are likely to grow as automation becomes more comprehensive. As machinery becomes more complex it also tends to become less reliable. Hence the ideal of the automated factory as a smoothly operating system free of human variability may be illusory. Instead it may well become a nightmare of uncontrollable problems requiring unanticipated human intervention at critical points and unexpected upheavals in material flow. Moreover, while the workforce may well be smaller in future production systems, it will have greater power to influence the effectiveness of much larger capital investments.

At this point it is important to mention the paradox highlighted by Clegg & Corbett [87:181];

"People, in this context might be their own worst enemies. In practice, many technologies were, and continue to be, designed on the premise that the human component in the system is inflexible and stupid, and that, where possible, the potential for human contribution should be minimized and designed out of the system, whereas, in practice, it is often people's flexibility and intelligence that allow reasonable levels of performance out of poorly designed systems."

It is interesting to observe here the process industry, where the high cost of down-time has been a motivating force behind the "enlightened" personnel practices of many companies, where workers are allowed to programme control systems, monitor and control plant, instead of passively observing instruments [Gough & Stiller, 83:10].

It is also important to mention that there is a growing body of opinion that, faced with evidence of the fragmentation of operators' skills, is beginning to ask where the next generation of skill and knowledge is to come from if the means of production is not so structured as to deal with those problems that relate to the reproduction of knowledge itself [Cooley, 86].
The third consequence of the technology-centred approach relates to management control of the production process. The primary aim of implementing computer-based technology in many companies has been to achieve a higher degree of control over manufacturing. However, the study by Blumberg & Gerwin [84:117-119] showed that the single-minded pursuit of the automated factory often leads to a "lack of fit" between the demands made by the technology and its organizational infrastructure. In addition to the motivational problems described earlier, this "lack of fit" also led to problems in quality control, maintenance and accounting. Since these are the very areas that manufacturing management counts on to control operations, the basis for judging and improving the efficiency of operations was rendered partially ineffectual. This tended to mean that the companies studied could not properly evaluate whether to purchase computer-based equipment, or effectively evaluate the equipment once it was implemented.

Given this array of potential problems associated with a technology-centred approach to the design and implementation of AMT, it is difficult to understand why this approach predominates, but a variety of factors serve to encourage and preserve its use.

First, the Scientific Management technique of division of work and task specialization, as still applied in many "modern" manufacturing systems, is in many ways self-perpetuating, as shown by Figure 5.1 below. Designing systems for low skill, low discretion work tends to lead to a decrease in job satisfaction and thereby employee commitment. This behaviour is often interpreted as indicating a need for greater control, which in turn leads new technology to be applied in such a way as to increase management control by reducing still further the skill and decision-making requirements of a job. There is thus a danger, expressed by Goodridge [86:53], that a failure to manage human resources effectively in the past, might become an excuse to use AMT to eliminate them from future strategy.

Figure 5.1 The Vicious Circle of Control [Buchanan & Huczynski85:244]
A New Approach to the Design and Implementation of AMT

A second, crucial reason for the dominance of the technology-centred approach lies in appraisal techniques for investments in new technology, that place their greatest emphasis on reducing direct labour costs. As highlighted by Hill [85:201-226] and Slatter [86], the most widely used accounting techniques concentrate on tangible benefits such as labour savings, when used to justify the purchase of manufacturing equipment. Bessant & Haywood [88] found that British companies;

"continue to seek justification for investment on the traditional basis of labour saving. It appears therefore that...we are unable to break out of an outmoded frame of reference in evaluating new technology investment."

There is a danger that such appraisal techniques could cause companies to lose sight of strategic objectives or benefits since, as observed by Jones [86:9];

"Larger flexibilities and longer-range profitabilities may be missed because management's eyes are on the trees of cost-output ratios per man-hour employed rather than on the forest of profitability from ease of product change and market response."

In any case, Hannam [85] points out that the labour costs of technologies such as FMS are generally a small proportion of total operating costs and thus the true benefits of seeking ever lower manning levels are debatable.

Thirdly, the manner in which systems are designed tends to reinforce the technology-centred approach. The complexity of many modern manufacturing systems dictates that their design be undertaken by groups of specialists. Although undoubtedly highly competent in their particular fields, their expertise generally lies outside the experience of the typical manufacturing engineer, who has limited knowledge of computers and data communications. Conversely, many systems experts have little knowledge and certainly no sustained experience of a real manufacturing environment. Such systems engineers can hardly be expected to understand the important role that the human being can play at the point of action [Craven & Slatter,88:14].

Often because of their training, system designers will view the human decision-making process in narrow systems terms, where it will be perceived as a source of uncertainty and hence will lead to the conclusion that good system design is that which reduces human intervention to a minimum [Cooley,87:37]. Furthermore, because of the esoteric nature of much of the system designer's work, the traditional manufacturing engineer can make little input at the planning stage to "modify" this viewpoint. The author's experience, though anecdotal, is that there may be insufficient consultation and, as important, even a highly experienced manufacturing engineer may feel reluctant to reveal his lack of knowledge of information technology. The system operators simply have no say whatsoever.

It is worth reflecting though that many systems designers undoubtedly regard the technical aspects as difficult enough to deal with, without the burden of having to make human factors considerations as well. One of the key objectives of the research underpinning this thesis has been to provide comparatively simple guide-lines to facilitate the inclusion of human aspects in the system design process.
A New Approach to the Design and Implementation of AMT

A fourth possible reason for the predominance of the technology-centred approach relates to the popular view that technology is used as a political tool by management to reduce the discretion of the worker over work methods [Buchanan & Huczynski, 85:243]. This view, implicit in the Marxist explanation of Braverman, mentioned earlier, is based on the belief that the development of technology is carried on in the interests of capital, and that the technology incorporates these interests in itself [Kaplinsky, 84].

However, there is precious little evidence to support this line of argument. If it did hold true, then it would be difficult to explain the uniformity of the design of work in capitalist, socialist and cooperative organizations [Rosenbrock, 84:129]. It is also worth reminding ourselves here that Lenin regarded Scientific Management techniques, the bête noire of Marxist commentators, as the best basis for Soviet industrialization [Child, 84:29].

Moreover, much of the most oft-quoted "evidence" that has been presented in support of this view is flawed. For example, Noble [79] argues that in the early days of computer-controlled machine tools numerical control was developed at the expense of record-playback technology, because it offered more scope for taking "control" away from the shop-floor. The truth lies nearer to the fact that numerical control offered a better opportunity to exploit the capabilities of the computer to produce complex components difficult, if at all possible to make on a manual and, thereby, record-playback machine tool.

A fifth reason, that ultimately provides the basis for the author's research, is that there are no accepted alternatives to the technology-centred approach. This reflects the argument that the message regarding the importance of the human aspects of AMT has failed to get across to those designing and selecting AMT. Here the author concurs with most of the observations of Clegg & Corbett [87:180-181] and Blackler & Brown [86:289-290] with respect to the difficulties of developing alternative approaches and getting them accepted.

The author's experience within both SERC/ACME and ESPRIT-funded projects confirms the contention that previously there have been too few opportunities for engineers and social scientists to undertake joint research and acquire mutual understanding of each other's fields. In both projects it also proved difficult to get manufacturing engineers to adopt a more psychologically or organizationally-oriented view of their work, especially in areas which were difficult to quantify. These problems will be discussed in more detail in a later chapter. However, the main problem was that the case for adopting an alternative approach had yet to be argued in a manner comprehensible and plausible for manufacturing and systems engineers. This thesis is an attempt to redress this problem.

In the next section the key points arising from this first part of the thesis, that together constitute the case for a new approach, will be summarized.
5.2 The Need for a New Approach

Despite the inherent problems described above, the technology-centred approach still predominates when companies select or design advanced manufacturing systems. One powerful reason offered at the start of the chapter was the implicit belief that the human aspects of AMT will gradually lose importance as the technology develops. This view rests on the belief of the inevitability and desirability of the "automated factory", that is, unmanned shop-floor. This belief is difficult to disprove and, as pointed out by Blackler & Brown [86:288], the public imagination has become dominated by "science-fiction" scenarios of robots and automated factories, the extensive use of contract labour and "homeworkers", and the widespread adoption of "intelligent" machines. This vision of the future also features with disturbing regularity in the technical literature, as exemplified by Groover [87:776-789], who states that the only "non-automated" factories of the future will be "foreign" factories with low labour rates, small businesses with marginal economic returns, companies employing emerging technologies and "companies going out of business"!

But the limited diffusion and variable results of AMT to date, as detailed in Chapter 3, raises questions as to the likelihood of a future such as that described by these "visions", even when no time-scale for such developments is given. Indeed, experience with the new manufacturing technologies has been so inconsistent that Skinner is forced to ask whether the "Factory of the Future" will always be in the future? [85:131]

A more realistic view of likely future developments can be made by extrapolating some of the trends highlighted in Chapter 2, to predict the nature of the technological changes to be expected and to speculate as to the extent to which human aspects remain important.

There is little doubt that the diffusion of "stand-alone" technologies, as represented by CNC machine tools or CAD workstations, will increase steadily, if unspectacularly. The complexity of individual machines is likely to increase, as typified by the development of CNC lathes to incorporate "live" tooling, automated workpiece handling and measurement etc. Furthermore, efforts will be made to make it easier to incorporate such stand-alone technologies into integrated systems, by means of data communications standards etc.

At the same time, more companies will implement integrated systems, such as FMS or CAD/CAM, expectant of improved performance by being able to better co-ordinate activities through improved information flow and control. Similar hopes will drive considerable efforts to develop computer-integrated manufacturing systems. However, with the exception of government-funded "showpiece" projects and implementation in highly predictable, that is, low variability production environments, such as in the mass production of cars or consumer electronics, progress will be gradual and is unlikely to extend as far as "unmanned" factories. This will be the result not only of a lack of reliable enabling technologies, but also of the inability of most companies to address adequately the complexities and expense of extensive system integration.
A New Approach to the Design and Implementation of AMT

As indicated in Chapter 2, the area where AMT has the greatest potential impact is in companies engaged in small- and medium-batch production. Here, too, progress is likely to be slower than predicted and will lead to AMT being implemented in the midst of older technologies. Accordingly, a situation in which "islands of automation" feature in such companies is likely to persist for the foreseeable future. As pointed out by Clegg & Corbett [87:180], in such cases the performance of the new technologies will be influenced by working practices for the old, with the result that it will become increasingly common for larger companies to try to avoid such problems by implementing their newest production technologies at separate production units set up on "green-field" sites.

With respect to the effect of AMT on the market, those companies that keep sight of strategic objectives when implementing AMT and are successful in increasing their competitiveness by improving their market response, will thereby encourage customers to demand more choice and better service. Thus AMT, by at once encouraging and enabling more product variants to be offered in smaller batch sizes, is likely to increase the level of "uncertainty" in the market.

There is every indication that flexibility of response will become a key competitive factor in the future, not just in batch manufacture, but also in mass production industries [De Meyer,87] [Slack,88]. This pressure for increased flexibility will be passed on from the larger high-volume production companies to their smaller suppliers, such that the feature of high production variability is likely to pervade the metalworking market.

Bearing in mind the discussion of Chapter 4, then future developments along the lines described above lead to a clear conclusion: The human aspects of AMT will remain important for the foreseeable future and, indeed, are likely to increase in importance.

It was shown earlier that integrated systems, that cut across existing organizational structures, can only achieve the desired benefits of improved information flow and closer operational control if corresponding organizational changes are made. A considerable volume of empirical evidence indicates that the real benefits are derived from role convergence or the tighter coupling of roles that is enabled by AMT, rather than from the technology alone. Accordingly, more extensive diffusion of more highly integrated systems will demand greater attention to organizational design if these systems are to be fully successful.

Furthermore, as AMT systems increase in size, sophistication and complexity, so the need grows for well-trained, well-managed and well-co-ordinated support from operators, engineers, programmers and managers. It is clear from the earlier discussion that the advanced technologies of the future will not design, run, support or manage themselves any more than did their simpler predecessors. Indeed, the evidence would indicate that the greater the complexity of a given system, the more it's performance is a function of the skills of it's operator(s). This relationship is shown by the studies of Sorge et al [83] and Daly et al [85], which both showed that the better performance obtained from CNC machine tools in West Germany, when compared to Britain, was not a function of how advanced the technology used was, but rather of the skill level and educational background of the operators involved.
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Increasing system complexity implies, in turn, that systems must be designed so that they are comprehensible to the operators if performance is to be satisfactory, though Alic warns: "Improving the efficiency of such systems will take more than user-friendly computer programs or well-designed instrument and control panels, common data-bases or far-flung management information systems. It will take a better sense of how to allocate tasks and responsibility among people and their machines." [84:11]

This view will grow in importance as advanced manufacturing systems are increasingly applied to, and indeed themselves encourage, what we can term "uncertain" production environments. The discussion in Chapter 4 showed how increasing uncertainty places a premium on the problem-solving abilities and skills of direct production personnel, and on the capability to apply these skills flexibly and organize them effectively.

Thus, all the leading indicators point to a future role for humans in advanced manufacturing systems that will be as important, if not more important, than this role today.

If we accept this view of the future, in which it becomes essential to carefully consider and consistently design for the human aspects of new manufacturing systems, then we are at once confronted with a fundamental flaw in the technology-centred approach to the design and implementation of this technology.

This approach, related as it is to a vision of the unmanned factory, has led automation to be associated with the polarization and differentiation of skills away from shop-floor functions and direct production personnel. Increased productivity and capital intensity have therefore been associated with a "crowding out" of shop-floor workers. These principles are embodied in the design of the majority of present generation FMSs, which, as shown in Chapter 3, are characterised by limited flexibility, limited diffusion and questionable success in high variability environments, as well as a work organization with strict vertical and horizontal division of labour.

Moreover, FMS is used most frequently in companies engaged in low variety, medium- to high-volume production, rather than in high variety, small batch production as conventionally portrayed and predicted in the technical literature. This would seem to lend support to the view of Sorge et al [83:162], that this approach to automation is founded on past experience with the expansion of homogeneous mass markets with stable demand for specialized products over time, that is, with a low variability production environment.

However, as explained above, the market is characterised by increasing variability. Sorge et al argue that in this new environment it will be inappropriate to refer to the impact of new technology as "automation", which raises connotations of empty factories, because increasing productivity, increasing flexibility and increasing use of computer-based technologies on the shop-floor will be associated with the continued presence of directly intervening production personnel. Whilst reduced in number, labour will not necessarily be "crowded out", and a key effect of the new technology will be to depolarize and integrate skills, as shown in Figure 5.2 overleaf.
Thus FMS can be viewed as part of a "misguided trend extrapolation" [83:162-163], that is, a misunderstanding of the most effective way to apply AMT in batch manufacturing. As stated by Goodridge [86:53], there is a fundamental flaw in that this trend is based on the assumption "that employees, particularly at the operative level, can be designed out. The traditional role of management as omnipotent masters of ill-behaved labour is enforced."

It can be argued that the first evidence for this view is already at hand, since "complex FMSs" have been conspicuous by their absence at recent machine tool exhibitions, vendors focusing their efforts instead on more "compliant" stand-alone machine tools and flexible machining cells.

Broedner describes the current situation as one in which; "The factory of the future is at the crossroads." [86:5], implying that a new path of technological development must now be taken if the real opportunities provided by AMT are to be fully exploited. If systems for batch manufacturing continue to be designed using a technology-centred approach, then the likely results will be an increasing "lack of fit" between the technology and its organizational infrastructure, expectations not being met as a consequence and slow diffusion. Blumberg & Gerwin [84:127] suggest that companies should cease to strive towards the "automated factory" and concentrate rather on simpler technologies more compatible with their skills and organization, but as Senker [84:230] rightly points out, this approach runs the risk that competitors will be successful in achieving strategic benefits from the advanced technologies.

A better policy is to seek to match the latest technology with an appropriate organizational infrastructure. Here, it is important to reflect that in Chapter 4 it was shown that new computer-based manufacturing technologies not only provides opportunities for organizational change, but can also act as a constraint. Certainly, the limited "compliance" of much of the equipment in contemporary manufacturing systems constrains decision-making freedom with respect to modifications to the organization of work associated with the system. This is an important point to consider when attempting to design new systems that enable and encourage appropriate organizational changes, because;

"Proceeding on the assumption that the room for designing work is limited by technical and organizational conditions, the technical ones being primary and decisive, organizational variations can than only slightly influence the consequences of a certain technical alternative for human work. Therefore guide-lines for design should be devised which can intervene at the earliest stages of planning and development engineering of the technology." [Wittkowsky & Gottschalch, 87:5]

In other words, what is required is a "holistic" or "total system" approach, where the technology and associated organizational infrastructure are designed in parallel. To quote Child [87:108]:

"The guiding principle lies in the integration of both technological and organizational design to suit strategic requirements, and in so doing to organize in a way that helps to break down barriers of perspective and discourse between those responsible for strategic, technological and work organizational policies within the enterprise, as well as between the people who contribute to different stages of the production cycle itself."
A New Approach to the Design and Implementation of AMT

Part II of this thesis describes the development of such a holistic approach and details its practical application to the design and implementation of flexible machining cells, both in research and industrial environments.

Figure 5.2 A New View of "Automation" [Sorge et al, 83:162-163]
6. Human-Centred AMT

In the preceding chapter the need for a "holistic" approach to manufacturing system design was established. Without such an approach, whereby technology and its organizational infrastructure are designed in parallel, it is unlikely that the full strategic benefits of AMT will be realized.

In order to provide necessary background information for the development of guidelines upon which to base a change process of this nature, it is sensible to review the knowledge-base comprising previous research into job design and work structuring. Commensurate with this aim, the first section of this chapter concentrates on a brief historical review of the efforts of social science researchers to develop new criteria for effective job design and work organization. The second section focuses on a description of the basic principles of a new "human-centred" approach to the design and implementation of AMT. This approach, drawing on the experience and problems of previous research, provides an interesting alternative to the "technology-centred" approach, as well as the basis for the author's practical research efforts, to be described in subsequent chapters.

6.1 Technology and Work Design

In reviewing the efforts of the social science community to influence the way in which new technology is applied in organizations, the discussion will concentrate on three approaches of particular importance and relevance to the authors research:

i) Ergonomics
ii) Psychology of work and job design
iii) Participative System Design

The discussion will concentrate on a brief historical review and a description of current thinking in each of these areas, together with an analysis of the key limitations of each approach. The three different perspectives are treated separately for the purpose of explanation, but as will become more apparent in practice they overlap and share common aspects.

No effort will be made to go into the fundamentals of behavioural science, or organizational theory, these being covered in more detail elsewhere [Brown,80] [Handy,81] [Child,84] [Bailey,83].

6.1.1 Ergonomics

Ergonomics, also often referred to as "human factors engineering", is primarily concerned with the study of equipment, methods, layout and environment of work in terms of human abilities and limitations, that is, with designing equipment for human use. Typical issues, therefore, include workplace layout, design of instrument panels etc. The basic unit of analysis is the man-machine
system, and the main factors regarded as dependent on system design are system efficiency and the demands made on operator knowledge and skill.

In the 1950s the central issue for ergonomists was the division of tasks between operators and machines, and Table 6.1 is typical of the resultant HABA/MABA lists (*Humans Are Better At Versus Machines Are Better At*) [Clegg, 88:29].

<table>
<thead>
<tr>
<th>People</th>
<th>Machines</th>
</tr>
</thead>
<tbody>
<tr>
<td>are flexible</td>
<td>are rigid</td>
</tr>
<tr>
<td>can cope with uncertainty</td>
<td>cannot cope with uncertainty</td>
</tr>
<tr>
<td>can perceive and organize information</td>
<td>have limited ability to organize information</td>
</tr>
<tr>
<td>keep going when parts fail</td>
<td>stop when parts fail</td>
</tr>
<tr>
<td>get tired, bored and distracted</td>
<td>keep going for long periods</td>
</tr>
<tr>
<td>are slow at computing</td>
<td>are fast at computing</td>
</tr>
<tr>
<td>have limited information storage ability</td>
<td>have unlimited information storage ability</td>
</tr>
</tbody>
</table>

Such lists are based on the conventional wisdom of that time, which was that human operators were at their best when doing least, that is, the ultimate goal was to design systems requiring little or no human intervention, the *comparative* design approach encouraged by lists comparing the respective abilities of people and technology involved system designers simply analysing the functions of the required system and allocating tasks to operators and machines according to the list.

As pointed out by [Buchanan & Boddy, 83:23] though, this approach was not without problems:

- a) As generalizations, these comparisons always fail,
- b) System designers satisfice rather than maximize their designs,
- c) Factors other than cost and efficiency affect allocation decisions,
- d) As technology develops, the comparative advantages change,
- e) Engineering precision and reliability problems prevent clear choices.

Furthermore, Jordan [63] argued that it was wrong to *compare* people with machines in this way, since they are more correctly viewed as *complementary*. He identified four components of *complementarity* where people are required to cope with contingencies; for maintenance, for repair; as manual backup; and to take responsibility for getting the work done. Jordan had observed effects similar to those described above for the technology-centred approach, where operators are only given those tasks too difficult or too expensive to design into machinery, and are only given enough information and means to perform a 'link' role.
Human-Centred AMT

This approach has the inherent problem that when the system breaks down

"a man in a link position is as helpless as any other machine component in the system. We have tended to design out this ability to take over as a manual backup to the system."

[63:36].

The concept of complementarity was taken up by subsequent researchers with the result that the operator in a man-machine system is now regarded as an information processor and machine controller. This has led, in turn, to a change of emphasis, in that the aim is now not to reduce errors by eliminating human intervention, but by utilising human flexibility to guarantee reliability. Thus, as Singleton [74] argues, it is more appropriate to regard human operators as central components in system design and to delegate, rather than allocate functions to equipment.

The bulk of human factors research in the manufacturing industry has been concentrated on equipment for use in continuous flow or mass production environments, where the operators act as supervisory controllers. It is interesting to note here how problems encountered with the implementation of automated process controllers, such as a loss of manual skills on behalf of system operators that may be required when the automated system breaks down, are similar to problems encountered with more integrated forms of AMT, such as FMS, in discrete parts manufacture. Accordingly, work by ergonomists in this area, such as the supervisory control paradigm developed by Sheridan [76], has been applied recently to the allocation of functions between humans and computers in an FMS, where Hwang et al [84] and Barfield et al [86] have produced tables comparing the capabilities of humans and computers in operation and control tasks.

However, these lists still suffer from a number of the problems described above and, more importantly, the focus on cognitive, visual and anthropometric factors means that the crucial relevance of factors such as authority structures and patterns of control etc are overlooked. This leads Blacker & Brown to warn that,

"it would be foolish to expect human factors engineering, practised in isolation from other social science approaches, to do much to alert people to the broad organizational options that the new information technologies make possible." [86:290].

6.1.2 Psychology of Work and Job Design

Although psychologists have highlighted the negative effects of "Scientific Management" principles since the 1920s, it was the production demands of the Second World War that first brought the effects of job design and work organization on employee morale and productivity to general attention. During the 1950s there was increasing concern that the fragmented, repetitive and boring jobs in highly structured manufacturing environments were leading to a "de-humanization" of work, resulting in increasing employee dissatisfaction and inefficiency. In terms of research effort, the main focus of attention was work on long flow-production lines with short cycle times, where operators repeated the same simple task very many times during the working day, but many problems were also associated with the batch production functional layout shop, where it is essential to plan and control the whole working day of each individual.
The central concern of the new job design approaches that began to be developed at that time, was to take human skills, abilities and motivation into account when allocating tasks and organizing work.

Importantly, these approaches have developed with two different units of analysis as shown in Figure 6.2. Job restructuring, or job redesign approaches, including job design techniques such as job rotation, job enlargement and job enrichment, take the individual job as the unit of analysis. These techniques were all originally associated with work by different American psychologists. Work organization approaches, on the other hand, take the work group as the unit of analysis, and have been developed and applied mainly in Britain and Scandinavia, with the most fundamental contribution being made by researchers connected with the Tavistock Institute of Human Relations in London. The key principles of this latter approach are shown in Figure 6.3.

**Figure 6.2 Job Restructuring and Work Organization [Wild, 84:238].**

**Job Rotation**

Job rotation involves rotating people between jobs on the same horizontal plane, either on an agreed or informal basis. This goes some way to achieving some of the desirable job characteristics of increased variety, use of different skills and the opportunity to learn. It offers management the potential benefits of increased operator skills and therefore increased flexibility. However, despite quite extensive use, it makes only a limited contribution to improving the motivational content of jobs.
Job Enlargement

Job enlargement involves combining a number of tasks on the horizontal plane to increase the work cycle time and create more complete and hence more meaningful jobs. It has the effect of reducing the degree of specialization involved and may, particularly where use is made of buffer stocks, reduce the degree of pacing in an individual's job. Nevertheless, as with job rotation, some of the other desirable job attributes, such as increased autonomy, decision-making, interaction and responsibility are not fulfilled. This has led to criticism of both job enlargement and rotation, since "adding one mickey mouse job to another does not make any more than two mickey mouse jobs" [Child, 77:35].

Job Enrichment

Job enrichment, by contrast, introduces changes on the vertical plane by giving operators greater responsibility for decisions relating to their work. Accordingly, they may be involved in the planning and organization of their work, for quality control, or certain tasks of routine maintenance. The aim and effect of this reduction in vertical specialization is to enhance the motivational content of jobs in terms of increased autonomy, decision-making, responsibility, recognition and individual
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devlopment. Importantly, job enrichment has significant organizational implications, since it gives employees greater involvement in decisions that have traditionally been the responsibility of management or specialist functions.

Group Working

A criticism of the job restructuring approach to job design is that their focus is on individual jobs rather than on work groups. In many environments work groups can be identified where closely-related jobs contribute to a common task which can be distinguished from other tasks in the production system. As pointed out by Child [84:351 there are various reasons that the work group should be the focus of design rather than individual jobs. First, the effective functioning of work systems is generally the result of group activity rather than individual activity carried out in isolation. Secondly, a group-based approach to work design offers more scope for individual differences in competence and preference to be taken into account when tasks are allocated, than does a job-by-job approach. Thirdly, a group-based organization provides for more effective learning, since problems can be readily discussed with colleagues and information shared.

Work organization experiments, primarily in Scandinavia, as reviewed by Sandberg [82], have led to considerable success with autonomous work groups in which groups of workers are made responsible for the allocation and scheduling of their own work within a whole activity cycle, for example, assembling a complete car engine. Advantages of group work of this nature include an increase in the confidence of workers through recognition of important skills, development of social skills and the opportunity to influence and exercise leadership. The group setting is regarded as providing support, encouragement and security and, since individuals are interdependent, there is more scope for delegating complete task responsibility to the group.

As implicit in the above summary autonomous work groups, like the job restructuring techniques described earlier, have been applied predominantly in mass production environments, notably in the automotive industry [Bailey,83:106-112]. But the concept of autonomous groups working is one aspect of a wider perspective on the way in which organizations function, namely the systems approach. As outlined by Buchanan & Huczynski [85:250-253], this relates to the idea of the enterprise as a socio-technical system, a concept that has formed the basis for a number of experiments in a batch manufacturing environment.

Socio-Technical System Design

The socio-technical system approach was developed through studies carried out by research at the Tavistock Institute of Human Relations, notably by Eric Trist [Trist et al, 63]. The concept of a socio-technical system arises from the fact that any production system requires both technology and a social organization of the people who operate the equipment. Trist argued that the social organization has social and psychological properties that are not dependent on the demands of the technology. This means, importantly, that the socio-technical systems approach rejects the concept of technological determinism. The system design problem is then to find the "best fit" between the social and technical components which are not completely independent. They must be designed in such a way that the needs of each aspect are met as fully as possible. If the technical system is designed without taking into account the needs of the social system, then the system as a whole will not operate effectively. Conversely, the social system design must be
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consistent with the demands of the technical system. The corresponding design process is shown diagramatically in Figure 6.4.

Figure 6.4 Socio-Technical Systems Design [Mumford, 83:58].

As summarized by Mumford [83:57] the studies undertaken by Tavistock Institute led to a set of work design principles intended to act as an "antidote" to the Scientific Management philosophy of small tasks, tight controls and limited responsibility:

1. The work system, comprising a number of logically integrated tasks or unit operations, should be the basic design unit, rather than the single tasks or operations that together form the system.

2. The work group should be the primary social unit, not the individual job holder.

3. Internal regulation should be by the work group itself.

4. Because the work group is the primary social unit, the jobs of individuals should be multi-skilled.
5. Greater emphasis should be placed on the discretionary as opposed to the prescribed part of the work roles.

6. People should be treated as complementary to machines, not as extensions of, or subservient to, machines.

7. Work organizations should be aimed at increasing, not decreasing work variety.

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The particular importance of this approach for work design in a batch manufacturing environment lies in its association with Group Technology. As outlined in Chapter 2, GT involves a reorganization of the shopfloor, away from a functional layout, in favour of the grouping of machines in cells by contribution to a common product, or family of parts. This change has the potential to greatly simplify problems of co-ordinating work between different functional operations, reduce the level of work-in-progress and simplify the overall workflow. Typically, the cell operators carry out a variety of operations on dissimilar machines, and in some examples the control of material flow, and balancing of workload for equipment and personnel has also been delegated to the cell personnel. The potential not only for job enlargement and rotation, but also for increasing work group autonomy that GT thus provides, suggested that sociological needs coincided with technological needs and that the two streams of thought would complement each other. [Lockyer, 83:172].

Indeed, there are many examples of experiments in which the "human benefits" of autonomous groups working played a not insignificant role in the overall success of GT implementation [Williamson, 72] [Craven, 74] [Sandberg, 82]. Despite such apparent successes, neither the technical nor human case for GT has been without criticism. Leonard & Rathmill [77] and Huber & Hyer [85] point out a number of key constraints on the applicability of GT cells and question whether expected benefits, such as increased autonomy, are in fact experienced in practice.

Nevertheless, GT and autonomous work groups have provided the basis for more recent experiments incorporating CNC machine tools within machining cells. Bjorke [80] describes a flexible machining cell incorporating robotic workhandling that was developed at the Production Engineering Laboratory of the NTH-SINTEF in Trondheim, Norway. A key feature of this project is vertical job enrichment for the cell operators, with the cell work group being responsible for technological planning, production planning, quality control and production control activities within the cell.

A similar project has been undertaken in an industrial environment in the pump-making factory of Sulzer Weise in West Germany. This project, carried out in collaboration with the Rhein-Ruhr University in Bochum, involved the development of an "autonomous production island" for the manufacture of small size, small batch components for centrifugal pumps [Witte, 83] [Gauderon, 83] [Massberg & Kreimeier, 86]. In this island, 'autonomy' meant the delegation of essential production planning and control tasks, with a time horizon of two weeks, to the cell operators. It is interesting to note that while long lead-times and an excessive administrative burden in production planning and control provided motivation for the search for a "new solution"
to the company's problems, an equally important reason offered by the company was a perceived need to offer modern and attractive jobs [Gauderon, 83:80].

The concept of autonomous work groups has also been applied to FMS, as in the example of the FMS at Zahnradfabrik Friedrichshafen (ZF) in West Germany, which is used for the production of gears. The "alternative" approach to the manning of this FMS is characterized by the following features

- the FMS features homogeneous job structures at a high skill level.
- the tasks within the FMS can be carried out by each of the workers, who rotate to different tasks
- the planning and preparation of production tasks is mainly executed by the "FMS-team" itself; only the most demanding programming and major repairs have to be carried out by staff from outside the team [Koehler & Schultz-Wild, 83].

This approach, with its low division of labour, contrasts strongly with the "traditional" work organization typical of the majority of current FMS installations, with its pronounced vertical and horizontal division of labour, as shown in Figure 6.5 (b).

Figure 6.5 a) Floor-plan of FMS at ZF, West Germany
In concluding this brief review of experiments in socio-technical system design it is important to note two features common to most of these studies. First, they have tended to concentrate on the variations thought possible on the social side of the equation alone, that is, they have focused on improving the social system associated with a given technology but have not contributed to the design of this technology. It is only recently, mainly as a result of the emergence of information technology, and its application in manufacturing in the form of AMT, that the central question of how the technology itself should be designed, has come to be addressed. This has revealed a weakness in this approach, namely that it proves difficult to use by designers working on novel projects. That is, when applied to situations where no known solutions have yet been produced, and therefore observations of, and consultation with, existing workers is not possible, the ‘principles’ of socio-technical system design are difficult to apply [Blackler & Brown, 86:291].

The second common feature is that the experiments have generally involved shop-floor personnel and have not involved office personnel or been used in the design of higher levels of the organization. This represents another gap in the knowledge-base available to guide new experiments with AMT, since the capability of AMT to integrate activities in the vertical plane, for example, the integration of CAD with NC part programming means that the design of future production systems will need to consider multiple levels in the organization.

In reviewing the impact of job design approaches as a whole, Child [84:43] observes that the scale and scope of experiments in job redesign and work restructuring remains extremely limited.
One reason provided as explanation for the small number of experiments is resistance to job and work redesign. Not only will junior management and supervisors frequently resist increases in the responsibility and autonomy of shop-floor workers that threaten their traditional roles and authority, but there is also considerable evidence from failed experiments that many workers do not wish to assume greater responsibility or commitment to their work. Child goes on to make the important points that in many experiments, including some of the best-known, job redesign and work restructuring has only applied to a small proportion of the workforce and, in several cases, the new designs and structures have "regressed" over time to more conventional ways of working [84: 43-48].

6.1.3 Participative Systems Design

The third approach to the application of new technology that is of direct interest to the author's work, is participative systems design, whereby part of the responsibility for the design of a new work system is handed over to the staff that will eventually use it. This approach has been applied in a number of experiments in Scandinavia and in the USA, but the focus of our attention here is the ETHICS (Effective Technical and Human Implementation of Computer-Based Systems) method, developed by Enid Mumford at the Manchester Business School [Mumford, 83]. Notably, this method is based on a socio-technical systems approach and as suggested by its title, has been primarily associated with the introduction of computers. This approach, which has been developed as a result of action research projects in a number of companies, involves the development of a framework and guidelines for the process of analysis, diagnosis and consideration of design alternatives, and also for participation in the process and production of the ultimate design. The objective of this participative design process is to maximise job satisfaction by achieving the "best fit" between employee expectations and the actual requirements of the work organization.

The basic stages in this design process are:

1. **Diagnosis**
   - This is the diagnosis of the job satisfaction and efficiency needs of any group of employees whose work is to be redesigned.

2. **Objectives**
   - Here job satisfaction and efficiency objectives are set in such a way that it is possible later to measure whether or not they have been achieved.

3. **Alternatives**
   - Once a diagram has been made of human and efficiency needs and problems, then alternative ways of meeting these needs and solving these problems must be formulated and the human and technical advantages and disadvantages of each alternative must be set out.

4. **Work Design Approaches**
   - Particular attention must be paid to the best way of restructuring work so as to achieve job satisfaction and efficiency objectives.
5. The Design Process - a decision must be taken on the best ways of handling the process of design and implementation so that the enthusiasm and co-operation of employees is stimulated and maintained.

Whilst proponents claim that this design approach can bring considerable advantages in terms of the "ownership" that people feel for the new system and their level of involvement in the problems and performance of the system as a whole, there is also evidence of shortcomings. A general criticism from a management perspective is that participative design is slow and expensive when compared to "conventional" system design approaches, whilst Trade Unions fear manipulation, in the sense that user involvement in system design will only be tolerated by management as long as it does not extend beyond very limited boundaries [Fricke, 83] [Frei, 83].

Other problems constraining effective employee participation in systems development result from unfamiliarity with the technology involved. Particularly in the case of a complex and versatile enabling technology such as IT, employees may not be aware of the full range of options that they could consider, nor are they likely to have much more than a superficial understanding of the alternative hard/software that is available, or of the technical solutions that are possible [Blackler & Brown, 86:295]. Furthermore, user involvement is not possible when a system is being designed for sale on the general market, where users are yet to be identified on any but a very general level [Corbett, 85]

6.1.4 Conclusions

A useful summary of alternative approaches to the design and implementation of new computer-based technologies into work organizations is provided by Blackler & Brown [86]. They have developed three models of the process of introduction of new technology, which are shown in Tables 6.1, 6.2 and 6.3.

Model 1, termed the 'task and technology approach,' relates directly to the 'technology-centred' approach described in the preceding chapter. Model 2, termed the 'organization and end-user approach' represents an approach where human and organizational issues are taken into account, and serves to summarize the principal recommendations of the various social science approaches discussed above. Model 0 represents the view of the practice in many companies, as described in Chapters 3 and 4.

The model 0 is indicative of the lack of influence of social science recommendations on the way that new technologies are implemented. Given the limitations highlighted for each of the different approaches, this is not altogether surprising, but Blackler & Brown [86:287] blame this situation on the "prevailing climate of opinion" which they regard as "not being very supportive of social science orientations." A more self-critical view is adopted by Clegg [88:33], who makes the point that most social science approaches are based on "negative justification," that is, concerned with avoiding problems, rather than being based on predicted benefits or positive opportunities.
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### Table 6.1 Task and Technology Approach [Blackler & Brown, 86:298]

<table>
<thead>
<tr>
<th>Phases</th>
<th>Guiding premises</th>
<th>Key actors</th>
<th>Work organization issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial review (initial recognition of possible opportunity)</td>
<td>In addition to operating considerations is the view that people are a costly resource to the organization to be reduced if possible</td>
<td>Top management, or senior management from operating divisions</td>
<td>General concern with reduction of operating costs, with quality, flexibility and operational control</td>
</tr>
<tr>
<td>2. Exploration and prior justification (analysis, discussion, feasibility review, recommendations)</td>
<td>Tightly prescribed planning objectives formulated at this stage Central coordination and control Heavy reliance on the views of experts &quot;Most modern&quot; syndrome</td>
<td>Managerial project team, including technical experts, approved by top/central management and their financial advisers</td>
<td>Change used as an opportunity to review current operational arrangements Policies formulated on equipment, work system and planning levels Technical and operational considerations a priority</td>
</tr>
<tr>
<td>3. Design of system (design operationalization and detail or &quot;off the shelf&quot; choice)</td>
<td>Machines over people Task fragmentation &quot;Clean design.&quot; &quot;Final design.&quot;</td>
<td>Design engineers, technical consultants</td>
<td>Specific design work including automation, staffing arrangements and ergonomic considerations</td>
</tr>
<tr>
<td>4. Implementation (construction or installation, trial, operation)</td>
<td>Emphasis on machine capability Minor modifications only are expected Once-off skill training for operators Responsibility for operation passes to line management</td>
<td>Design engineers, consultants, manufacturers, line management, end-users Union negotiates over conditions of employment</td>
<td>The detail of design errors are corrected Operating issues resolved and roles determined Operator training completed</td>
</tr>
</tbody>
</table>

### Table 6.2 Organization and End-User Approach [Blackler & Brown, 86:299]

<table>
<thead>
<tr>
<th>Phases</th>
<th>Guiding premises</th>
<th>Key actors</th>
<th>Work organization issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial review (initial recognition of possible opportunity)</td>
<td>In addition to operating considerations is the view that people are a costly resource to the organization that should be more fully utilized</td>
<td>Initially from any part of organization then with top management</td>
<td>General concern with reduction of costs, and with quality and flexibility. Opportunities sought to increase employee contributions and organizational integration</td>
</tr>
<tr>
<td>2. Exploration and prior justification (analysis, discussion, feasibility, review, recommendations)</td>
<td>General policy on objectives formulated at this time Decentralization and attention to potential for expanding staff involvement Concern with involvement of potential users Priority to system development potential rather than machine capability</td>
<td>A diverse and representative group, or consulting project group or management plus &quot;shadow&quot; group</td>
<td>Change used as an opportunity to review current operational and organizational arrangements Policies formulated on equipment, work system and manpower levels Attention in the policy to organizational priorities as well as functional matters</td>
</tr>
<tr>
<td>3. Design of system (design operationalization and detail or &quot;off the shelf&quot; choice)</td>
<td>People to use machines Job enrichment, team working and intergroup liaison Priority to operator needs and to maintenance facilitation Incremental and educational approach to the design process</td>
<td>Design engineers, technical consultants, behavioural advisers working with mixed group, project group, or and management and &quot;shadow&quot; group</td>
<td>Specific design work including automation, staffing arrangements and ergonomic considerations Consideration of the likely social and psychological impact of the designs</td>
</tr>
<tr>
<td>4. Implementation (construction or installation, trial, operation)</td>
<td>Emphasis on user support Pilot projects used where possible Continuing staff and organization development anticipated Continuing reviews of operation of system and of problems and needs</td>
<td>Design engineers, consultants, manufacturer, line manager, end-users, union representatives</td>
<td>Ongoing system, employee and organizational development Adaptability of work roles</td>
</tr>
</tbody>
</table>

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Furthermore, whilst there is seemingly no limit to studies of the problems associated with particular technological solutions, and generalized advice on what to achieve and avoid in the way of human aspects, there is:

"precious little in the way of models, checklists, methodologies or tools to help practitioners solve their problems, and this is particularly true with respect to strategic choices over the sorts of technology to be pursued, the allocation of system functions, the choice of appropriate organization designs, and the design of methods and procedures for managing change more appropriately."

This reflects what Clegg & Corbett [87:182] refer to as a "retrospective" methodological bias in the bulk of the work to date by social scientists in this field, though what is clearly needed today are recommendations for the design of new systems, so that they incorporate human considerations from the outset.

Table 6.3 Dominant "Practical" Approach ("Muddling Through") [Blackler & Brown, 86:304]

<table>
<thead>
<tr>
<th>Phases</th>
<th>Guiding assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Initial review</td>
<td>Vague awareness that interesting technologies are becoming available</td>
</tr>
<tr>
<td>2. Exploration and</td>
<td>Fascination with the technology</td>
</tr>
<tr>
<td>prior justification</td>
<td>Expectations that it can be &quot;injected&quot; within present organizational arrangements</td>
</tr>
<tr>
<td></td>
<td>Short-term marginal improvements sought</td>
</tr>
<tr>
<td></td>
<td>Short-term return on investment orientation</td>
</tr>
<tr>
<td>3. Design of system</td>
<td>Technological development understood to be controlled by inherent laws</td>
</tr>
<tr>
<td></td>
<td>Heavy reliance on systems designers</td>
</tr>
<tr>
<td></td>
<td>Heavy reliance on the promises of suppliers</td>
</tr>
<tr>
<td></td>
<td>Machines to enable staff economies</td>
</tr>
<tr>
<td>4. Implementation</td>
<td>&quot;Compensation&quot; approach to the unions</td>
</tr>
<tr>
<td></td>
<td>Unanticipated preoccupation with systems debugging</td>
</tr>
<tr>
<td></td>
<td>Unanticipated organizational problems, staff motivation, demarcation disputes, etc.</td>
</tr>
<tr>
<td></td>
<td>Unanticipated need to undertake staff training and to resource end-users</td>
</tr>
</tbody>
</table>
6.2 Human-Centred AMT - A New Approach

A notable exception to the retrospective research described in the previous section is emergent research into "human-centred" systems, where human aspects are considered explicitly from the beginning of the design process.

This approach, pioneered by Rosenbrock, [84], Broedner [86] and Cooley [87] is based on a fear that AMT may act as a means by which to extend Scientific Management principles of skill fragmentation to human mental work, that is, just as machines have substituted human physical labour, so computer-based equipment will increasingly come to substitute human mental effort. This fear is founded on the uncertainty regarding the future role of AMT. Whilst the inherent compliance of information technology, particularly with respect to software, provides system designers with the opportunity to enrich operators' work and so improve the quality of working-life, the ever increasing information processing power and control capabilities of the new technology enables a wider range of human manual and cognitive skills to be incorporated into hardware and software.

Whereas "first generation" AMT, for example, stand-alone CNC machine tools, does not appear to be necessarily associated with fragmentation or simplification of work, more highly integrated "second generation" AMT, such as FMS, is often associated with jobs with low levels of control over work methods and the place of work, yet with high levels of attentional and cognitive demand [Corbett, 88]. This leads to the understandable worry that "third generation" AMT, in the form of computer-integrated manufacturing, will lead to a further subordination of operators to machines, and will extend deskilling effects into functions such as design [Cooley, 87:40].

Both Rosenbrock [84:127] and Cooley [87:37] perceive a path of development for AMT that is leading to an increasing marginalization of human intelligence, with the result that one of the major assets of any company, namely the skill, ingenuity, creativity and enthusiasm of its workers, goes to waste.

In itself, this is by no means a new viewpoint, as shown by the following quote from Williamson [72:140], who in turn acknowledges the earlier ideas of Skinner [71]:

"The scientist and the engineer by their mechanistic concepts, initially in the relationship between man, machines and processes, and continued more recently in the field of computers and information handling, have encouraged a belief in the superiority of the machine. We seem to be encouraging a ludicrous vision of industry where computers will do the decision-making, while men provide low-grade motive-or brain-power to carry out increasingly simple and repetitive tasks.

A little reflection reveals the ultimate lunacy of such a proposition, and it can be recognized for what it is, a misuse of technology, and a misunderstanding of the proper functions of man and machine."

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Whilst agreeing with this viewpoint, Broedner [88] takes a wider perspective, similar to that expressed in Chapter 4, namely that the flexibility of production demanded by current market imperatives is incompatible with deskilling and constraining the autonomy of shop-floor workers.

Like Williamson before him, Rosenbrock [84:129] lays the blame for this apparent path of development on the conventional design values of scientists and engineers. He expresses this view thus:

"Is there something which human beings will always do better than machines? (where computers are included among machines). To answer yes, we either have to believe that human beings have properties not possessed by machines, or we have to believe that our ability to construct machines is inherently limited. That is, we shall never, despite all advances in science and technology, be able to build a machine which has capacities equal to or exceeding those of a human being. It is self evident from their writings that a great many scientists and technologists do not hold either of these beliefs" [84:131].

Rosenbrock thus considers the scientific-technological outlook as the primary reason for the predominance of the technology-centred approach, with its vision of the workerless factory.

Rather than minimising the scope for human intervention, the "human-centred" approach to system design, presented as an antithesis to technology-centred design, is based on the principle of the complementarity of machines and people, and therefore takes account of, and seeks to enhance, the skills and abilities of the system operators. Broedner defines the anthropocentric, or human-centred approach as one which:

"Regards man as acting consciously and purposefully, being able to plan and control his actions even under uncertainty. This, in turn, requires the man-machine system to be analysed and designed in such a way that man is enabled to interact with the machine purposefully. Therefore, the division of functions between man and machine, the functional requirements of the technical system and the man-machine interface have to be derived from and adjusted to the specific capabilities of man to produce certain results and to his bounds to bear loads." [Corbett, 85].

Thus the human-centred approach is holistic in that human and technical aspects are both included in the design process.

Apart from avoiding the problems associated with technology-centred design, as discussed in the previous chapter, there are a number of positive reasons for adopting a holistic approach [Clegg & Corbett, 87:177-178].

i) Careful consideration of human aspects, perhaps to the extent of involving system users and managers in the design process itself, is likely to result in a better design, since it will suit particular needs better, or because users may have job-specific knowledge about the production process that should influence the system specification.

ii) Human aspects need to be well-designed to optimize the performance of AMT. If the interface is difficult to comprehend, if operator jobs are poorly designed, if their training is
inadequate, or if the support given by programmers and engineers is ineffective, then no system will be able to perform to its full potential.

iii) Human aspects need to be considered so as to promote a good quality of working life for the people working in the system, the objective being to develop the skills of the users to allow them to derive satisfaction from their jobs. This is important in its own right, psychologically, and also makes it easier to attract and retain skilled staff.

iv) If human aspects are successfully managed, then it is likely that the system will reach its performance targets sooner than would otherwise be the case [Marsden, 86]. This is particularly important in the UK, where industrial relations problems can significantly delay implementation.

v) The human aspects of the system need to be designed carefully to ensure that a company’s resources, both technical and human, are fully utilised, so as to achieve maximum competitive advantage.

In terms of experimental work the best known example of applying a human-centred approach to the design of shop-floor AMT has been the attempt at the University of Manchester Institute of Science and Technology (UMIST) of a research group under the aegis of Professor Rosenbrock, to develop a 'human-centred FMS,' that is, an FMS that "did not subordinate workers to itself, but instead acted an aid to them in making their skill and ability more productive." [Corbett, 85]. The FMS consisted of an NC lathe, NC milling machine and robot, and the cell operator was responsible for generating part-programs as well as programming the robot. Most effort was focused on developing 'user-friendly' software for the NC lathe, and a list of design criteria was developed to help guide the design of software in other manufacturing environments [Clegg & Corbett, 87:184].

The work at UMIST was subsequently incorporated in the EEC-funded ESPRIT project 1217 (1199) entitled "Human-Centred CIM Systems", which started in May 1986 with a planned duration of three years. This project was based on the premise that,

"A CIM system will be more efficient, more economical, more robust and more flexible if a person is directly in charge than a comparable unmanned system."

The project had six stated objectives:

i) To establish criteria for the design of human-centred CIM systems,
ii) To establish their economic and commercial competitiveness,
iii) To achieve a better shop-floor environment and better working practices,
iv) To achieve a high level of robustness in CIM systems,
v) To define the training requirements for a new type of multi-skilled worker,
vi) To demonstrate at a number of production sites that there are better means of organising manufacturing especially suited to Europe.
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The research was aimed at developing a CIM solution "appropriate" for European industry, that is, for the small-and medium-sized firms undertaking small batch work that make up the bulk of the metalworking industry. This solution was to be readily applicable to companies presently with a predominance of manually-operated machines, as they transfer through CNC machine tools to "flexible" manufacturing technology. Therefore it was to be suited to progressive implementation over an extended period in established factories as well as to the installation of new facilities on green-field sites.

To this end, partners in West Germany, Denmark and Britain each concentrated on a different CIM sub-system. The West German Group developed a factory information system for production planning, scheduling and control, whilst the Danish group attempted to develop a new means of computer-aided design using an electronic drawing machine that could be interfaced directly to existing CAD packages or workstations.

The British group, comprising Greater London Enterprises (prime contractor), RD Projects Ltd, UMIST, Rolls Royce and BICC, concentrated on the development of prototype turning cells incorporating CNC lathes and workhandling equipment.

During this project the author was seconded to RD Projects and developed software for use on the cell computer in the turning cell implemented at Rolls Royce, Leavesden.

However, the main focus of the author's research was the demonstrator turning cell developed as part of the SERC/ACME-funded project in the Department of Mechanical Engineering of Imperial College, entitled "The Operation and Management of Flexible Human-Centred Turning Cells." The arguments developed by the author to justify a human-centred approach, as collated in Part I of the thesis, supported the proposal for funding that initiated the project. This project commenced in December 1986 with a planned duration of three years. In addition to the contribution of the SERC, four industrial partners were involved in this project:

- Digital Equipment Corporation, Reading.
- Harmonic Drive Ltd, Billinghamurst.
- Matrix Machine Tools Ltd, Coventry,
- RD Projects Ltd, London.

This project was intended to complement ESPRIT Project 1217 (1199) and accordingly had the following four primary objectives:

i) To provide flexibility when dealing with the manufacture of turned components with small batch sizes and high part variety, by adopting the concept of a human-centred turning cell and constructing a demonstrator facility.

ii) To develop the software tools that will assist the cell operators to program, schedule and operate the cell efficiently.
To determine the best method for the automated handling of rotational parts.

To test the proposed methodology through practical industrial experiments.

To fulfill these objectives a demonstrator human-centred turning cell was to be built, so that hardware and software designed according to human-centred criteria could be evaluated and the effects of different task allocations between the cell operators and the various machines and computers could be tested.

Within this project the author's research concentrated on the development of a framework of human-centred design criteria to guide the design of both hardware and software, which is described in the next chapter, the design of the turning cell itself, described in Chapter 8, and the development of software for use on the cell computer to assist the cell operators in their management of the cell, described in Chapter 9.
A Design Framework for Human-Centred AMT

7. A Design Framework For Human-Centred AMT

Although the justification for carrying out research into human-centred systems was discussed in the preceding chapter, no concise definition was offered for what constitutes a human-centred system. Corbett [88:35] was also unable to find such a definition in the literature, though he identified five fundamental qualities as characteristic of human-centred technology:

1. Human-centred technology accepts the present skills of the user and allows them to develop. Conventional technological design approaches attempt to incorporate elements of these skills into the systems hard/software, with a resultant de-skilling of human operators. Existing skills should not be preserved indefinitely, becoming thereby "fossilized," but should be developed into new skills to match subsequent evolution of the technology [Rosenbrock, 84:129].

2. The human controls the technology, rather than vice-versa. Accordingly, the more "degrees of freedom" available to the users of a particular system to shape their own working methods and objectives, and to time their own actions, the more "human-centred" the technology is.

3. Human-centred technology unites the planning, execution and evaluative components of work, thereby minimising the division of labour characteristic of many modern manufacturing systems.

4. Human-centred technology should encourage both formal and informal social communication between users. This reflects the growing concern that new technology is devaluing social, face-to-face interaction, in favour of electronically transmitted data exchange.

5. Generally, human-centred technology should contribute to a healthy, safe and efficient working environment, that is, ergonomic factors should be optimised.

These basic qualities are essentially an amalgam of recommendations emergent from the different social science approaches discussed in Chapter 6, which, in turn, are based on what Wittkowsky and Gottschalch [87:4] term the "general psychological guide-lines" for the design of work.

Equipped with this list of fundamental qualities, the system designer is confronted with three problems in attempting to use them to design a human-centred system: First, by which process should these human considerations be mapped onto the design process for the technical aspects of the system?; Secondly, given the generalized nature of the above qualities, what guidelines are available for more detailed design? and; Thirdly, how should the "human-centredness" of different design options be evaluated and compared?

The objective of this chapter is to attempt to resolve these problems. In the first section, a "parallel" design procedure will be proposed, by which technical and human aspects are both taken into account from the beginning of the system design process. The second section...
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focuses on a review of guidelines available from social science research to influence system design, and in the third section various alternative methods for the prospective measurement of "human-centredness" will be discussed.

7.1 A "Parallel" Design Procedure for Human-Centred AMT

It is important to establish first an overall framework for the design and implementation process for AMT. Useful for this purpose is the model for technical change offered by Buchanan & Huczynski [85:284], which resulted from research investigating the impact of various different IT-based technologies [Buchanan & Boddy, 83].

This model, shown in Figure 7.1, is based on the proposition that the consequences of technical change in an organization is dependent on managerial choice, with respect to objectives, technical design and layout, and work organization. In other words, technology is not "deterministic," but simply acts as a trigger to processes of management decision-making, a view largely supported by the empirical evidence discussed in Chapter 4.

Figure 7.1 Technical Change: The Management Decision-Making Process
[Buchanan & Huczynski, 85:284]
With respect to management objectives, Buchanan & Boddy found that new technologies were not only implemented to combat competition, but for a variety of further motives, including the career aspirations of individual managers. Their research indicated that three types of objectives were associated with the introduction of computer-based technologies:

**Strategic Objectives** - These are external, economic, customer-oriented objectives, such as the desire to increase capacity to meet increasing demand, give better delivery, be leaders in the use of new technology to attract new customers, and to improve quality and reduce prices to meet competition.

**Operating Objectives** - These are internal, technical, performance-orientated objectives, such as the desire to reduce production costs, replace obsolescent equipment, overcome bottlenecks in production, reduce numbers and costs of support staff etc.

**Control Objectives** - These objectives include the desire of management to reduce human intervention, reduce uncertainty and increase predictability and consistency in production operations, increase the amount of information on performance and the speed at which it is generated.

While it is clear that strategic and operating objectives are closely related, it is important to point out that the above objectives are not always mutually consistent. Much of the earlier discussion has shown that control objectives, such as the desire to limit human influence in a manufacturing system, can conflict directly with strategic objectives, such as a desire for flexibility.

Turning to the technology, the capabilities of computer-based manufacturing technology to increase integration and control, and so satisfy management objectives, were described in Chapter 2, though the evidence presented in subsequent chapters suggests that these capabilities should be described as *enabling characteristics*, that is, they do not on their own "determine" organizational functions or structures [Buchanan & Huczynski, 85:282]. However, if the technology has been designed with control objectives in mind, then it can subsequently be difficult, if at all possible, to achieve work designs congruent with strategic objectives.

Here, attention is focused on those forms of AMT *perceived* to be most suited to high variety, small batch manufacturing, that is, stand-alone CNC machine tools, flexible machining cells and flexible machining systems.

This brings us to the question of "how?", posed in Figure 7.1 with respect to the organization and design of work. As has been argued in earlier chapters and as implied above, this cannot be divorced from the design of the technology. To re-iterate briefly, the "sequential" design process characteristic of the technology-centred approach, usually involves designers in the practice of human-machine comparison, whereby functional system requirements are realised with respect to the technological state-of-the-art, leaving operators to take over those functions which are technically not yet solved. Under this technology-driven approach, the end users do not become involved until the system is implemented, by which time few, if any, changes can be made to the
technology. Yet even where human skills are made largely redundant, people are still required to carry out residual tasks to keep the system functioning. Once again the pursuit of control objectives may conflict with strategic and operating objectives by leading to work designs that eliminate discretion and thereby provide operators with neither the skills nor motivation to perform their functions effectively. It is worth reflecting that despite this neglect of human considerations, it is the adaptability of the remaining operators that enables systems designed in this way to still function in the face of problems and disturbances unforeseen by system designers. It is important to add that attempts to reduce the dependence of equipment and processes on human control appear to be associated with reduced flexibility, which is contrary to current and likely future requirements of the market.

The alternative, human-centred, approach to man-machine system design, rejects the concept of comparability, and focuses instead on how people and machines may complement each other. The resultant "parallel" design approach involves the incorporation of human considerations from the start of the design process, and means that the technology and work organization elements in Figure 7.1 must be dealt with together.

It is necessary to look first at the various factors involved in designing the technical aspects of an advanced manufacturing system. Figure 7.2 shows a typical planning methodology for FMS as presented by Crookall [85]. (It is interesting to note, in passing, how late organizational considerations feature in this methodology....) In brief, the specification of machine tools is dependent on a definition of machining tasks which, in turn, requires an analysis of the workpiece spectrum and the recording of all machining requirements. The machine tools will be connected by a materials handling system, which means that suitable methods for the transport, storage and pre-setting of workpieces, jigs, tools etc must be determined. The interaction of the components of the machining and materials handling systems is controlled by the overall system computer. The latter must co-ordinate the time requirements of manufacturing orders with the capacity of the manufacturing system and is responsible for distributing, collecting and evaluating the information necessary for the running of the plant.

The planning procedure shown in Figure 7.2, in common with the more detailed procedures offered by Rockstroh [85], Rudolph & Wirth [86] and Greenwood [88], is directed purely at technical issues, though the basic order of steps for the design of the technical aspects of the manufacturing system will remain the same when human issues are also taken into account. In seeking to add the "parallel" aspect of this design procedure, the first question to answer is where human considerations must be taken into account?

Figure 7.3 shows the relationship between the various levels of "control" in a manufacturing system and the influence of the various social science approaches discussed in the previous chapter. This diagram is important for showing that different approaches will influence different levels in the hierarchical design process. For example, psychological approaches focused on work organization and design act on a much more general level than, say, software ergonomics, which is much more specific and detailed in scope.
Figure 7.2 FMS Planning Methodology [Crookall, 85]

- Factory Planning
- Parts Selection and Manufacturing Plan
  - Preliminary Design
  - Simulation with Analytical Methods
  - Final Design
  - Discrete-event Simulation
- Machine System Specification
  - Machine layout
  - Links between machines
  - Required speed
  - Number of transport devices
  - Number of pallets
- Materials Handling System Specification
  - Distribution of tools and workpieces
  - Alternate manufacturing plans
  - Batch subdivision
- Manufacturing System Control Specification
  - Distribution of tools and workpieces
- Planning of Hardware
- Planning of Software
- Planning of Work Organization
- Flexible Manufacturing System
- Extent of Planning

Figure 7.3 Human Considerations in the Design of AMT

- Man-Man Allocation of Responsibilities
- Organizational Structure
- Man-Machine Allocation of Function
  - Production Equipment
    - Hardware, Workplace & Workplace Environment
  - Software
    - Man-Machine Interface
      - Application Software
        - System Software
- Hardware & Environmental Ergonomics

= Information flow

Work Organization & Job Design
Allocation of Function
Software Ergonomics

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Figure 7.4, which is a composite of the "parallel" design procedures proposed by Mumford [83], Ravden et al [86] and Shackel [86], shows a simplified design procedure in which the human considerations shown in Figure 7.3 are "mapped" onto the design procedure for the technical aspects of the manufacturing system.

Overall Objectives
- Strategic
- Operating
- Control

Define system boundaries

Analyze present system → "Is" model

Define desired system → "Should be" model

Requirements spec. (Scenario)

"Human" Objectives

Work Organization & Job Design

Allocation of Function

Software Ergonomics

Hardware Ergonomics

Environmental Ergonomics

Evaluate Technical

Detail system / work design
- Hardware
- Software
- Personnel training & development

Functional Spec. (Scenario)

Identify key material & information flows
Identify key tasks

Assess technical, organizational options and job design options

Integration
Some important points must be highlighted with respect to this procedure; First the procedure has been formulated such that it is broadly applicable at different levels of abstraction. This is important since the various component sub-systems of a manufacturing system, such as machine tools, materials handling system, computer system etc. all constitute man-machine systems, in the design of which human considerations must be taken into account. In other words, dependent on the definition of the boundaries of the system, the same basic procedure would apply to the design of a complete machining cell as to the design of the CNC controller for an individual machine tool, though the relative importance of the different social science recommendations will vary according to the scope of the system being designed.

This relates to the second point, which is that the procedure is necessarily simplistic, since in practice the design procedure is an iterative, cyclic process, with the designer or design group continually returning to preceding stages to reconsider decisions in the light of developments at later stages.

A third point requiring explanation is the inclusion of the term "allocation of function" in Figure 7.4. This addresses the methods by which functions (or tasks) within the system are allocated between humans and machines. As will be seen later in this chapter, these methods impact primarily on the structural design of software, and as such do not fall conveniently within the scope of job design, which is concerned more with the allocation of responsibilities between humans, or software ergonomics which is directed more at the design of the man-machine interface (MMI).

The details of each individual stage in this design procedure are best explained by way of example, and will therefore be discussed by means of the case study in the next chapter.

As pointed out by Ravden et al [86], the design process itself is subject to human considerations, that is, some mechanism or methodology must be found for ensuring that the various human aspects are included in the effective practice of design.

In Chapter 6, research into participative system design, whereby eventual users take over part of the responsibility for the design of a new system, was discussed. However, various drawbacks were highlighted, in particular the difficulties faced by users, even when thoroughly familiar with the technical system under scrutiny, in conceiving alternative system design solutions. A further problem reveals itself in the case of vendors seeking to develop systems for sale on the general market, where the "eventual user" is difficult to identify.

In the light of similar experience, the alternative approach adopted by the research group at UMIST, responsible for the development of a human-centred FMS, was to develop design criteria to guide the design process. However, as Corbett comments [86:20],

"Our experience suggests that tight formulations of human work design criteria may do little to help engineers modify their present approach, as design involves far more than the methodical application of formulated criteria (whether technical or social)."
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It was thus concluded that the most effective procedure in projects where social science inputs are regarded as significant, is for engineers and social scientists to spend time helping each other to recognize and, if necessary, modify tacit assumptions guiding their approaches to problem solving [Corbett, 86:20].

Whilst the author agrees, in principle, with this conclusion, it ignores the fact that most companies have neither the time nor appropriate personnel to engage in such a process. Indeed, one of the basic issues of the author's research was to investigate whether an approach could be developed from available social science research, whereby manufacturing and system engineers could design human-centred systems without requiring support from social science specialists.

It was therefore decided to establish a framework of design recommendations and criteria, by reviewing recent contributions from social science research, to guide the design of the demonstrator turning cell at Imperial College.

7.2 Human Considerations in the Design of AMT

Commensurate with Figure 7.3, this collation of recommendations and design criteria for the "parallel" design of AMT will be divided into three parts, each associated with an increasing level of detail in the overall design process. The discussion will focus first on guidelines for the allocation of responsibilities between humans in the manufacturing system, that is, on work organization and job design. This will be followed by recommendations for the allocation of functions between man and machine, and finally, criteria will be listed for the design of the man-machine interface, that is, guidance will be sought from research in the field of software ergonomics.

7.2.1 Work Organization and Job Design

With respect to guidelines for the allocation of responsibilities between humans within a manufacturing system, the most widely acknowledged social science approach to work organization and job design is the socio-technical systems approach, as indicated in the last chapter.

A list of socio-technical design criteria is provided by Cherns [76] which, while useful for providing "hints" as to desirable features of a socio-technical system, is too generalized to provide much practical guidance to a manufacturing system designer. More useful in this respect is the work design framework proposed by Cummings & Blumberg [87:37-60], which is based on a socio-technical viewpoint. According to this viewpoint, work design is aimed at jointly satisfying technological and personal needs, and matching environmental conditions. Cummings & Blumberg thus identify various technical, personal and environmental contingencies and then describe specific work designs appropriate to various combinations of these contingencies.

**Technical factors** - Technical interdependence and technical uncertainty are identified as two key technological features that will determine the success of a particular work design. Technical interdependence refers to the extent to which the technology requires co-operation...
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among workers to produce a product or service. A high degree of interdependence suggest that work should be designed for groups composed of people performing inter-related tasks, rather than on the basis of individual jobs, which is appropriate for low interdependence. Technical uncertainty refers to the amount of information processing and decision-making that employees must carry out during task execution. Low technical uncertainty lends itself to external control mechanisms, such as supervision or scheduling, whilst high technical uncertainty is more compatible with work designs in which workers have more scope for self-control and decision-making.

Personal factors - Research indicates that at least two kinds of personal need can influence the effectiveness of a particular work design: social needs, or the desire for significant social relationships; and growth needs, or the desire for personal accomplishment, learning and development. Social needs are clearly significant in deciding whether to design work for individual jobs or work groups, whilst growth needs play a role in determining whether work designs should be routine and repetitive or complex and challenging to offer increased autonomy, task variety and feedback of results.

Environmental factors - A third group of contingencies relates to the task environment of the socio-technical system, that is, how the system exchanges material and information with its environment. In a stable task environment these exchanges can be pre-programmed and standardized, with a resultant emphasis in work designs on routine performance. However, a dynamic and unpredictable environment means that exchanges must be managed adaptively as circumstances demand, with a corresponding need for high levels of information processing and decision-making, which must be reflected in job designs emphasizing flexible behaviour.

As shown in Figure 7.5 overleaf, these technical, personal and environmental contingencies affecting work design can be used to identify the type of work design best suited to a particular combination of contingencies.

To identify the kind of work design necessary for operating different forms of advanced manufacturing technology effectively, it is necessary to analyse the relationship between the technology and the various contingencies described above.

The integrative capabilities of IT which lie at the core of AMT, by enabling the integration of materials handling and machining activities in an FMS, or by linking CAD to NC part program generation, serve to accelerate the overall flow of production and to link its constituent elements more tightly. AMT thus tends to encourage a higher level of technical interdependence.

Similarly, work in highly-integrated manufacturing systems, such as FMS, is associated with the need for operators to respond rapidly to unforeseen and non-routine variances that are not readily dealt with by computers. In order to deal with such disturbances rapidly, and as close to their source as possible, operators must engage in complex problem-solving in real-time involving a high level of information processing. Thus AMT of this form is associated with high technical uncertainty during task execution.
Turning to environmental stability, it was argued in Chapter 5 that AMT both enables and itself encourages a more "uncertain" market, characterised by greater product variety, smaller batches and reduced delivery times. Not only does the technology enable closer links between different functions within the company, but also serves to couple the company more tightly to vendors and customers. Taking the example of FMS again, the low levels of raw material and finished goods stocks typically associated with this form of AMT, mean that it is not decoupled to any great extent from external disruptions to raw material supplies, quality etc. Accordingly, the tighter coupling of the manufacturing system to its task environment requires rapid innovative responses when unforeseen disturbances of this nature occur.

In summary, FMS, as an example of AMT, would appear to be associated with high levels of technical interdependence, technical uncertainty and environmental uncertainty. Reference to Figure 7.5 indicates that the most appropriate work design for an FMS would be self-regulating, or autonomous work groups. In this work design groups are organized around interdependent tasks to facilitate co-ordination of task execution. Members of the group are provided with the necessary skills, information and decision-making freedom to respond to disturbances arising from within the manufacturing system itself and its task environment. The group members are provided with multiple skills to deploy themselves as circumstances demand, and can carry out evaluative tasks so as to detect and control non-routine variances. To acquire a better understanding of the overall manufacturing process, group members can rotate between jobs and will be responsible for solving problems together with management and support specialists [Cummings & Blumberg, 87:48-49].

---

**Figure 7.5 Work Designs and Contingencies [Cummings & Blumberg, 87:44]**

<table>
<thead>
<tr>
<th>Work Designs</th>
<th>Technical Interdependence</th>
<th>Technical Uncertainty</th>
<th>Environmental Dynamics</th>
<th>Growth Needs</th>
<th>Social Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>&quot;Traditional&quot; Jobs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Traditional&quot; Work Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enriched Jobs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-autonomous Work Groups</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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In the case of shop-floor AMT, be it in the form of stand-alone CNC machine tools, or FMS, the recommendations of this work design framework are associated with a move from "control by specialists" to "control by operators." The former scenario relates closely to the polarized work organization typical of many current shop-floor applications of AMT and which, according to Figure 7.5, is more appropriate to a manufacturing content exhibiting low technical interdependence, technical uncertainty and environmental uncertainty. Table 7.1 indicates key differences between these two work design options.

<table>
<thead>
<tr>
<th>Table 7.1</th>
<th>&quot;Control by Specialists&quot; vs &quot;Control by Operators.&quot; [Clegg, 88:30]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCENARIO 1: Control by specialists</td>
<td>SCENARIO 2: Control by operators</td>
</tr>
<tr>
<td><strong>LOGIC</strong></td>
<td>Expensive equipment, therefore needs managing and controlling by 'experts'</td>
</tr>
<tr>
<td><strong>EMPHASIS:</strong></td>
<td>Specialisation, Centralised control</td>
</tr>
<tr>
<td><strong>ROLES:</strong></td>
<td>Specialist machine setters, More programmers to write, prove-out and edit programs, More engineers to maintain/repair electrical, electronic and mechanical components of cell, Operators who: mind machines and call for help when required, More quality inspectors</td>
</tr>
<tr>
<td><strong>COST/BENEFITS:</strong></td>
<td>Low direct labour costs, High indirect costs, Low motivation/commitment of operators, Waiting for experts, therefore poorer utilisation, Experts deal with simple problems, which is wasteful of their expertise and distracts them from other, more specialised problems</td>
</tr>
<tr>
<td><strong>LOGIC:</strong></td>
<td>Expensive equipment, needs to be controlled by an expert who can solve problems as they arise</td>
</tr>
<tr>
<td><strong>EMPHASIS:</strong></td>
<td>Self-control and flexibility, Local control with support specialists</td>
</tr>
<tr>
<td><strong>ROLES:</strong></td>
<td>Operators set machines, Fewer programmers (writing only), Fewer engineers as operators carry out routine maintenance and error recovery, Operators who: set machines, prove-out and edit programs, carry out routine problem-solving, Fewer inspectors as operators are responsible for wider areas of quality control</td>
</tr>
<tr>
<td><strong>COST/BENEFITS:</strong></td>
<td>High direct labour costs, Low indirect costs, High motivation/commitment of operators, Speedy resolution of problems, therefore better utilisation, Operators deal with simple problems, leaving experts free to deal with more specialised problems</td>
</tr>
</tbody>
</table>

Apart from rare experiments, such as the use of autonomous work groups in the FMS at Zahnradfabrik Friedrichshafen, as described in the preceding chapter, the evidence shows that very few companies currently adopt a work design approach such as that described above. This makes it less surprising that system reliability and flexibility should prove so poor, and that employees should experience undue stress in trying to operate with an inappropriate work design. This is despite the fact that IT enables and facilities the role convergence and role coupling necessary to enrich jobs or to create autonomous work groups and their associated support structures.
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Various obstacles to organizational change have already been discussed in an earlier chapter and an additional factor that could explain the rarity of alternative work designs is that important work context modifications are required if such work designs are to be implemented and operated effectively. This reflects the fact that a company’s selection, training and reward practices need to complement and reinforce the kind of task behaviours encouraged by the work design [Cummings & Blumberg, 87:57].

Selection practices should be aimed at the recruitment of employees with high growth needs and high social needs, whilst training programmes must be designed to provide employees with multiple skills to detect and rectify technical and environmental variances, and with social skills to facilitate group problem-solving (see also [Rothwell, 87:61-82]).

Reward systems must also be designed so as to promote flexibility and skill enhancement, in other words, individuals should be paid for what they are capable of doing within the organization, rather than what they actually do on a day-to-day basis [Goodridge, 86:51]. Possibilities include a skill-based pay system, where employees are paid for the breadth and/or depth of skills that they have acquired, or a group-based, performance-related system, where the whole work group is rewarded for improved productivity.

Management style must also be oriented to help group members develop the competence necessary for work-related decisions and to solve complex problems at the workplace. This form of leadership needs to be highly consultative and, as described by Walton [85], requires a move from a "control" to a "commitment" orientation in the workplace. The key features of this change are shown in Table 7.2 overleaf, which serves also to summarize the various work context modifications described above.

In the above discussion, the impact of AMT has been treated in a very general manner, and there is little to reflect the more specific features of computer-based technologies that should influence job design.

Here, a useful check-list of desirable job features has been collated by Spinas et al [83: 78-81] for guiding the design of work involving computers. This check-list, shown in Table 7.3, is based on the same basic psychological guidelines as the work design framework described above and, accordingly, is a "super-set" of the job and organizational features implicit in that framework. By focusing more closely on the technology itself, the check-list also provides a useful link to the next level of analysis shown in Figure 7.3, that is, to the allocation of function between humans and machines in the manufacturing system.
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Table 7.2 Work-force strategies: Control to Commitment [Walton, 85]

<table>
<thead>
<tr>
<th>Control</th>
<th>Commitment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job design principles</td>
<td>Individual attention limited to performing individual job.</td>
</tr>
<tr>
<td></td>
<td>Job design de-skills and fragments work and separates doing and thinking.</td>
</tr>
<tr>
<td>Accountability focused on individual.</td>
<td>Frequent use of teams as basic accountable unit.</td>
</tr>
<tr>
<td>Fixed job definition.</td>
<td>Flexible definition of duties, contingent on changing conditions.</td>
</tr>
<tr>
<td>Performance expectations</td>
<td>Measured standards define minimum performance. Stability seen as desirable.</td>
</tr>
<tr>
<td>Management organisation: structure, systems, and style</td>
<td>Structure tends to be layered, with top-down controls. Coordination and control rely on rules and procedures. More emphasis on prerogatives and positional authority.</td>
</tr>
<tr>
<td>Compensation policies</td>
<td>Variable pay where feasible to provide individual incentive.</td>
</tr>
<tr>
<td></td>
<td>Individual pay geared to job evaluation.</td>
</tr>
<tr>
<td></td>
<td>In downturn, cuts concentrated on hourly payroll.</td>
</tr>
<tr>
<td>Employment assurances</td>
<td>Employees regarded as variable costs.</td>
</tr>
<tr>
<td>Employee voice policies</td>
<td>Employee input allowed on relatively narrow agenda. Attendant risks emphasised. Methods include open-door policy, attitude surveys, grievance procedures and collective bargaining in some organisations.</td>
</tr>
<tr>
<td></td>
<td>Business information distributed on strictly defined &quot;need to know&quot; basis.</td>
</tr>
<tr>
<td>Labour-management relations</td>
<td>Adversarial labour relations: emphasis on interest conflict.</td>
</tr>
</tbody>
</table>

Table 7.3 Check-List for Psychologically Adequate Work Design [Spinas et al, 83: 78-81]

A. Level of Individual Job

Basic Principle:
There should be guaranteed a room for action adequate to the needs, qualifications, and capacities of the person employed in a certain position. For carrying out his work assignment the person should be able to make avail of the computer if required.

1. Creation of an interesting, diversified work assignment, which integrates elements of planning, preparation, execution, and control.
2. The assignment should represent a challenge with realistic demands for the working person and should enable him to make use of his knowledge and skills. Tasks which are too simple and monotonous lead to boredom, a lack of interest, and a lack of exertion. Tasks which are too difficult can lead to excessive exertion and possible to stress.
3. For carrying out the assignment, no single method should be prescribed. Certain degrees of freedom in the fulfilment of tasks will enable the employee to realize his personal working style and to develop his own strategies of action.

4. The concession of a certain degree of autonomy allows the employee to time his work according to his individual working rhythm and speed, thus diminishing time pressure, hectic and stress.

5. The possibility to exercise self-control and responsibility during the process of task fulfilment, instead of being externally controlled by a superior, or by the computer, will raise the self-esteem of the employee and will transmit a feeling of personal success.

6. The assignment of tasks connected in a complete and meaningful way allows the employee to recognize the meaning and importance of his activity as well as the progress of his work more clearly.

7. Suitable structures of co-operation without strict forms of dependency offer a chance for communication and social support at the work place; this contributes to a reduction of professional stress.

8. The feeling of making no progress can be avoided by work containing learning potential, which open developmental possibilities to the employee.

9. Due to different work experiences, levels of demands, vital life interest so far acquired, it will not be possible to develop one single optimal working system for all employees. This circumstance can be taken into account by simultaneously offering different working systems, between which the employee may take his choice.

10. Apart from common workaday tasks, creative tasks demanding problem solutions should be reserved especially for the human being. Therefore he should as far as possible be relieved of routine tasks, the greater part of which will be taken over by the computer. To avoid an excess of strain, however, it should be possible to switch over to "relief routines" from time to time.

11. The human being's dependency on the computer should be minimized wherever possible; this is of special importance with view to system interruptions and long answering times in case of system overload.

12. Instead of mere screen work mixed activities should be designed.

13. Work at the screen should not be restricted to the recording of data (data collecting work place), but should make possible a dialogue with the computer (dialogue work place).

14. The daily screen work should be limited to a maximum of four hours, or to half of the daily working time respectively.

15. The regulations for working breaks should take into account the work content and working process, without interfering with the working rhythm of the employee. In order to avoid an excess of strain a break of 5 to 10 minutes after each hour, or a break of 15 to 20 minutes after every two hours should be inserted, if longer daily screen work is demanded.

16. Too high a demand on concentration is to be avoided by optimizing the monitor (screen) design.

17. The man-machine dialogue should be designed according to psychological insights.

18. The threat of social isolation (communication only with the computer or via technical means) should be diminished by co-operation requirements and by suitable room design.

19. The understanding of the technical system should be promoted by continuation courses.

20. The human being's achievement should not be registered and controlled by the computer. There should rather exist the possibility to derive the feedback on work achievement on one's own or to receive it from a superior.
B. Level of Organization

1. In order to avoid dysfunctional effects (demotivation of the employees, high rates of fluctuation, etc.) extreme forms of work assignment (specialization) should be avoided.

2. As far as the new technologies offer possibilities for creating flexible, decentralized structures of organization, these should be exploited.

3. Alternative forms of work such as "job enrichment" and "semi-autonomous teams" are suited for organizational models of designing which will more strongly decentralize the tasks and which will delegate decision competence.

4. One should take care not to interfere with the employee's room for action and with the flexibility of work organization by inappropriate standardization and formalization of work processes and flows of information.

5. Well before acquiring new technical systems there should already exist a complete technological-organizational concept for their use, thus decreasing the risk of unplanned, negative effects on work organization.

6. Before employing the technology in any part of the organization its effects on other parts have to be carefully examined in order to avoid unlooked-for radiating effects, which might perhaps arise quite uncontrolled.

Translation from German by Wittkowsky & Gottschalch [87]

7.2.2 Allocation of Function

As indicated in Chapter 6, there have been a number of studies by ergonomists, analysing human-computer supervisory performance in the operation and control of FMS [Hwang et al, 84] [Barfield et al, 86]. The basic procedure adopted in these studies for comparing the abilities and limitations of human and computers has been to sequentially list the task components associated with the operation and control of an FMS and then to tabulate the human and computer's respective abilities [Hwang et al, 84: 848-851]. The intention is that tables such as these, when fully developed, should be used by FMS designers to allocate tasks and responsibilities between humans and computers more effectively. It is interesting to note that Barfield et al [86:386] seek to justify this approach by criticizing conventional task allocation, whereby the human simply controls by default those tasks that the computer cannot perform. Yet ultimately they recommend an allocation of function that differs little from that found in most current FMSs, as indicated by the following quote [86:400]:

"Tasks which require extensive pattern recognition, such as tool set-up, loading/unloading of parts, and inspection, should be assigned to the human. Tasks which require extensive calculations or redundancy in operation should be performed by the computer. Those tasks which should be controlled by the computer are tool transportation, machining and tool changing. Considering the operation and control of an FMS, the human can increase system reliability by acting as a backup decision-maker."
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Reflecting on the problems of designing work, and as well be seen later, the technology, in such a way that operators have both the skills and motivation to carry out such a backup role, it would seem that this narrow view on cognitive, visual and anthropometric factors is not satisfactory. Essentially the analysis is based on the allocation of tasks in a "given" system and little attention is addressed to how the technology is designed in the first place. Furthermore, the bulk of this type of research has been directed at systems exhibiting a very high level of integration of materials handling and machining tasks, which, therefore, exhibit characteristics similar to flow-production lines or process plant. Empirical evidence indicates that such "flexible transfer-line" - type systems are comparatively rare and not the most appropriate for the high variety, small batch manufacturing environment that is the focus of attention here.

Accordingly, it is essential to look for an approach to the allocation of function, that is based on the concept of complementarity and that is more readily applicable to the work design for AMT used in a high variability production context.

One such approach is that employed by Corbett [85] in the prospective work design of a human-centred CNC lathe, carried out as part of the 'human-centred FMS' project at UMIST. As listed at the start of the chapter, one of the basic principles of the human-centred approach is to utilise existing skills and to allow them to develop into new skills. This immediately presents the designer with the problem of deciding which skills to develop further and which skills to allow to degrade. It is here that the concept of complementarity plays an important role.

Corbett chose to base the allocation of function for the human-centred CNC lathe on the basis of "choice-uncertainty," that is, allocated tasks requiring creative, discretionary skill, unique to the human. Thus the human complements the computer, which is fast, precise and reliable, but totally uncreative. By this approach the first step is to identify those tasks containing a high degree of choice-uncertainty, that is, those tasks subject to technical or environmental uncertainty. In the case of a CNC lathe, such tasks include machine set-up and part program generation and proving. When tasks such as these are defined or carried out away from the machine, be it by an office-based programmer or, indeed, by the machine software designer, then any unforeseen disturbances, such as variable raw material quality, excessive tool wear etc. will cause errors. Willenborg & Krabbendam [87:1690] point out that such problems can be avoided to a certain extent by, for example, extensive raw material quality control or comprehensive automatic process monitoring. However, for companies engaged in small batch manufacturing, such pre-emptive measures are often impractical.

Moreover, effective handling of such disturbances depends to a great extent on "tacit knowledge" [Polanyi,67], that is, craft knowledge derived through "learning by doing". As noted by Jones [83], such knowledge is extremely difficult to formalize, as is necessary if such knowledge is to be modelled in software. This greatly limits the effectiveness of automatic process monitoring systems, as shown by the limited success of tool wear monitoring systems.

Accordingly, problems of this nature are dealt with most effectively at the machine, and the machine operator, who will see both cause and effect of such disturbances, is in the best position to deal with them, assuming he is able to "take control."
Since variances such as those just described lead to a "mismatch" between the computer part program and what is actually required in terms of speeds, feeds, etc, it is essential that the operator can determine and change all data that are susceptible to error, that is, data relating to cutting sequences, tooling, speeds, feeds etc. In order to correctly translate skill into action it is then essential that the machine operator should have full knowledge and understanding of this data. Thus, in the words of Corbett:

"The aim of human-centred design is ... to fit the codes and strategies of the computer processes to the needs and skills of the operators."

To this end he developed various design principles, described briefly below, to help evaluate software conceived for the human-centred CNC lathe as it was written [Corbett, 85] [Corbett, 86: 18-19].

Figure 7.6 Design Principles for Allocation of Function in Human-Centred AMT [Corbett, 85].

1. Complementarity - As outlined above, this principle is based on the belief that man and machine should help each other to achieve an effect of which each is separately incapable. Briefly this means that routine and repetitive tasks should be reserved for machines, where possible, and qualitative, subjective tasks allocated to the operator.
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2. **Interactivity**
   - Input and output data should be negotiable and software should therefore allow interaction between the operator and the computer. The level of interaction will clearly depend on the nature of the task, such that operator-activated tasks, that is, involving choice-uncertainty, will need a higher level of interaction than routine, software-activated tasks.

3. **Operator control**
   - The efficient use and further development of operator skills depend on choice-uncertainty being "built-into" the system. However people differ in the amount of 'control' that leads to cognitive overload, hence the level of choice-uncertainty must be selected by each particular user of the machine. Accordingly, software must be designed to allow a flexible allocation of tasks involving choice-uncertainty between the user and the machine, so allowing for a variety of users and permitting users to develop their skills at a pace suited to their abilities.

4. **Compatibility**
   - Operation should not require skills unrelated to existing skills, but should allow existing skills to evolve. In other words, the operator should input and receive information which is compatible with conventional shop-floor training and practice. In this way the man-machine interface will conform to the users prior knowledge and intuition.

5. **Transparency**
   - In order to exercise 'control,' the operator must accept responsibility for a particular task, which demands that the operator must be able to "see" the internal processes of the software in order to facilitate learning. A "transparent" system makes it easy for the users to build up an internal model of the functions the system can perform. This should apply to decision-making and control functions, as well as the dialogue functions.

6. **Accountability**
   - The principle of transparency becomes difficult to satisfy if the operator allows the computer to carry out a large number of tasks involving choice-uncertainty, that use algorithms or procedures written in the software. In this case it is important that the operator should be able to find out what the program is doing through, say, an integral "help" facility.

7. **Minimum shock**
   - The system should not do anything which the operator finds unexpected in the light of his knowledge of the present state of the system.

The above criteria were applied to all tasks and software functions, but for tasks containing a degree of choice-uncertainty a further four design criteria were also used to evaluate the software:
8. Disturbance control - This criterion relates to the principle of complementarity by stating that all tasks containing choice uncertainty should be under operator control with computer support. This reflects the fact that software cannot predict all possible disturbances, whereas an operator can cope with the unforeseen.

9. Fallibility - Operators' tacit skills should not be designed out of the system, that is, the operator should always have the opportunity to "override" the computer in tasks involving choice-uncertainty. The operator should never be put in the position of helplessly watching the computer carry out an incorrect operation that he had foreseen.

10. Error Reversibility - As the operator develops his skills by exploring various alternatives, there will be an element of trial and error which, in the case of modern manufacturing equipment, could prove both dangerous and expensive. One means of reducing risk is to limit the range of alternative options, but this is difficult to do without constraining learning effects. A better approach, by which the effects of errors are observable and reversible, is to supply "feed forward" information to the operator to show the likely consequences of a particular course of action.

11. Operating Flexibility - This principle stipulates that the system should offer operators the freedom to trade-off requirements and resource limits by shifting operating strategies without losing software support. This begs the question as to how many operating strategies should be designed into the system? As described in more detail by Corbett [85], for the human-centred CNC lathe the number of "useful strategies" was limited to those involving choice-uncertainty.

In summary, the objective of these criteria at the general level is to ensure that the technical system provides the experience out of which tacit knowledge can be built and machining skills can be utilised and developed. More specifically, they aim to maximise the degrees of freedom available to the operator within the constraints of hardware and the limits of the desired system output.

From the above descriptions it is clear that a number of these principles relate not only to the allocation of functions between operator and machine, but also to the design of the man-machine interface. This is therefore an appropriate point to extend the discussion to recommendations from the field of ergonomics for the design of human-centred systems.
7.2.3 Ergonomics

As described in the preceding chapter, ergonomics deals primarily with the design of equipment for human use. As implicit in Figure 7.7, which shows a simplified man-machine system, ergonomics thus deals with the following issues [Wild, 84: 221]:

a) design of information displays,

b) design of controls,

c) environmental factors.

Figure 7.7 Simplified Man-Machine System (adapted from [Wild, 84: 222])

Hardware and environmental ergonomics have been dealt with very thoroughly in the literature, for example, by Corlett & Richardson [81] or Osborne [82], and accordingly will not be discussed in detail here.

Software ergonomics, on the other hand, is a relatively new field of study and particularly important with respect to computer-based technology. It is therefore worthy of more detailed discussion here.

There are two primary motivating factors behind the increasing interest in this area, as evident from the growing literature, for example [Gaines & Shaw, 84] [Norman & Draper, 86] [Shneiderman, 86]. One reason has been the rapid diffusion of computers in both office and factory, with the result that companies have become increasingly dependent on the effectiveness of interactive computer systems. The second factor relates to the total reversal in the cost relationship between man and computer since the introduction of interactive computing.
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Poor user-interface design leads to less than optimal efficiency of the human component of man-machine (computer) systems. This leads, in turn, to lowered productivity and effectiveness of the system as a whole, thereby lessening the benefits to be gained from using computers, and raising the human costs of the system even further. There is therefore a growing awareness within industry of the need to apply ergonomics knowledge to the design of the user-software interface, in order to facilitate accurate and efficient human-computer interaction, with an acceptably low error rate and an acceptable cost in personnel time, together with user acceptance and satisfaction with the system.

A thorough literature review by Ravden et al [86] has identified 8 key human factors principles to guide the design of the user-interface, the salient features of which are described briefly below:

1. **Consistency**
   - All terminology, formats, operational procedures, abbreviations etc. should be standardised as far as possible, and should be consistently applied across all displays both within applications and where possible, across applications throughout the whole system.

2. **Visual Clarity**
   - Data should be organised on the screen in a clear, logical, unambiguous and easily readable format.

3. **Compatibility**
   - Terminology, formatting, results of and responses to entries etc. should follow users' conventions and expectations, thereby avoiding the user having to translate and transpose.

4. **Informative Feedback**
   - Users should be given clear, informative feedback regarding where they are in the system, what actions they have taken, whether these actions have been successful and what actions should be taken next.

5. **Minimal Response Time**
   - The timing of the system response to user input should be predictable, and should be kept to a minimum as far as possible.

6. **Flexibility**
   - The software interface should have sufficient flexibility of control and operation so that both novice and more experienced users working at different paces, can use the system effectively.

7. **Error Control & Recovery**
   - Users should be given every opportunity to check their input and to correct errors or potential error situations before the input is processed.

8. **User Guidance & Support**
   - A comprehensive guide to the system and its usage should be available to the operator, both on the computer (on-line "help" facility) and in hard-copy document form.
Clearly, all these criteria must be applied to achieve a satisfactory user-interface design. As Ravden et al [86] point out, a well-laid-out, clear visual display loses its impact if consistency is not applied, and fields appear in different positions on the screen from display to display. Similarly, consistent positioning of data fields across screens has little purpose if the layout of the screen is confusing.

7.3 Evaluation of Design Alternatives

Having now provided a framework of design guidelines to help influence the design procedure outlined in Section 7.1, the question remains as to how the "human-centredness" of a particular combination of technological and organizational options should be measured?

Once a system has been implemented, various techniques can be employed to measure job satisfaction and, thereby, the success of a particular system design in terms of encouraging employee motivation. For example, questionnaires can be used to establish the motivating potential score for a job [Buchanan & Huczynski, 85:65]. However, how should the effects of different allocations of function between humans and machines, and of different forms of work organization, be measured during the early stages of system design?

An interesting approach is that of work organization action simulation developed by Kember & Murray [88:133-142]. This method, used initially for teaching the basic principles of socio-technical systems design to engineers, involves a set of individuals performing quasi-real tasks and relating to each other in an organizational structure.

The objective is to enable system designers to fully explore and evaluate organizational options while jointly designing the technical and social systems. Whilst offering interesting possibilities to designers for the "prototyping" of systems, perhaps by combining conventional computer simulation techniques with organizational simulation, and providing a means to facilitate operator participation in the design and commissioning process, this approach is still in an early research stage in terms of its application to the design of complex systems such as FMS. As will be seen in Chapter 9, the author did make use of simulation techniques to evaluate alternative design options, but then in conjunction with other evaluative techniques, as described below.

Within ESPRIT Project 1217 (1199) "Human-Centred CIM Systems" the social science group working within the project defined six "dimensions" of work for the purpose of measuring "human-centredness" [Rauner et al, 87:22-23].

*Time Structure* - includes both time-pressure from outside, and the degree to which it is possible for the individual and/or group to plan the use of time themselves.

*Space for Movement* - includes the degree of explicit formulation of moving from one position to another as part of the job function. It further includes the implicit possibilities to move or not if the person feels the need or wish to do so.
### Figure 7.8: Matrix for Shaping Technology and Work Design (Rauner et al., 87: 28)

<table>
<thead>
<tr>
<th>Time Structure (1)</th>
<th>Space of movement (2)</th>
<th>Social Relations (3)</th>
<th>Responsibility and control flexibility (4)</th>
<th>Qualification level (5)</th>
<th>Stress-control (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-rhythm bound programme, Time schedule</td>
<td>Strictly bound to one place, without possibility of place change, or change in movements</td>
<td>No minimum work related social connections; maximum control (technically facilitated)</td>
<td>Total control via higher factory department; technologically transmitted</td>
<td>Sensoric abilities</td>
<td>Stress completely steered externally (technologically transmitted)</td>
</tr>
<tr>
<td>Hot time-rhythm bound, but definite handling times for definite processes</td>
<td>Largely bound to one spot, with markedly reduced freedom of movement, e.g., machine oriented</td>
<td>Formal hierarchical work related minimum cooperation, no informal contacts possible during work; extensive control (technically transmitted)</td>
<td>Broad control, technologically and socially (personnel) transmitted</td>
<td></td>
<td>Stress largely externally steered (technologically and socially transmitted) little variation in the work speed</td>
</tr>
<tr>
<td>Variable time organization within the AV blueprint (e.g., optimizing of CNC program and varying of technology input data)</td>
<td>Largely bound to one spot (machine group) and occasional shift in space, dependent on cooperation</td>
<td>Cooperation via work based communication technology, minimal formal cooperation possible; social and technological control</td>
<td>Broad control due to planning structures and personal control</td>
<td>Controlled, understood and self-optimized work (e.g., skilled machine work)</td>
<td>Stress largely externally controlled (technologically and socially transmitted) variation of the work speed possible within defined limits</td>
</tr>
<tr>
<td>Workshop oriented organization (subject to cooperation and work diversity, e.g., by means of secondary skilled work)</td>
<td>Technologically and socially transmitted cooperation on the workshop level necessary, informal social cooperation possible in a limited extent (technically transmitted)</td>
<td>Limited control (reduced to more complex work situations)</td>
<td>Self-programmed, planned manufacturing on diverse manufacturing installations; experimental abilities (above all, in secondary skilled work)</td>
<td>Work speed externally and self-controlled by work breaks and a combination of work activities (primary and secondary skilled work)</td>
<td></td>
</tr>
<tr>
<td>Open time organization on workshop level in the frame work of definite time sectors (e.g., 14 days for the lots to be handled, including maintenance, servicing, repair)</td>
<td>Good possibilities for movement (necessary because of broad responsibility on the shop floor level)</td>
<td>Social and technologically induced cooperation and communication with relevant informal components; social control</td>
<td>Largely (cooperative) collective social control</td>
<td>Planning in the frame of part goals within a broader given goal; carrying out of diverse duties/tasks in the workshop</td>
<td>Participation in decisions about stress/burden largely possible; decentralized work planning</td>
</tr>
<tr>
<td>Open time organization of the workshop, and participation in production planning; autonomous workplace oriented work planning</td>
<td>Good possibilities for movement on the shop floor level and beyond</td>
<td>Social and technologically induced cooperation and communication (horizontal structure), with well-developed informal components; great degree of self-control</td>
<td>Largely self-responsibility and self-control in a work collective</td>
<td>Planning of complex work relationships; carrying out of complex tasks (in manufacturing and production)</td>
<td>Maximum involvement in the decision making process concerning stress, possible via decentralized work shaping</td>
</tr>
</tbody>
</table>
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Social Relations - refers to the degree of explicit formulization regarding whom to contact and when, as well as the informal possibilities to communicate across or behind the formal structures.

Responsibility & Control Flexibility - concerns the scope and degree of responsibility placed on the person or group themselves. It includes, as well, the possibilities and actual practice of controlling how this responsibility is managed by the group or individual.

Qualification - concerns the functional abilities more or less related to the single job and/or the process of work as a whole. It also includes the more comprehensive aspects of self-renewal and self-transcendence as essential human abilities.

Stress control - includes the degree to which the individual and/or group is able to control the physical and/or psychological pressure that is felt either explicitly or implicitly, in the work organization or man-machine relationship.

These dimensions were used to form the matrix, shown in Figure 7.8 which, in turn could be used to form "profiles," such as that shown in Figure 7.9, for a particular combination of technological and organizational options.

Figure 7.9 Application of the "Shaping" Matrix [Rauner et al, 87:26]
Whilst useful for indicating the "general direction" of human-centred design (Level '0' in Figure 7.8), this matrix method proved too general to differentiate adequately between different design options. Moreover, within the ESPRIT Project it was found that the specialised language used in the definitions of the dimensions of work led to problems of understanding between engineers and social scientists [Barth, 89:12].

Accordingly, for the purpose of the project at Imperial College, attention was turned to the literature for alternative prospective methods for evaluation.

Weber et al [86], describe the application of psychological job analysis methods, developed by Resch and colleagues at the Institute for Social Science in Work and Education of the Technical University Berlin, to the prospective evaluation of work design in an FMS. Two different techniques, both based on the "theory of action regulation" [Hacker, 80], were applied; VERA (Verfahren zur Ermittlung von Regulationserfordernissen in der Arbeitstätigkeit = Method to identify control requirements in industrial work), to analyse the demands of a particular work design for planning activities, that is, intellectual requirements, and RHIA (Verfahren zur Ermittlung von Regulationserfordernissen in der Arbeitstätigkeit = Method to identify control barriers in industrial work), to measure mental load, that is, job-related stress.

In this application VERA was used by dividing each proposed work design for the FMS into work units, each of which was then evaluated according to the ten-point scale shown in Table 7.4. The $R$ indicates that the task does not require active planning from the worker at the respective level, only the execution of an existing plan.

Essentially, the lower the value on this scale for a particular work task, the more the worker is denied planning freedom and possibilities for learning, with consequent negative effects on his psychological well-being.

The RHIA technique concentrates on the measurement of what are termed "regulation hindrances," that is, working conditions that prevent the worker from fulfilling his tasks while giving him no opportunity to prevent these interruptions in advance. As shown by Figure 7.10, there are two forms of "regulation hindrance."

"Regulation barriers" are defined as;

"Specific conditions of the technology, the organization of work, or occurrences in the environment that interfere directly with the normal work process of the employee. He is forced to do additional work or to run avoidable risks, because he is not allowed to remove the cause of these occurrences."

Hindrances through "overtaking of workers' capacities" are defined as;

"Certain continual conditions that reduce the mental or physical achievement capabilities of men in the long run."

In this application, RHIA was simply used to identify "regulation hindrances" inherent in the various work units, as described in more detail in Weber et al [86].
Table 7.4 VERA Scale [Weber et al, 86: 24]

<table>
<thead>
<tr>
<th>Level 5</th>
<th>Establishing new working processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 5</td>
<td>New interactive working processes to be introduced, their co-ordination and the material conditions for them.</td>
</tr>
<tr>
<td>Step 5R</td>
<td>As for step 5, the new working processes are complements to working processes already in operation, to which as few changes as possible must be made.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 4</th>
<th>Co-ordinating several working processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 4</td>
<td>Several sub-goal plans (step 3) for interacting parts of the working process are to be co-ordinated with one another.</td>
</tr>
<tr>
<td>Step 4R</td>
<td>Although only sub-goal planning is required, conditions for other sub-goal plans must be considered here.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 3</th>
<th>Sub-goal planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 3</td>
<td>Only a roughly determined sequence of sub-activities can be planned in advance. Each sub-activity requires the worker to make plans of his own.</td>
</tr>
<tr>
<td>Step 3R</td>
<td>A sequence of sub-activities is determined in advance. Each sub-activity requires the worker to make his own plans.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 2</th>
<th>Action planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>The sequence of work steps must be planned in advance; the planning only extends to the result of the work, however.</td>
</tr>
<tr>
<td>Step 2R</td>
<td>The sequence of work steps is pre-ordained. However, it varies repeatedly to such an extent that it has to be mentally processed in advance.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Sensory-motor regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>No conscious planning is required for the projection of the sequence of work movements to be requisited, although a different tool has to be used occasionally.</td>
</tr>
<tr>
<td>Step 1R</td>
<td>As for step 1, but only the same tools are required in each case.</td>
</tr>
</tbody>
</table>

Table 7.10 Forms of Regulation Hindrances [Weber et al, 86: 24]

```
Regulation Hindrances

Regulation Barriers

Impediments

Motoric

Interruptions

Not task-specific

Inherent in the task

Monotonous work conditions

Time pressure

Disruptions

Blockages
```
The method ultimately used to assist in the design of the demonstrator turning cell was the similar, though more comprehensive VEMAS (Verfahren zur Entwicklung modular aufgebauter Arbeitssysteme = Method for the development of modularly designed worksystems), method, developed by Bohnhoff and Wankum in the Department of Cybernetics and Engineering Education at the Technical University Aachen. The decision to use VEMAS formed part of a co-operative agreement with the Technical University of Aachen, whereby experience in the use of VEMAS was to be gained by its application in the work design for the demonstrator turning cell.

As described by Hancke [88:46-48], this approach evaluates work design on the basis of the extent to which jobs satisfy the basic requirements of human-centredness. Further favourable characteristics that the work-place should exhibit are also taken into account, as well as negative aspects that should be avoided. To this end the characteristics of a particular work design are grouped into three categories:

First order criteria are essential characteristics for a human-centred work place;
- operator control
- responsibility (for people, materials, work results),
- possibility and need for social communication (formal or informal)
- mental and physical challenge (as distinct from mental and physical strain)
- possibility to apply skills and knowledge
- variation in the task.

Second-order criteria are characteristics desirable in a human-centred work design;
- possibility to extend skills and knowledge,
- possibility to be creative,
- recognition,
- supervisory opportunities.

Third-order criteria are characteristics of the work-place or task that might cause strain, or unnecessary work, or even danger for the individual, and should, therefore be avoided;
- unfavourable environment (noise, lighting etc),
- hazardous environment (eg. fumes),
- lack of, or dependency on information,
- external control of individuals,
- pacing,
- imminent danger,
- need to fix attention onto a particular object,
- monotony.

The use of VEMAS for the design and evaluation of work-places involves a three stage procedure;
1. The basic idea is that each work-place, whether extant or planned, is made up of a number of tasks. These tasks are split up into activities or functions which can be performed independently.
2. Several functions are then combined (reflecting human and technical considerations), as shown in Figure 7.11, where the relative size of each portion of the "pie" represents the proportion of the overall job spent carrying out a particular function. The resultant sets of functions are examined as to whether they constitute a module. In short a module represents a human-centred combination of functions with an overall meaningful task content. Once constituted a module should not then be "disassembled" again in the design process, although clearly different combinations of functions can be suggested until modules are obtained.

3. The modules formed are then combined with remaining functions that have not yet been included in any modules and allocated to the planned work-places. Clearly the available time share of the modules for a particular work-place has to be larger than that of the sum of the functions.

Figure 7.11  VEMAS-Model for Designing Work-Places with Meaningful Task Contents
[Hancke, 88:48]

For an evaluation the extent to which each criterion features in each function is investigated, and numeric values entered on an evaluation sheet, such as that designed by Barth [89:20], which is shown in Figure 7.12. The numeric values are given on a scale from 0 to 4, where 0 indicates that the criterion does not feature in the function, whilst 4 indicates that the criterion features strongly in the chosen function.
The conditions that a combination of activities or functions has to fulfil in order to represent a module are then defined as

**First order criteria:**
- Each criterion has to obtain a value of at least 3 and if possible 4.
- The weighted average over time for the first-order criteria should be at least two.

**Second order criteria:**
- The weighted average over time for the second-order criteria should be at least 2.

**Third order criteria:**
- The weighted average over time for the third-order criteria should be less than 2.

This module definition enables the evaluation of existing as well as planned work-places and also provides recommendations for re-designing the work-place or re-organizing tasks, as will be seen later in Chapter 9.

**Figure 7.12: VEMAS Evaluation Sheet** [Barth, 89:20]
8. Design and Implementation of a Flexible Human-Centred Turning Cell

In Chapter 6, the background to the SERC/ACME-funded project "The Operation and Management of Flexible Human-Centred Turning Cells" in the Department of Mechanical Engineering of Imperial College, was described briefly. As implied by its title, the centrepiece of the project is a flexible turning cell, which forms the "shop-floor end" of a human-centred CIM system, developed to match the guidelines laid out in the preceding chapter.

The main contribution of the author in this project, apart from the collation of the aforementioned guidelines, was in the basic design of the turning cell and in the detailed design of software for the turning cell computer.

The design process for the overall CIM system, and its constituent elements, was iterative and therefore difficult to describe in a straightforward chronological manner. Therefore, for the sake of explanation, the description of the design and implementation process will be divided up into three parts, each corresponding to a different level in the design process hierarchy.

In the first section of this chapter, a scenario, or vision of human-centred CIM is presented. This scenario is important for providing the basis for the design of the overall CIM system, which provides the manufacturing environment for the demonstrator turning cell.

In the second section there is a more detailed discussion of the design of the turning cell itself. The cell was designed to fulfill a requirements specification formulated by one of the industrial partners involved in the project and has acted as a test-bed for hardware and software designed according to human-centred principles as well as for alternative work designs around the technology. The cell has thus provided a useful means for testing ideas subsequently implemented by the author in an industrial setting, as described in the Appendix.

The third part, namely the design of software for use by the cell operators, is described in detail in the next chapter.

8.1 A Scenario for Human-Centred CIM

As pointed out in Chapter 6, it is a fundamental principle of human-centred system design and development that the specification of the technical system cannot be viewed in isolation from the human and organizational system within which it will operate. It has been seen that in most cases the design of conventional manufacturing technology is dominated by technical specialists driven by purely technical objectives and considerations. In order to avoid a variety of problems associated with this technology-centred approach, as also identified earlier, the human-centred approach involves consideration of both technical and human aspects from the beginning of the design process, so as to harness the skills, knowledge and flexibility of system users and support personnel fully, both during the design process itself and after the system has been implemented.
Design and Implementation of a Flexible Human-Centred Turning Cell

It is clear from earlier chapters that the technical aspects of AMT, and thereby CIM, do not completely determine the design of work and organizational structure around the technology. However, the degree of "choice" available can be constrained by system designs that do not take human or organizational aspects into account.

Conversely, it is conceivable that a "traditional" work design, characterised by a high vertical and horizontal division of labour, could operate around human-centred technology, though this would clearly negate many of the benefits expected from technology designed in this way.

This means that a system specification for a human-centred system needs to express the human aspects of the design explicitly, if the resultant system is to operate in the spirit in which it has been designed, and if it is to achieve the full range of desired technical, economic and social objectives, as summarized in Figure 8.1.

![Figure 8.1 Objectives for Human-Centred Manufacturing Technology](image)

It is thus essential to find a means by which to describe the organizational context that is most appropriate for a particular technological specification and that reflects the spirit of "human-centredness".

To this end, it is useful to create a scenario, or vision, of human-centred manufacturing technology, that encompasses the key recommendations from organizational theory and social science, discussed in earlier chapters. In the case of the project at Imperial College, a scenario provided a useful means for describing the manufacturing context in which the human-centred
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turning cell is intended to operate. As will become apparent in later sections, this was essential to the design of the cell, because a "model" of the factory in which the cell would be implemented is necessary to establish inputs and outputs of both materials and information to and from the cell.

The scenario described below, which was created at the start of the project, is based on that developed by Rosenbrock et al [87] for ESPRIT Project 1217(1199) "Human-Centred CIM Systems". This scenario, in turn, is based heavily on ideas expressed by Broedner [86c], who presents a vision of what he terms the "skill-centred" manufacturing system of the future in his thought-provoking book "Fabrik 2000" (Factory 2000).

This scenario, representing as it does the "model" of an ideal factory, differs markedly from the typical contemporary manufacturing organization that is based on the principles of "Scientific Management". It thus provides an illustration of the human-centred "factory of the future".

The model is based on a small- to medium-sized company engaged in small batch production. The company produces a broad range of products with a certain common core. In other words, the product range includes standard "catalogue" products, as well as products adapted for, or specific to, a particular customers requirements. Accordingly, component parts will be manufactured in various batch sizes, down to a "batch of one".

The factory itself is made up of three sub-systems, or departments:
- **co-ordination**
- **design**, and
- **production**.

Importantly, these are organized by product and not by function, so as to maximise flexibility. According to Broedner [86c:149], organizing work by dividing products and product orders, rather than by dividing labour, provides the means by which job shop manufacturing, with its inherent drawbacks, can be changed into group (i.e. cellular) manufacturing, where part families are manufactured in their entirety. This is achieved by extending the principles of Group Technology into a general organizational concept, as shown in Figure 8.2 overleaf.

The objective here is to achieve a "flat" management hierarchy, that is, with the minimum possible number of hierarchical levels in factory management. By thus limiting the length of the managerial chain, people are more in touch with the wider aspects of factory life, management is likely to be more reactive and flexible, and the overall quality of decision-making is likely to be improved.

As implied above, the factory's part range is divided into part "families", that is, groups of parts with similar manufacturing requirements. Accordingly, production "islands" are formed that are responsible for the production of a particular part family or families. The production islands have the task of producing parts and, if viable, complete products in so far as possible from raw materials, and all necessary human, technical and material resources are thus concentrated within the island.
This production structure not only serves to improve material flow (when compared to a functional machine shop layout), but also provides a means by which to simplify the production planning and control task. It further provides the opportunity to devolve a degree of planning responsibility to the island personnel, thereby fulfilling a basic human-centred principle by integrating planning and executive tasks.

In Broedner's vision both design and production departments should be organized around these part families, or product groups, so that each production island has a corresponding design "island". As a result, two skill-centred sub-systems are formed, each with local computer assistance and, as shown in Figure 8.3, interlinked by the basic components of a CIM architecture:

- a common database,
- a data highway, and
- data exchange interfaces.

Importantly, in contrast to the centralized control characteristic of systems associated with "Taylorist" work structuring, this CIM system is integrated in terms of information rather than of control. In other words, rather than representing an attempt to formalize and incorporate all production knowledge and work planning into the computer system, the system serves as an integrated information system, that is, as a further "tool" for use by the system operators.
Although computers are used to control routine operations, their decisions are subject to amendment and can be overridden by the system users, who do not lose computer support when they exercise this supervisory control. The planning of work activities is left up to island personnel, who use their knowledge and skill to optimize island performance, with the computer system providing accurate information and simulations to support this decision-making. How this information is structured and presented can be modified by the island personnel to suit their preferred methods of working and decision-making. Thus the constituent computer systems in human-centred CIM are consciously designed as "tools" for use by system operators, rather than as a means of control.

The interlinking of island activities is organized by the co-ordination department, which is responsible for maintaining the flow of information and materials between islands, for distributing tasks to the relevant design and production islands, and for providing the link to sales and order processing.

Importantly, the presence of a co-ordination department does not lead to a strict separation of planning and doing tasks. Parts being produced in a production island do not require detailed process planning information from the co-ordination department, since this activity can be carried out within the island.
Accordingly, allocation of jobs to the islands and medium-term production scheduling are all that must be carried out by the co-ordination department, whilst production sequencing and monitoring becomes the responsibility of the production island personnel.

There is extensive collaboration between all constituent departments by means of both electronic data exchange and face-to-face communication. It is thus perhaps more appropriate to describe this system concept as computer-aided integrated manufacture (CAIM), rather than computer-integrated manufacture (CIM) [Rosenbrock et al, 87:5]. This reflects the fact that in many circumstances verbal communication and debate provide a much more effective medium for the exchange of information and ideas. For example, new inter-departmental groups will be formed whenever a new product or product group is to be developed. This will enable the manufacturing capabilities of the production islands to be taken into account from the beginning of the product design process to ensure adequate consideration of "design for manufacture".

On a daily basis, the interactions between co-ordination, design and production enable all personnel to see their work from the perspective of its wider implications for the factory overall, and also to be involved in a wide range of decision-making activities. For example, once a product delivery date has been agreed by all departments, any unforeseen problems arising from within the production island that could prevent punctual completion, will be dealt with by production personnel. If re-scheduling within the island cannot solve the problem, then attempts will be made to share the load with other islands, before alerting the co-ordination department that the overall production schedule requires re-processing. This re-scheduling activity would then be carried out with the aid of a factory-level computer-aided production planning system acting at the inter-cell level.

Despite the author's reservations about various aspects of this scenario, in particular the practicality and good sense of extending GT techniques to the organization of the design function, and the use of the term "island", which immediately leads to association with "islands of automation", a situation which CIM is intended to overcome, it nonetheless provided a useful framework for the design of the human-centred CIM system. This system provides the context for the demonstrator turning cell, by simulating the activities in a "human-centred factory".

Figure 8.4 shows the hardware configuration for the CIM system developed at Imperial College. The activities of the design and co-ordination departments are simulated by means of software developed on VaxStation II/GPX graphics workstations supplied by one of the industrial partners in the project, Digital Equipment Corporation (DEC). These powerful multi-processor 'super-mini' computers were selected for their powerful graphics capabilities, essential for the development of a versatile man-machine interface for the various software packages required.

As will be described in more detail in the next chapter, the turning cell has been provided with a PC-type computer on which software to support the cell operators in their management and operation of the cell has been developed. As shown in Figure 8.4, the three "departmental" computer systems are linked by means of a local area network (LAN).
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Figure 8.4 Computer Hardware for the Human-Centred CIM System

Key: CAD - Computer-Aided Design
      PPC - Computer Aided Production Planning
      CNC - Computer Numerical Control
      LAN - Local Area Network

Figure 8.5 Scope of Human-Centred CIM Software
Figure 8.5 shows the scope of the software developed within the project in terms of the CIM "model" presented in Chapter 2. It is important to note the "overlap" shown in the diagram, which reflects the basic principle that it should be possible to locate certain tasks, and thereby computer support, in different departments, dependent on a company's particular circumstances.

For the design "department", a new user-interface has been developed for an existing CAD/CAM system. This system can send CAD geometry and, in the case of highly complex components, part programs, to the production "department" [Besant et al, 88]. To assist in design for manufacture, and in design rationalization, a Group Technology parts coding and classification package has also been developed [Wong, 87].

However, the bulk of the research effort has been aimed at activities in the co-ordination and production "departments". As described by Hatzikonstantis & Sahirad [89] and Sahirad et al [89], an integrated software suite for inter-cell scheduling and tool management has been developed to simulate the operations of the coordination department. More detail on these developments will emerge in the next section, when the design of the demonstrator turning cell, which serves to demonstrate the activities of the production department, is discussed.

8.2 Design of the Demonstrator Turning Cell

The demonstrator turning cell has been constructed so as to show in practice a system embodying the best of current manufacturing technologies, making full use of human interest, commitment, motivation and creativity, and which proves itself to the traditional manufacturing world as an economically viable solution. The design of the turning cell has been aimed at a high variety, small batch production environment, such as is predominant in the European discrete part manufacturing industry. This situation is not only limited to small- and medium-sized companies, but, as pointed out by Craven [86], small batch production of this nature is also frequently found in the machine shops of major manufacturing companies. Many such companies have a wide range of products requiring small job lots and, accordingly, often have prototyping or pre-production machine shops manufacturing a constantly changing variety of components in small batches.

The human-centred turning cell developed at IC contains two CNC machine tools: a CNC lathe and a CNC milling machine, the latter carrying out limited milling and drilling operations, so allowing the cell operators to produce a higher proportion of completely finished work. The cell is capable of producing a wide variety of primarily rotational, turned components from bar, billets, castings and forgings. The CNC lathe has been provided with an automated workhandling device and the cell operators have been provided with various computer-based "tools" to help their management of the cell.

The cell fulfils the role of a "production island" within the CIM scenario described above. The human-centred principles underpinning task allocation and the design of the software distinguish this cell from other cells with ostensibly similar technology [Cutkowsky et al, 84] [Vernon et al, 86].
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The choice of equipment in the cell reflects the fact that it is also intended to provide a means of testing various technological and organizational options for a prospective "user" company. The cell has thus been designed for the manufacture of components for the HDGM range of gearboxes of Harmonic Drive Ltd. As can be seen from Figures 8.6 and 8.7, the components to be machined in the cell (housing, clamping ring, input shaft and adaptor flange) are rotational components, where primarily turning operations are required, with secondary milling and drilling operations. For the turning cell at IC, attention has been focused on the machining of these components for three different sizes of gearbox, as well as the machining of a wide range of additional adaptor flanges for mounting alternative gearbox types to various DC and AC servo-motors.

Importantly, for each size of gearbox, the housing and clamping ring are standard components, whereas the adaptor flange and input shaft both have to be modified to suit the mounting dimensions of a particular servo-motor. Accordingly, housings and clamping rings can be produced in larger batch sizes, although for the purposes of performance tests and the simulation of different work organization options, the maximum batch size expected for any component was set at 50. The requirements specification formulated by Harmonic Drive Ltd also stipulated that the cell should be able to deal effectively with the machining of "one-off" customer specific housings or flanges.

Figure 8.6 HDGM Series Gearbox (Harmonic Drive Ltd.)
Since the design of the cell has been undertaken using the "parallel" procedure outlined in Chapter 7, it is difficult to clearly separate the discussion of the work design of the cell from the design of the technology. However, for the sake of explanation, it is helpful to deal with each separately, and having just described the key criteria determining the technical specification of the cell, it is convenient to deal with the technical aspects of cell design first.

8.2.1 Cell Hardware and Design

Machine Tools

The CNC lathe selected for the turning cell is an HC2/10 lathe from Matrix Machine Tools Ltd., one of the industrial partners involved in the project.

The HC2/10 has a 15 Kw main spindle motor capable of driving the spindle at up to 6000 rpm and has the following key capacities:

- Bar capacity: 42 mm
- Turned diameter (max): 160 mm
- Turned length (max): 300 mm
It is a two-axis lathe with a 12 station bi-directional tool turret using qualified tooling with endworking / boring and turning tools mounted alternately. Although the machine tool was not supplied with a bar feed, a turret mounted bar puller was purchased to allow bars up to 1m in length to be machined. For bar work the machine is equipped with a workcatcher, and a retractable, programmable tailstock enables "between centres" shaft work to be accommodated.

Initially the lathe was equipped with a Fanuc 10TF CNC controller, but this was replaced in the later stages of the project by a "human-centred CNC controller", developed by RD Projects Ltd., another industrial partner in the project. Based on principles emerging from the work at UMIST described in the previous chapter, this controller has a highly interactive graphics system for conversational programming, and also has facilities for multiple part program storage, rapid edit/filing and parallel programming. A powerful, user-friendly controller of this nature was deemed necessary to allow the programming even of highly complex turned components by the cell operators.

Due to financial constraints the lathe could not be purchased with "live tooling". This term refers to driven tooling which, in combination with an indexable spindle, or spindle C-axis, can be used to perform drilling and milling operations without the need to remove the component from the machine. This facility provides the opportunity to completely finish machining of components on a single turning centre, a capability often termed "one-hit machining". This not only offers quality benefits by reducing the number of set-ups necessary in the machining of a particular component, but also serves to reduce lead times and greatly simplify the production planning and control task [Buehler, 87].

In order to enable the complete machining of the above-mentioned gearbox components in the cell, a CNC milling machine has been incorporated. The machine is a Bridgeport 2HP knee-type machine, retro-fitted with a CNC controller developed within the Department of Mechanical Engineering. This controller is also to be replaced by a 'human-centred' CNC unit from RD Projects Ltd. In the early stages of the project various experiments were carried out to analyse the use of automatic workpiece clamping on the milling machine, but the part mix and the nature of the milling and drilling operations to be carried out meant that the setting up of components on the milling machine was retained as a manual task.

Workhandling Equipment and Cell Layout

Given that the parts to be produced by the cell are predominantly turned components, most attention has been focused on the automation of materials handling activities for the lathe, the "primary" machine in the cell. As shown by Figure 8.8, it is possible with current technology to automate the handling not only of workpieces, but also of cutting tools and chuck jaws.

Before looking in detail at the choice of equipment made, it is important to point out the reason for considering automated materials handling in the context of a human-centred turning cell. Most materials handling devices implemented in industry are used for handling operations that repeat frequently over extended periods. Many such devices can only deal with a limited range of part shapes within a closely prescribed family and are therefore examples of "hard" rather than truly flexible automation. They are often used in order to ensure a constant, short cycle time.
for loading and unloading, or in situations where the work would be onerous if carried out manually, due to, say, heavy components. Automated materials handling is also a benefit in hazardous or unpleasant working environments, such as press shops, foundries etc.

However, the primary reason for considering the automation of materials handling activities in the turning cell is to decouple the cell operators from the machine, so as to allow them to leave the machine unattended for extended periods and to engage in planning and evaluative tasks without interruption. This need was shown by the use of discrete-event simulation to model the operation of the cell, as will be discussed in more detail later.

The decision as to the extent of automation of materials handling tasks is complex, depending on batch sizes, machining cycle times, programming and set-up times for the automated materials handling equipment, and not least, cost, as shown by Figure 8.8. In the case of the demonstrator turning cell, the decision was made to concentrate on automated workhandling, since resources were inadequate to deal with the additional tasks of automatic tool changing and chuck-jaw changing. Furthermore, the afore-mentioned simulation studies showed that automation of workpiece loading/unloading, for the part mix and volumes specified by Harmonic Drive, would decouple the cell operators from the machines to an extent sufficient to enable them to carry out their allotted planning and control activities. Automated workhandling also makes the greatest contribution to improved machine utilisation, by allowing the lathe to operate through lunch breaks, shift changes etc.

For the automated handling of workpieces for the lathe, in all cases, apart from first operation bar work, raw material and part machined components have to be inserted into, or removed from the chuck, whilst shaft work has to be placed and removed from between centres. Given the range of parts to be produced by the cell, the latter category is the smallest and generally has all turning operations carried out at one set-up. Components machined from bar stock also usually have all operations carried out at one set-up and in this case finished components are deposited after parting-off in the lathe's work chute by means of an automatic work-catcher.

For chucking work the main loading, unloading and transfer movements are as follows;

1) Raw material from loading point into chuck, and

either 2) Re-insert part in chuck after 180° rotation for second operation,
or 3) Remove part from chuck and move to finished component location.

Similar movements are required for shaft-type components held between centres, although rotation of the part for a second operation is only likely to be encountered infrequently.

As outlined by Schuler & Uetz [84], there are at least four methods of executing these movements:

a) Manually,
b) Floor or jib-mounted industrial robot,
c) Machine dedicated workhandler,
d) Gantry-type loader.
Before outlining the relative advantages and disadvantages of the three methods of automated workhandling listed above, it is instructive to consider briefly how the workhandling device can access the chuck. As shown by Figure 8.9, the HC2/10 is a flat-bed lathe and can therefore be loaded from the front, back, above and from one end. This affects the suitability of the various automated methods for use in the cell and this, in turn, largely determines the cell layout.
**Floor or jib-mounted industrial robot**

Many cells have been demonstrated where workhandling has been carried out by an industrial robot (see [Schuler & Uetz, 84]). However, even if the robot is suspended from a jib, it must, for safety reasons, be surrounded by a cage with interlocks. Since the cell operators must have easy and immediate access to the machine tool, such a means of workhandling cannot readily be employed in the human-centred turning cell.

**Machine dedicated workhandler**

This device is defined here as a programmable mechanism for loading and unloading an individual machine. As such it can meet the requirement for releasing an operator to carry out further tasks, in that it will carry out work loading and unloading operations, but without further devices, such as conveyors, it cannot cater for the inter-machine transport of parts.

A number of machine tool vendors offer machine dedicated workhandlers, generally mounted on or above the headstock, or programmed to travel along a linear track mounted along the front of the lathe. These devices typically consist of a small mechanical arm with limited degrees of freedom, together with a controller and simple programming pendant. As shown in Figure 8.10(a), they are typically used in conjunction with a carousel from which parts are picked up, before being re-oriented by the arm for insertion into the chuck. Usually there is just one carousel, finished or part-finished components being removed from the chuck and replaced on the same carousel.
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Figure 8.10 a) Machine Dedicated Workhandler (loading from front of machine)

b) Machine Dedicated Workhandler (loading from back of machine)

c) Gantry-type Loader
Another possibility with a flat-bed lathe is to use a dedicated workhandler that loads parts into the lathe from the back and places components on a lightweight conveyor running behind the machine. As shown in Figure 8.10(b), raw material and machined components could be carried on pallets on the conveyor. Because the lathe's workguard could remain closed while workhandling operations are being carried out, this method has a number of advantages from a safety viewpoint. However, problems could arise when trying to load, rotate or unload components, due to the comparatively limited room between the tool turret and the chuck, especially if boring tools and drills occupy several turret positions. Apart from this, the main drawbacks with this configuration, from the point of view of the demonstrator turning cell, are high cost and substantial floor-space requirements.

Further possibilities are to mount a compact workhandler within the confines of the machine tool itself, such as used by Lister-Petter in their turning FMS [Willows,87], or to mount a gripper in one of the positions on the tool turret.

Gantry-type loader

Gantry loaders are used frequently for loading and unloading parts from CNC lathes [Thorneycroft & Atkinson,81], but most current installations cater only for large batch sizes, usually due to the difficulty of handling parts of widely differing shapes and sizes, and the extended programming times associated with most existing loaders.

Importantly, a gantry-loader can be made safe from the point of view of the cell operators. The arm for vertical axis movements could move through flaps in the top of the workguard, the latter remaining closed during automated workhandling operations to protect the cell operators from possible danger. Moreover, in the case of a flat-bed lathe, the chuck can be accessed most easily from above and, accordingly, this method of workhandling places the least constraints on the size and shape of part that can be handled.

Furthermore, gantry-loaders are comparatively cheap and do not require excessive floor-space. An important operational advantage is that the gantry can be extended longitudinally before and beyond the lathe to cater for upstream and downstream equipment (see Figure 8.10(c)).

Thus the gantry-loader appears to offer the best solution to the problem of automated workhandling for the human-centred turning cell. After an initial layout by the author, the detail design of a gantry-type workhandler and its control system was continued by Weidlich [89]. Mindful of the problems associated with most existing devices of this nature, particular attention was paid to the programming system and to gripper design.

For the former, software has been developed to provide a highly interactive programming procedure to enable rapid programming and program verification. Running on the cell computer, this software makes extensive use of graphics to guide the cell operators through the set-up procedure for the gantry, and enables the operators to use stored programs for the same or similar components, to save the need to completely re-program the loader's movements.
Following an initial design project by Khalili [87], resulting in the gripper design shown below in Figure 8.11, a pneumatically-actuated gripper has also been developed for use with the gantry-loader.

Important features of this gripper are the readily exchangeable fingers and adaptor plates. These not only provide the facility for handling a wide range of different parts, but also enable an operator to rapidly set up the gripper fingers for the next batch of parts whilst the gantry-loader is still in operation.

Pallet design for the part carousel has also been an important consideration. As with gripper design, the viability of using modular elements that could be assembled by the cell operators to deal with a wide range of components of different shapes and sizes was investigated. The design proposed by Kiskinis [87] is shown in Figure 8.12.

Further Cell Equipment

The HC2/10 lathe is not equipped with touch sensitive probes. Such probes can be used to measure and adjust tool offsets and, separately, using a turret mounted probe, to measure component diameters and lengths and subsequently to trim tool offsets. This in-process gauging method has the advantage over post-process gauging of not requiring a part to be accurately located again, having been removed from its accurate location in the machine tool, and
it enables a part to be immediately re-worked if it is oversize. However, the probe occupies a turret position that could be occupied by a cutting tool, and the measuring procedure is quite time-consuming. Furthermore, components with complex profiles can only have certain dimensions checked by the probe.

For the human-centred turning cell it has been assumed that for the proving of programs for complex components with tight geometric and form tolerances, "first-off" components would be measured in a specialised inspection department using equipment such as co-ordinate measuring machines, or form measuring machines. For less complex components, and for the measurement of components during the run of a batch, the operators have been provided with conventional metrology equipment in the form of digital micrometers and vernier calipers.

It is intended that the cell computer should be provided with software to carry out statistical process control for the quality control of large batches, where measurement data from the metrology equipment will be stored on a data logger before being passed onto the computer for analysis.

The cell has also been provided with a workbench, vice and general workshop tools. The cutting tools can be assembled and pre-set at this workbench. As shown in Figure 8.13, the cell is provided with storage for local stocks of materials and tools. This reflects the desire expressed in the scenario above, that for a given period the cell operators should be free to plan the sequence of work.
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Figure 8.13 Human-Centred Turning Cell Layout
8.2.2 Cell Work Design

It is apparent from the preceding sub-section that a number of human aspects were taken into account in the design of the cell hardware, in particular with respect to materials handling equipment. However, the impact of human considerations is more marked on the design of software, where the functional specification is directly determined by the design of work and the allocation of tasks both between the cell personnel and support specialists in the production department, as well as between humans and computers within the cell. It also plays an important role in determining the number of cell operators necessary to man the cell. Accordingly, it is essential to discuss the allocation of tasks and underlying thinking in some detail before describing the cell management support software in the next chapter.

It is instructive to first look back at some general issues of work organization for the turning cell, to show how this corresponds with the scenario described in Section 8.1.

In Chapter 7 the work design framework of Cummings and Blumberg was described, in which a variety of work designs are compared with respect to their appropriateness in the context of various technical, social and environmental contingencies.

The formation of a turning cell to which the complete machining of a range of part families is assigned, suggests a high level of technical interdependence between the cell operators, while the equipping of the cell with a comparatively high level of modern automated hardware, including automated workhandling, is likely to be associated with a high level of technical uncertainty. The desire for "just-in-time" production and the need to respond rapidly to the need for "one-off" or small batches of customer-specific parts, is indicative of a high level of environmental uncertainty as well.

According to this combination of contingencies, the most appropriate work design is an autonomous work group. This suggests that the cell operators should be provided with the responsibility for planning all activities within the cell. As outlined earlier, this work design is not only expected to have motivational benefits, but is also expected to reduce "value-less" costs by reducing the need to monitor production at the level of individual machines and so, in turn, reducing the ratio of indirect to direct labour.

However, the suitability of this work design and the extent of autonomy that can be delegated to the members of the work group is also dependent on the complexity and variability of the range of parts to be produced.

This is reflected in Figure 8.14, where "high suitability" indicates that the characteristics of the product range provide scope for the delegation of planning responsibility to the work group. As will be seen from the following discussion, certain part range characteristics, such as high part complexity (reflected in a large number of processing stages), will necessitate specialist support in particular tasks.
In the diagram, the particular characteristics of the range of parts selected by Harmonic Drive are shown in bold type, the resultant profile indicating that the parts are well suited to production in a cell operated by an "autonomous production group".

Whilst the definition of an autonomous work group given in Chapter 7 provides a broad outline of the key features of an appropriate work design for the turning cell, a closer analysis of the factors determining what tasks can be executed by cell personnel is required, to show where software support is needed.

For the sake of analysis it is useful to separate planning, that is, administrative tasks, from "doing", or physical tasks, the latter being dealt with first here.

Figure 8.15 shows a schematic of the materials flow in the production sub-system. In common with the scenario presented in Section 8.1, a three-level hierarchy is shown; the lowest level corresponds to functions executed at or with individual machine tools; the second level corresponds to functions executed in a cell or machine group; and the third level corresponds to functions executed on a factory-wide basis. As indicated earlier, each cell has local storage for tools, workpieces and jigs and fixtures to enable it to execute orders autonomously for a time.
According to this schematic, physical tasks will be associated with:

**Movement of:**
- tools
- workpieces
- swarf

**Monitoring of:**
- tools
- workpieces
- machine tools
- materials handling equipment

**Diagnosis and repair of:**
- tools
- machine tools
- materials handling equipment

These physical tasks can be further divided up into *direct equipment control* and *diagnostic control* tasks [Bjorke, 80:8].

*Direct equipment control* describes the control of machine tools, materials handling equipment etc. In the turning cell, tool path control is executed by CNC control, though, as will be discussed later in more detail, programming is to be carried out by the cell operators.
Materials handling in general has been discussed in detail above, and as indicated there, work handling is to be carried out with the assistance of an automated gantry loader. Work handling will be carried out manually for very small batches or one-offs, though the efforts described earlier, with respect to pallet and gripper design, are intended to reduce set-up times to the extent that the use of the work handler is practicable even for comparatively small batches.

For the chosen range of parts, it will be possible for the cell operators to construct appropriate work holding set-ups. This task relates closely to part programming, since part programs must take account of how the workpiece is located and held. For example, speeds and feeds must reflect the rigidity of the workpiece, which is a function of how it is held, and collisions with the work holding equipment must be avoided. In the case of the chosen part range, components can all be machined on the lathe using conventional general-purpose work holding equipment, such as 3-jaw and collet chucks, face-plate etc., whilst for milling operations a modular fixturing system is completely adequate. For components with highly complex fixturing requirements, jig design would have to be executed by support specialists working closely with both the cell personnel and the design department.

 Diagnostic control describes tasks associated with the monitoring and maintenance of production equipment and the production output itself. It was argued earlier that it is beneficial for “task identity” that evaluative tasks, that is, quality control activities, should be carried out by cell personnel. This also has efficiency benefits in that immediate feedback on quality enables problems to be sorted out quickly at source. As discussed above there are various methods of automatic in-process gauging available, but quite apart from the apparent limitations of these automated solutions, the allocation of manual inspection tasks to the cell personnel would make an important contribution to the development of “tacit” knowledge.

 Similar thinking can be applied to the task of tool condition monitoring. Equipment is available for the automatic monitoring of tool wear and tool condition, which does offer the potential advantage of decoupling the operators from the machines for longer periods, but the author’s own experience indicates that these systems are often ill-suited to small batch manufacturing and anyway simply provide a warning that a tool needs to be replaced. A skilled operator, on the other hand, is able to take account of a variety of interdependent factors, such as tool wear, surface finish, machining cycle time etc. when rectifying problems. Importantly, tool condition monitoring, relying as it does on vision, hearing and even smell, is a significant contributor to, and function of, “tacit” knowledge in a machining environment.

 It has also been suggested that preventive maintenance tasks could be undertaken in the cell. For minor maintenance tasks, such as lubrication, replacement of filters etc., this is a practical activity for cell personnel, though more complex tasks following, say, a collision, may need to be carried out by specialised personnel from within or outside the company.

 Turning to administrative tasks, these, too, can be divided into two categories; management control and technology control tasks [Bjorke, 80:8].
Management control, refers to tasks associated with daily production planning and monitoring, that is, when, where and how much to produce. In Chapter 2, the problems typically associated with production planning and control in a batch production environment were described. Attempts have been made to achieve optimal machine loading using centralized planning systems, but disturbances are so frequent and feedback so delayed that a far from ideal situation results. One approach has been to apply MRP with computerised shop-floor data collection to tightly plan and monitor the activities of all individuals and machines at all times, but, as also revealed earlier, this approach has not proven ubiquitously successful, largely because of “human” problems in the closely policed working environment that results.

An alternative solution, and one that is more congruent with both the basic human-centred principle of integrating planning and doing tasks, and the cellular manufacturing structure proposed for the human-centred factory, is decentralized planning, the basic principle of which is shown in Figure 8.16. This solution, which corresponds closely with the concept of autonomous work groups, is implicit in the scenario presented in Section 8.1.

Figure 8.16 Decentralized vs. Centralized Planning
Design and Implementation of a Flexible Human-Centred Turning Cell

Figure 8.17 shows the basic principle of the factory-level production planning and control system developed by Hatzikonstantis and Sahirad [89] for use in the human-centred CIM system at Imperial College. This is responsible for cell loading, that is, allocating work to the cells and then ensuring that materials and tools are available in good time, on the basis of a requirements plan created by each cell. The cell personnel are then responsible for sequencing work within the cell, that is, determining the order in which jobs are executed, and monitoring the progress of work to provide feedback to the co-ordination department when required. These activities will be described in more detail in the next chapter.

Technology control tasks are those associated with determining the methods of production. As outlined in the scenario, the design of the products to be machined in the cell is carried out by the design department, albeit with feedback on the quality of "design for manufacture" from the cell personnel.
Implicit in the scenario is the assumption that all parts can be completely finished in a single island, or cell. In practice, not all jobs can be completely processed in a single, specialized cell, for example, where a central heat treatment or testing facility must be used. This, together with the need for machined parts to be assembled, painted and packed raises the need for factory-level process planning, where the route that a batch must take between cells is laid down.

One alternative is to integrate activities such as assembly and packing within the production island, as was attempted in the BICC Demonstrator Cell for ESPRIT Project 1217(1199) [Hamlin, 88], to obviate the need for inter-cell scheduling, but this was not regarded as viable in the case of the turning cell.

In the CIM system at Imperial College, the inter-cell process planning function is carried out by the co-ordination department, whilst intra-cell process planning is carried out by the cell personnel. This consists of specifying the processing sequence for parts to be produced in the cell and the corresponding workhandling, workholding and tooling requirements. This is an intrinsic part of decentralized planning, in that the co-ordination department does not then have to plan and track each job at the level of individual machines, but only at the level of the cell, or machine group.

Process planning relates closely to part program generation and, indeed, on many modern CNC controllers (in particular for lathes), the specification of workholding and tooling forms part of the programming procedure. As outlined in Chapter 2, there are various methods of generating part programs, that can be used in conjunction with a variety of different work designs, in terms of where the programs are generated and by whom. Many CAD software vendors offer the facility for so-called CAD/CAM, where CAD is extended to incorporate NC part program generation. The advantages claimed are faster tape preparation and a reduction in errors by permitting the direct use of CAD geometry in the programming procedure. However, both the technical and economic case for integrated CAD/CAM are questioned by Kief[86: 11.51 and Leonard[88: 151, the most significant criticisms relating to the fundamental differences in the knowledge and skills of design and production personnel with respect to machining processes.

If programming is then to be carried out in the production department, the question still remains as to whether programming should be carried out within the cell or by support specialists using a dedicated programming system. It is clearly a basic human-centred principle that programming should be carried out by the cell personnel, but practical limits are set by workpiece complexity and the power of available programming systems. For highly complex workpieces, the difficulty and duration of the programming procedure may make programming in the cell impractical. This problem is more likely to be associated with the machining of prismatic components, where 4 or 5 machine axes may be in use, and several set-ups required to complete the part, or complex rotational components to be machined on, say, a 4-axis lathe with driven tools and back-end machining.

It could be possible to adopt a "mixed" programming approach where, for example, subroutines prepared by support specialists deal solely with highly complex components, or
Design and Implementation of a Flexible Human-Centred Turning Cell

prepare subroutines for use in programs generated on the shop-floor [Landolt, 87]. However, as Bergstermann & Brandherm-Boehmker [89] recommend, the development of a "co-operation culture" and means for "positive feedback" from the shop-floor to programming specialists are pre-requisites if such an arrangement is to function successfully.

The projected use of "human-centred" CNC controllers for both the machine tools in the turning cell, with powerful graphics support for a conversational programming procedure, means that the chosen range of parts described earlier in the chapter can be programmed directly at the machine. The capability for "parallel programming" offered by these controllers enables the generation of part programs whilst the machine tool is in operation. The use of automated workhandling enables the full exploitation of this capability, since it means that the cell operators are partly decoupled from the machines in the cell, in terms of part loading and unloading tasks, which will provide them with the opportunity to create part programs without continuous interruptions.

Based on this discussion, tasks in the four categories described above have been allocated to the different levels in the company hierarchy as shown in Figure 8.18.

Figure 8.18 Task Allocation in the Human-Centred CIM System (adapted from [Bjorke, 80: 9])
Design and Implementation of a Flexible Human-Centred Turning Cell

There are further tasks to be considered for the cell personnel that fall outside the framework used above. An important task is "boundary management", that is, managing the "interfaces" between the production cell/island and the design and co-ordination departments. This covers activities such as confirming completion dates and providing feedback on progress, as well as ensuring that sufficient tools and materials are available in the cell to meet commitments.

The task of the "boundary manager" also involves co-ordination of the distribution of tasks amongst the cell personnel. Whether this task is carried out by an individual or divided up between the group members, or whether the task is a full-time activity carried out by the group members in rotation, will depend primarily on the size of the cell, in terms of personnel, and the range of activities carried out in the cell.

In terms of scope, the role of the "boundary manager" has much in common with that filled in a conventional manufacturing organization by a supervisor, or foreman. The key difference here is that this role should be filled by a member of the cell work group, that is, the individual fulfilling the role of "boundary manager" at any one time, will not have a permanent and purely supervisory role, but will also be involved in direct production activities.

In addition to allowing the cell personnel to plan distribution of tasks within the cell, and the sequence in which work allocated to the cell should be carried out, they should also be able to plan for additional activities, such as product and methods development, and training.

The former might include the formation of "Quality Circles" [Slatter, 84], in which personnel from the design and co-ordination departments are also involved. The latter will not only involve the further development of technical skills through both on the job and off-machine training, but also of social and communications skills, to facilitate group working and group problem-solving. It is important that fixed resources and time are set aside for such activities. An allocation of time away from direct production work in this way, acts as a clear indication of management view that shop-floor workers' skills are a valuable resource which needs to be fostered and developed.

The complete task list for the cell personnel is given below in Figure 8.19, where the tasks are divided into groups of associated tasks to help subsequent explanation.

In a traditional work organization, characterized by strict vertical and horizontal division of labour, each of these task categories would be executed by a different group of specialized workers. The organization of work in a human-centred factory on the basis of autonomous work groups leads to the integration of these tasks as shown in Figure 8.20. Figure 8.21 shows where the various tasks are carried out in the cell.

Within the cells the work is carried out by "flexible craftsmen" [Cross, 84], or "computer-aided craftsmen", who must possess and develop skills in machining, machine setting and programming, machine maintenance, quality assurance and work scheduling and planning. This broad range of requisite skills has clear implications for training, which will be discussed in the next chapter.
### Design and Implementation of a Flexible Human-Centred Turning Cell

#### Figure 8.19 Task List for Cell Personnel

<table>
<thead>
<tr>
<th>Task Category</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Boundary Management</strong></td>
<td>- Interaction with design sub-system</td>
</tr>
<tr>
<td></td>
<td>- Interaction with co-ordination sub-system</td>
</tr>
<tr>
<td></td>
<td>- Interaction with other cells</td>
</tr>
<tr>
<td><strong>2. Production Planning &amp; Control</strong></td>
<td>- Requirements planning</td>
</tr>
<tr>
<td></td>
<td>- Scheduling &amp; loading</td>
</tr>
<tr>
<td></td>
<td>- Dispatching</td>
</tr>
<tr>
<td></td>
<td>- Sequencing</td>
</tr>
<tr>
<td></td>
<td>- Progress monitoring</td>
</tr>
<tr>
<td><strong>3. Process Planning</strong></td>
<td>- Process planning (intra-cell)</td>
</tr>
<tr>
<td></td>
<td>- Part program generation</td>
</tr>
<tr>
<td><strong>4. Machine Set-up</strong></td>
<td>- Program verification</td>
</tr>
<tr>
<td></td>
<td>- Workpiece clamping</td>
</tr>
<tr>
<td></td>
<td>- Tool changing</td>
</tr>
<tr>
<td><strong>5. Machine Operation</strong></td>
<td>- Load &amp; run part programs</td>
</tr>
<tr>
<td></td>
<td>- Tool path control</td>
</tr>
<tr>
<td></td>
<td>- Workpiece handling</td>
</tr>
<tr>
<td></td>
<td>- Tool handling</td>
</tr>
<tr>
<td></td>
<td>- Swarf removal</td>
</tr>
<tr>
<td></td>
<td>- Machine supervision</td>
</tr>
<tr>
<td></td>
<td>- Handling equipment supervision</td>
</tr>
<tr>
<td><strong>6. Quality Control</strong></td>
<td>- Workpiece quality control</td>
</tr>
<tr>
<td></td>
<td>- Tool wear monitoring &amp; failure control</td>
</tr>
<tr>
<td><strong>7. Preventive Maintenance</strong></td>
<td>- Of cell equipment:</td>
</tr>
<tr>
<td></td>
<td>- Machine tools</td>
</tr>
<tr>
<td></td>
<td>- Handling equipment</td>
</tr>
<tr>
<td></td>
<td>- Inspection equipment</td>
</tr>
<tr>
<td><strong>8. Training &amp; Methods Development</strong></td>
<td>- On the job training</td>
</tr>
<tr>
<td></td>
<td>- Theoretical training</td>
</tr>
<tr>
<td></td>
<td>- Methods development</td>
</tr>
</tbody>
</table>
Although the group should be free to organize and supervise its own behaviour, the internal division of labour should follow two guiding principles [Rosenbrock et al, 87:6]:

1) the division should always be horizontal rather than vertical, that is, planning and task execution should not be divided among group members. Each member should thus be responsible for the setting, programming and machining tasks for any given machine.

2) it should always be possible for every member to experience and develop an understanding of the relationship between quality of product and quality of production.
In the discussion above, the need for support specialists in certain circumstances was highlighted, but the particular features of the demonstrator turning cell and the range of parts to be produced mean that with appropriate software support all tasks listed in Figure 8.19 can be carried out by the cell personnel. The evaluation of the task allocation enabled by the cell management support software developed by the author, in terms of "human-centredness", is described in the next chapter, after a description of the design and operation of this software.
9. Software Design for the Turning Cell Computer

The cell computer and associated cell management support (CMS) software is of great importance in the human-centred turning cell, since it provides the cell operators with the "tools" necessary to plan and structure their work within the cell. The use of a cell computer thus enables the integration of planning and executive tasks on the shop-floor, so reversing the apparent trend towards an increasing division of work associated with many forms of shop-floor AMT.

As shown by Figure 9.1, a variety of planning and control functions are to be combined with direct production functions within the demonstrator cell, and this allocation of tasks provides the basis for the functional specification of the cell computer software, which is described in the first section of this chapter.

This is followed by a detailed description of the application of key software packages developed for use by the cell operators, namely, process planning, part program management and cell production planning and control, which together constitute the CMS software.

There is also a brief discussion of training considerations for the cell operators and of efforts made to evaluate the "human-centredness" of work in the cell.
Software Design for the Turning Cell Computer

9.1 Functional Specification

As indicated above, the main purpose of the cell computer is to provide the tools whereby the cell operators can carry out planning and control tasks in such a way as to allow them to use and develop their experience and expertise. Therefore the cell computer acts as a source, collator and presenter of the information required to support the operators in the decision-making associated with these tasks.

The activities shown in Figure 9.1 can be further sub-divided to generate the following list, which represents the various application packages required by the cell operators in order to structure and manage their work. This functional specification for the cell computer software is based on the assumption that part programs will be generated at the CNC control units of the machine tools in the cell.

a) Cell Production Planning
- the acceptance of batches from the work-to list offered by the co-ordination department, and the subsequent ordering of the batches to achieve some clear objective function, such as minimising set-up times, to satisfy the requisite due date for the completion of a particular job.

b) Cell Production Control
- the recording of batch start and finish times and logging of set-up, programming and machining cycle times. This information should be passed back to the co-ordination system to provide feedback on progress and to assist subsequent cell loading.

c) Process Planning
- the gathering and generation of data associated with a particular job, that is, sequence of machining operations, tool lists, workhandling and workholding requirements, material requirements etc. An additional module should provide the facility for assisting in the estimation of machining costs for the production of a particular batch, and for calculating costs actually incurred.

d) Part Program Management
- the storage and manipulation of part programs on the cell computer, including part program transfer to and from the machine tools.

e) Resources Management
- the recording and tracking of materials, tooling and workholding equipment, to indicate its availability and status.

f) Quality Control
- the cell computer should provide the facility for recording information such as percentages of rejected components, components reworked etc., as well as
Software Design for the Turning Cell Computer

providing statistical process control (SPC) software for those batches large enough to make such techniques viable.

g) Diagnostic Information
- the cell computer should be able to access and monitor the status of certain equipment in the cell, to provide the cell operators with warning of problems if they are engaged in other activities in the cell.

h) Operator Utilities
- this describes the provision of communication and storage facilities on the cell computer for operator use, for example, message transfer (mail) facility, provision of notepad and sketchpad etc.

As indicated in the introduction to the chapter, attention has been focused on three key application packages, that fulfil functions (a) to (d) in the list above:
- Process Planning
- Part Program Management
- Cell Production Planning and Control

A thorough analysis of information flow and data requirements for the individual application packages indicated that some data would be common to a number of applications. Accordingly, the CMS software has been designed as a suite of integrated packages accessing common databases. The overall software structure and corresponding hardware are shown in Figure 9.2. The inter-relationships between the constituent applications will be explained in more detail in subsequent sections. Software to assist the cell operators in executing the remaining tasks described in the list above is currently being developed by other members of the project team at Imperial College.

9.2 General Design Features

The nature and extent of software support offered to the cell operators is, to a significant extent, dependent on the capabilities of the computer hardware used. The CMS software was initially developed on an IBM PC AT compatible microcomputer, based on a 16-bit Intel 80286 microprocessor. This computer has an Enhanced Graphics Adaptor (EGA) card, supporting high resolution colour displays, and thus enabling the support of a WIMP (Windows, Icons, Mouse, Pull-down menus) graphics environment. Mass storage capability is provided by a 30 MB hard disc and a 1.2 MB floppy disc.

As shown in Figure 8.4 earlier, the use of such hardware supports communication to and from the CNC control units of the cells machine tools via bi-directional serial communications links, and also provides the capability for communicating with other computers in the overall CIM system via a local area network. Industrialized versions of the IBM PC AT and compatible computers are available for use in a shop-floor environment, and similar microcomputers are already commonly used in production control applications [Arai et al,82].
Figure 9.2: Structure of Cell Management Support Software (Current Version)

- Design
  - CAD
  - Tools
  - M/C's
  - Cell Info Database
  - Cell Info.

- Production
  - Process Planning
  - Tools
  - M/C's
  - Operator
  - Cell Info Database
  - Process Plans
  - Part Programs
  - Part Program Management

- Co-ordination
  - PPC
  - Technology Info.
  - Process Plans
  - Waiting
  - In-process
  - Completed
  - Job Record Database
  - Job Status Feedback

- Cell
  - Scheduling
  - Cell Schedule

- Machine
  - CNC M/C Tools

- Factory
  - Order Processing
  - Order for drawing

The diagram illustrates the flow of information and processes involved in the management of a turning cell computer, highlighting the integration of design, production, and co-ordination aspects in a factory setting.
Additional factors influencing this choice of hardware were cost, in that the basic hardware is relatively cheap, and hence more attractive to small- and medium-sized companies, and also the ready availability of proprietary software, so obviating the need to "re-invent the wheel" for particular applications or tasks.

The CMS software has been written in Turbo Pascal (Version 4.0) and utilises graphics routines from the MetaWindows graphics package. Together these enabled the development of the afore-mentioned WIMP graphics environment, which will be described in more detail later. This environment provides a versatile framework for the design of user-compliant interactive software, particularly since it enables the use of direct manipulation techniques.

As Hutchins et al [86] comment, "The promise of Direct Manipulation is that instead of an abstract computational medium, all the "programming" is done graphically, in a form that matches the way one thinks about the problem". The term is used to describe user interfaces that exhibit the following features [Shneiderman,87:201]:

1) continuous representation of the objects and actions of interest,
2) physical actions or labelled button presses instead of complex syntax,
3) rapid incremental reversible operations whose impact on the object of interest is immediately visible.

The real meaning of this definition will become more apparent when the CMS software is described later, but Shneiderman goes on to describe a number of beneficial attributes associated with direct manipulation techniques, that explain why they are so appropriate in the case of the software for the turning cell computer [87:201]:

1) novices can learn basic functionality quickly, usually through a demonstration by a more experienced user,
2) experts can work rapidly to carry out a wide range of tasks, even defining new functions and features,
3) knowledgeable intermittent users can retain operational concepts,
4) error messages are rarely needed,
5) users can immediately see if their actions are furthering their goals, and, if not, they can simply change the direction of their activity,
6) users experience less anxiety because the system is comprehensible and because actions are so easily reversible,
7) users gain confidence and mastery because they are the initiators of action, they feel in control, and the system responses are predictable.

Although some of these claimed benefits are not without doubters [Hutchins et al,86], there is an increasing amount of proprietary software employing direct manipulation techniques, inspired to a great extent by the success of the Apple Macintosh family of computers and their associated software. Due to this fact, and the expected benefits listed above, it was decided at an early stage of development to employ these techniques wherever appropriate.
Based on the decision to use direct manipulation techniques, as opposed to command language or menu-selection forms of dialogue, and in order to fulfill the software ergonomics design criteria listed in Chapter 7, the author developed a **graphics environment** consisting of a variety of graphics and interaction routines with which to rapidly construct a versatile user interface for each of the application packages listed earlier. The key features of the user interface that can be developed within this environment are shown in Figure 9.3 (a).

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**Figure 9.3 a) Key Features of the User Interface**

- Command Menu
- Scroll Bars
- Pull-down Menu
- Action Window
- Message Bars
- Pop-up Window
- Button

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**b) Title Screen for the Cell Management Support Software**

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**IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY**

**Department of Mechanical Engineering**

**DEMONSTRATOR HUMAN-CENTRED TURNING CELL**

**Application Packages**

- Production Planning and Control
- Process Planning
- Part Program Management
- Operator Utilities

**CELL SOFTWARE Version 1.0 Rolf-R. Slatter (Harmonic Drive Limited)**
The general screen layout depends to a considerable extent on the choice of input device. As described in more detail by Hancke [88:40-43], the selection of an appropriate input device is a complex decision resting on a wide variety of factors. For the turning cell computer, the choice of a mouse as input device was guided largely by the prior decision to use direct manipulation techniques wherever appropriate, since a mouse is the device best suited to the use of such techniques.

The screen layout has been designed to fulfill some basic software ergonomics design criteria, namely that the amount of information displayed should be limited as far as possible without omitting important information. Also color has been used extensively as the basis for distinguishing different types of data. Furthermore, to satisfy the need for consistency, the basic screen layout is essentially the same for all the application packages developed by the author.

As can be seen in Figure 9.3 (a), windows are used to divide the screen up into several display areas, so enabling the representation of several activities simultaneously on the screen. To avoid distraction and confusion the decision was made to limit the number of windows in any one display and also to make the windows "static", in the sense that they cannot be moved around the screen by the user. Where the contents of the window exceed the space available on the screen, the windows are provided with scroll-bars, which enable the user to "scroll" through the full contents.

The mouse is used to guide a cursor, which, as will be seen in the subsequent screen photographs, is represented by a hand icon in the case of the author's software. When the user moves the cursor to an area of the screen where a user selection is possible, the cursor adopts a "pointing hand" shape, to indicate that the pressing of one of the mouse buttons will trigger the execution of the activity at which the cursor is currently pointing. When the cursor is moved to an area of the screen where no user selection is possible, the cursor adopts a "raised hand" shape and the mouse buttons have no function.

At the top of each screen, a horizontal command menu lists the various commands available to the user in a particular display. On moving the cursor to the command bar and "clicking" on a mouse button, a vertically arranged pull-down menu appears, listing further possible user selections corresponding to the chosen command.

For some command selections, additional pop-up windows appear, providing the user with additional information or prompting a further selection. Action windows, such as that shown in Figure 9.3 (a), appear when the user is required to confirm or cancel input information, or to confirm or override a software-activated decision. Here the user makes a selection by means of screen buttons, activated by moving the cursor over the appropriate area of the screen and pressing one of the mouse buttons. Action windows are also used to provide a means of "undoing" incorrect actions and, by requiring user confirmation for particular actions, play an important role in avoiding errors with severe consequences in operations such as file saving, file loading and file creation.
Further guidance for the user is provided by message bars, which are used to inform the user of program status in the event of, say, delays due to file operations, report printing etc. They are also used to warn the user that information input is erroneous, or of the consequences of a particular selection. This fulfills the criteria of minimum shock and error reversibility.

In addition to the features described above, extensive use has been made in the software of icons, as can be seen from Figure 9.3 (b), which shows the opening screen of the CMS software, from which the desired application can be selected. This attempt to present a "workshop analogy", has been largely inspired by the "desktop analogy" employed by Apple in their "classic interface" [Hooper,86] for the Macintosh computer. As will be seen later, various hardware and software elements are represented as graphic icons to increase the transparency of the operation of the individual application packages. By providing a representation of reality that can be manipulated, the intention is that the cell operators expertise in the "task domain" can be readily employed in the use of complex software, without demanding more than a minimal knowledge of the computer or of computing.

An on-line "help" facility has been implemented in all the application packages using a proprietary hypertext software package called Guide®. Hypertext can be defined as non-linear or non-sequential collation of text and graphics that allows for interactive branching and dynamic display of information. In a hypertext system arbitrary links can be constructed from any point in a document to other points within the same document or within another document. By using the resulting sets of links as "access structures", the user can retrieve information in a dynamically organized fashion [O'Malley,86]. Hypertext is thus ideal for providing an easy-to-use and flexible "help" facility, in which the user is simply presented with a list of topics, each with links to textual explanations or diagrams, which in turn have links to further text or diagrams explaining the topic in increasing detail. Thus the user can very quickly and interactively focus in on the information required, rather than having to "page" through a help file text or search for the explanations of error codes in a user manual.

In the development of the software for the cell computer a prototyping approach was adopted, whereby a "user group", consisting of technician and workshop staff from the Mechanical Engineering Department and the authors sponsoring company, were involved in all stages of the design process, shown schematically in Figure 9.4 below. As pointed out by Heeg [87] and Pressman [87], this approach has a number of potential advantages:
- the end user is much "closer" to the software developers,
- development times are likely to be reduced,
- recognition of problems by the user results more rapidly in improvements,
- application documentation can be produced more rapidly and continuously,
- "learning time" for the end-users is reduced.

Figure 9.5 shows sample screen designs drawn in the early stages of the software development process, whilst the routines for the graphics environment were being written. Such screens were drawn to aid the discussion of screen layout and program operation with the "user group".
Subsequently the software was tested at regular intervals and review meetings held with the user group to discuss progress and guide further development.

Figure 9.4 Prototyping Procedure for Software Development [Heeg, 87]

Figure 9.5 Proposed Screen Layouts

a) Process Planning

Operations Planning

<table>
<thead>
<tr>
<th>Select Machine</th>
<th>Select Process</th>
<th>Select T-holders</th>
<th>Select Insert</th>
<th>Work-holding</th>
<th>Work-handing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roughing of Outer Figure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-finishing of O. Figure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finishing of Outer Figure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Toolholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCLN</td>
</tr>
<tr>
<td>PSBN</td>
</tr>
<tr>
<td>PTGN</td>
</tr>
<tr>
<td>PDJSN</td>
</tr>
<tr>
<td>PTGN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool Inserts</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNMM</td>
</tr>
<tr>
<td>SNMM</td>
</tr>
<tr>
<td>CNMM</td>
</tr>
</tbody>
</table>

Operations Plan No. 19876

<table>
<thead>
<tr>
<th>Op. No.</th>
<th>Operation Type</th>
<th>Holder ID</th>
<th>Insert ID</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Roughing of Outer Figure</td>
<td>PCLNR</td>
<td>CNMM</td>
<td>..........</td>
</tr>
<tr>
<td>20</td>
<td>Finishing of Outer Figure</td>
<td>PDJNR</td>
<td>DNMM</td>
<td>..........</td>
</tr>
</tbody>
</table>
b) Part Program Management

The Part Program Management section of the diagram illustrates the process of managing part programs for the Turning Cell Computer. It includes icons for parts such as a bearing flange, output shaft, and clamp ring. The software design involves downloading, uploading, searching, and deleting part programs, with options like unproven, proven, tooling family, and workholding.

A separate section for Turning Cell Hardware shows machines labeled as Machine 1, Machine 2, and Matrix Series 1-3, indicating the hardware components involved.

c) Cell Production Planning and Control

The Schedule Display section details the production planning and control in the cell. It shows a timeline for machine 1 and machine 2, with batch times and machine idle times displayed. The display also indicates the status of batches, machine setup, and at-machine times. The software design for the turning cell computer facilitates efficient management of these processes.
9.3 Process Planning

As described in the preceding chapter, the routing of jobs to particular cells is carried out by the co-ordination department, but the process planning within each cell is to be carried out by the cell operators themselves. As shown in Figure 9.2, the design geometry for a particular component is passed down to the cell by the design department. This can be carried out both by means of file transfer via the Local Area Network, shown in Figure 8.4 earlier, or by means of diskette, though a hard copy drawing still provides the most versatile medium for discussing machining requirements within the cell, or for pointing out potential machining difficulties to design personnel.

The process planning procedure itself consists of specifying the sequence of machining and handling operations for a particular part and, thereby, workhandling, workholding and tooling requirements. As indicated earlier, with advanced CNC controllers some of this activity can be carried out at the machine tool as part of the programming procedure, but for a cell incorporating machine tools with less advanced CNC controllers, or manual machines, tooling and planning information must still be collated for each operation on each machine. Typically tooling and program sheets are produced manually, but, for a number of reasons, it is useful to generate and store this information with computer assistance. If, as is the case here, a variant planning approach is adopted, then stored plans can be readily retrieved and edited for parts that are similar to parts already planned. Furthermore, information from process plans stored on the cell computer can be used in further activities such as cell production planning and control.

The operation of the software is best explained by means of a sample session, where the steps required to create and manipulate process plans are described.

Figure 9.6 (a) shows the title screen that appears when the user starts the application. It is important to note the message at the bottom of the screen, which is typical of messages that inform the user of the reason for any delays that exceed the typical response time of the package.

After program initialization the initial screen, shown in Figure 9.6 (b), displays the content of the process plan library, that is, shows those process plans stored on the cell computers hard disc. A scrolling window allows the complete library to be viewed. The icon representing each process plan shows whether the part has only turning operations, that is, is machined on the lathe alone, or whether it features milling operations as well, and also shows the part name and number.

The create command is used for the generation of totally new process plans. As shown in Figure 9.6 (c), the first step is to enter the part number and part name for the component to be planned. This alphanumeric information is input using a line editing feature, which allows the user to quickly correct typing errors.

The subsequent screen, shown in Figure 9.6 (d), provides the user with the opportunity to select the machine tool used for the first machining operation, material type and form of raw material used for the part. It is important that the machining operations are entered in their actual sequence, since the sequence in which the operations are planned provides the basis for
issued and the tool icon does not appear in the selected turret position. Similarly, if the turret is already full of tools, the user is shown the preceding screen, (see Figure 9.6 (h)), and a tool already present is suggested.

As shown in Figure 9.6 (i), once the tool turret position has been chosen, the user can enter tool offset data, cutting speed and feed rate for this process. In subsequent versions of the software a materials database is to be implemented that, dependent on raw material, machining process and chosen tool, will suggest appropriate speeds and feeds. These values will act as defaults that can be overwritten by the operator.

This procedure for describing the tooling set-up, from the screen shown in Figure 9.6 (h) on, is repeated until the sequence of machining processes for this machining operation is completely described. In the case of a first operation on a particular machine tool, the user is then asked if a second operation is required. If so, new information can be entered for workhandling and workholding, the selections made for the first operation being highlighted where appropriate. When selecting tooling for the second operation, first operation tooling is shown, although these selections can be overwritten. This feature is useful for helping the user avoid unnecessary tool changes. It reflects a basic assumption underpinning this application software, namely that no more than two set-ups are required on any one machine tool, for any part to be machined in the cell. For the Harmonic Drive parts described earlier, this assumption is completely valid.

Once the machining requirements for a particular part on one of the machine tools in the cell have been completely specified, the user is asked whether further machining operations are to be carried out on the other machine. If so, then the above procedure is repeated, albeit with modifications to suit the machine tool type. At the end of the create procedure the process plan is saved automatically on the hard disc.

The view command enables the user to "view" the contents of a process plan in summarized form. This is a useful facility when preparing tools, workholding devices etc. for repeat batches. As shown in Figure 9.6 (j), the first step is to select a process plan icon from the library window. In this version of the software only a rudimentary "search" facility, searching on the basis of part name or number, has been implemented. In later versions a more powerful searching command, based on the work of Wong[87] on part coding and classification, that can search for parts with similar processing characteristics in terms of tooling etc., is to be built in. As will be seen later, this is very important for use with the edit command when creating plans for part variants.

After using the simple search facility presently available, to highlight the requested process plan icon, the pull-down menu shown in Figure 9.6 (j) shows the various constituent sections of the process plan that can be viewed. In this case tooling has been selected. After the user indicates whether first or second operation tooling is required, the screens shown in Figures 9.6 (k), (l) and (m) are presented. Figure 9.6 (k) shows a list of text process descriptions, which is followed by a more detailed list of tooling information, including process type, tool holder code, tool offsets etc., shown in Figure 9.6 (l). The third screen, shown in Figure 9.6 (m), shows the full tool complement for the chosen part.
As indicated above, the software is based on a variant or retrieval approach to process planning, which means that a versatile edit command is essential to enable the rapid and easy modification of plans for the machining of part variants. Following selection of a process plan icon from the library window, the user can select the section of the process plan that is to be edited. This obviates the need to run through the complete plan when making changes. As shown in Figure 9.6 (n), in this sample session the user wishes to edit the tooling set-up described in the process plan for the part called "flexispline".

In editing the tooling set-up, the user must first use the mouse to select the appropriate process from the list presented in Figure 9.6 (o). The user then has various editing options open; modification of an existing process, insertion of a new process, or deletion of an existing process. The insert option enables the addition of further machining processes at any desired point in the overall machining operation. Once the position for the new process has been chosen the user then follows the same procedure as described above for the create command to enter the new information. The delete option enables the erasure of selected processes. As with all actions that cause data to be deleted or overwritten, the user is asked to confirm the action. The modify option, which has been selected here, enables the alteration or amendment of the data entered previously for the selected process.

As shown in Figure 9.6 (p), the existing choices are presented to the user in the same sequence as described above for the create procedure, and the user has the choice to alter or to confirm as appropriate. The turret position for the tool can also be changed, as shown in Figure 9.6 (q), where the guiding message for the user, that appears at the bottom of the screen if an attempt is made to place the tool in a prohibited position, should be noted. Once the turret position has been altered, or confirmed, the user can edit or enter new data for tool offsets, speed and feed rate, as shown in Figure 9.6 (r). The new process information is displayed in summarized form, as shown in Figure 9.6 (s) to be confirmed, corrected or cancelled. If the correct button is selected then the user retraces the steps described above, whereas if the cancel button is selected the modifications made are ignored and the user is returned to the screen shown in Figure 9.6 (o). If the confirm button is selected, the user is returned to the same screen, but with the modified information now included in the selected plan, and can modify, insert or delete further processes in the plan as desired.

To end the editing procedure, the user selects end edit in the screen shown in Figure 9.6 (o). The user must then confirm that the changes made to the plan should be saved to hard-disc, as shown in Figure 9.6 (t).

Further commands available with this application are; copy, erase, print, and help. The copy command enables process plans to be copied (with the same or a new part name and number) on floppy disc or on the cell computers hard disc itself. This enables plans to be archived or to be transferred to another cell. To reflect this latter possibility, plans can also be copied to the hard disc from floppy disc. If the plan to be copied to the hard disc has the same part name and number in its header as an existing plan, then the user is asked to confirm that the existing plan be overwritten.
The *erase* command enables plans to be erased from the hard disc. To avoid inadvertent erasure the user is asked for confirmation of this action. The *print* command enables process plans to be printed. This hard copy is particularly useful when preparing tooling and workholding devices at the workbench in the cell. As described earlier, the *help* function has been implemented using a proprietary *hypertext* package, and provides the user with both text and graphic guidance on how to use the software.

**Figure 9.6 Sample Screens from Process Planning Application**

a)

![Sample Screen 1](image1)

b)

![Sample Screen 2](image2)
Create - Workhandling (First Operation)

Select U-handling Method: Manual, Automatic
Select Gripper: 3-Finger, Parallel

Confirm Workhandling: Workhandling: Automatic, 3-Finger
Software Design for the Turning Cell Computer
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PROCESS PLANNING - TURNED PARTS

How select process

1. Face forging
2. Rough turn outer shape
3. Semi-finish outer shape
4. Finish outer shape
5. Centre drill 5mm
6. Drill 5mm
7. Drill 10mm
8. Drill 30mm
9. Rough bore
10. Finish bore

PROCESS PLANNING - TURNED PARTS

Please select tool insert

Edit - Tooling (First Operation)

Select Process

Centre Drilling
Drilling
Roughing - Ext.
Roughing - Int.
Semi-Finish - Ext.
Semi-Finish - Int.
Finishing - Ext.
Finishing - Int.
Grooving/Parting-Off
Threading

Select Toolholder

Drill Dia. (mm) ID
20 680
25 681
30 682
40 683
45 684
50 685
55 687
9.4 Part Program Management

For many CNC controllers, the number of part programs that can be stored at the machine is limited. Furthermore, it is often difficult to store important information with these part programs, such as who created the program, and whether it has been "proven out" or not. Thus in the turning cell, the computer is used for central storage of part programs. As shown in Figure 9.7, serial communications links are used to transfer programs to and from the machine tool controllers, though with the RDP CNC controllers it is also possible to transfer the programs by means of floppy discs. The part program management software must not only provide a user-friendly means for storing and retrieving part programs, but also control the serial data communications with the CNC controllers.

**Figure 9.7 Cell Computer to Machine Tool Data Communications**

- RDP CNC
- IBM PC AT
- Up to 4 RS 232 Serial Communication Links

HDD: Hard-disc drive
FDD: Floppy-disc drive
Following the title screen shown in Figure 9.8 (a), which is displayed while the program is initialized, the opening screen of the application proper is shown in Figure 9.8 (b). The left-hand window shows the part program library, that is, all part programs stored on the cell computers hard disc. The part program icons show the part name, part number, machine type and also the type of part to which the program corresponds (chucking part, shaft or bar part etc.). The right-hand window shows icons representing the hardware in the turning cell, that is, the machine tools, cell computer and peripheral devices.

The Info. command enables the user to read the "header" information associated with each part program as stored on the cell computer. When the user has selected a program icon from the library window, the header information corresponding to this program is displayed in a pop-up window, as can be seen from Figure 9.8 (c).

The upload command enables the user to transfer programs from the cells machine tools to the cell computer, for storage or editing purposes. The first step is for the user to select the machine tool from which the program is to be uploaded. The icons representing the selected machine tool and the computer are then highlighted in the cell hardware window, as shown in Figure 9.8 (d). This provides visual confirmation of the selection made. The operator can then enter information relating to the program to be uploaded, for example, whether the program has been "proven out" yet. Following the uploading procedure this information is stored with the program for future reference. When the header information has been completed, the software checks whether a program for a part with the same name and number already exists, and if so, the user is asked whether the existing program should be overwritten. Once this step has been completed the part program can be uploaded from the CNC controller of the machine tool. If this procedure is successful, then a new icon appears for the program in the program library window. If, however, no information is received from the machine tool, then after a given period a warning message is issued.

The download procedure is, as its name suggests, effectively the reverse of the upload procedure, in that a program is transferred from the cell computer to one of the cells machine tools. The user first selects a part program from the library window and is asked to confirm this choice, as can be seen from Figure 9.8 (e). The user can then select the machine tool to download the program to, and as shown in Figure 9.8 (f), the active hardware elements involved in this procedure are highlighted in the hardware window. If the machine type registered in the program header (this information could also describe the CNC controller type) does not agree with the selection made, then a warning message is displayed. Once the CNC controller has been prepared to receive the downloaded program, the program can be transferred by selecting the ready button shown in Figure 9.8 (g).

As can be seen from Figure 9.8 (h), there are further copy, edit, erase and help commands that can be used in this application. As can be seen from the pull-down menu in the screen shown, the copy command can be used for copying programs to and from floppy disc, as well as for the creation of further copies of a program on the hard disc itself. It is also possible to generate a hard copy of any program stored on the hard disc. The icons representing active
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hardware elements are highlighted whenever programs are copied or printed, in the same way as for the upload and download procedures. The erase command is used to delete programs on the hard disc. As for all actions involving the erasure or overwriting of information, the user must confirm this command.

To edit part programs, use is made of a proprietary word processing package. Since the part programs are stored as ASCII text files, they can be read and modified using Microsoft Windows Write®, which has a broadly similar user interface to the cell management support software. After selection of a program from the library window, a batch file transfers the chosen program to the word processing package, which is started automatically. The user can then use the various Write commands to edit the part program. On exiting from Write the user is passed back to the initial screen of the part program management application, shown in Figure 9.8 (b). However, for later versions of the cell computer software, a purpose-written editor should be developed, both to avoid losing consistency with respect to screen layout and command functions, and to provide some specialized editing functions, such as automatic line renumbering, not available in proprietary word processing packages.

As shown by Figure 9.8 (i), and as already described above, the proprietary Guide® hypertext package is used to provide an on-line help facility. By selecting a topic from the menu shown, the user is provided with both text and graphics explaining the use and operation of a particular command. The figure is useful for highlighting some of the problems of consistency pointed out above. Despite some common features, the differences in commands and in cursor operations could lead to confusion for someone not conversent with both applications. Thus, whilst the use of proprietary software for functions such as text editing and on-line help, was necessary to reduce the burden of creating new software within this project, customized software is ultimately preferable for preventing such problems arising.

Figure 9.8 Sample Screens from Part Program Management Application
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Figure 3.3 Disk Storage and Retrieval System Diagram

Guide

Guide: Edit Search Display Format Size Make

Guide Help

Key to cursor shapes in "GUIDE":

1. Info
2. Upload
3. Download
4. Copy
5. Edit
6. Erase
7. Help
8. Quit
9.5 Cell Production Planning and Control

The basic features of the decentralized production planning philosophy underpinning the corresponding software developed for the turning cell computer have already been outlined in Section 8.2.2. above.

A number of different methods have been proposed for the allocation of orders to cells in cellular manufacturing systems, as reviewed by Sinha & Hollier [84]. Amongst the best-known methods are Period Batch Control proposed by Burbidge [75] and the load-oriented planning procedure of Wiendahl [87], both of which have found quite extensive practical use. Interesting recent work has been that of Shaw [87] [88], investigating a distributed scheduling method, in which the cells, acting as "mini-factories", are connected by means of a communications network and effectively "bid" for orders [87:1286]. The anticipated advantages of this distributed scheduling method over centralized planning methods are shown in Figure 9.9.

The author's work, however, has been focused on the sequencing and scheduling of jobs within the cell, rather than between the cells, this latter work being undertaken for the project at Imperial College by Hatzikonstantis & Sahirad [89].

![Figure 9.9 Distributed vs. Centralized Scheduling (Shaw, 87:1289)](image-url)
Figure 9.10 shows the basic production planning procedure embodied in the software developed for the cell computer. According to this procedure, jobs are offered to each cell in the form of a *work-to list*, consisting of a list of the batches to be completed together with their due dates. The cell computer software enables the cell operators to add jobs from the work-to-list to the running schedule for the cell. The software enables the user to re-sequence the batches so as to minimize the make-span, to see whether the due date constraints can be met. If the expected completion date/time, established by the cell operators as a result of simulating the amended schedule for the cell, is acceptable to the co-ordination department then the job is allocated to that cell. The requisite information and materials are forwarded to the cell, which is then committed to completing the batch by the time given. If the due date constraint cannot be met then the job remains in the work-to-list for re-allocation to another cell, or for adjustment of its due date.

**Figure 9.10 Schematic of Cell Loading and Scheduling Procedure**

- **Production Orders**
  - Distribute orders to cells
  - Allocate to alternative cell
- **Cell Orders**
  - Allocate orders for correct time period (if possible)
- **Allocated cell orders by period i.e. "Work-to" List**
  - Add orders to current schedule
  - Schedule Simulation
  - Apply heuristic rules
  - Schedule Simulation
  - If due date constraints cannot be met
- Feedback to Customer

**Co-ordination Department**

**Capacity Data**

**Cell Routing Data**
Clearly both production planning and production control activities must be supported by the
cell computer software. Discussing planning issues first, an important point to make immediately is
that in developing software to assist the cell operators in sequencing work within the cell, the
author has subscribed to the view expressed by Bestwick & Lockyer [82:348] that for any
scheduling system,

"...It is... essential that the solution and its presentation are easy to understand and
possess some structure which has an intuitive appeal. This need for simplicity and clarity
is so great that it may well be worth sacrificing 'performance' for intelligibility. An optimal
solution which cannot be comprehended by the appropriate supervisor is useless. A
non-optimal but comprehensible solution will stand some chance of being completed."

Accordingly, the cell production planning and control software embodies a variety of heuristic
rules for sequencing jobs for a given machine (mindful of precedence constraints) [French,82]:

i) Earliest due date rule - batches are sequenced according to the due date
provided by the co-ordination department.

ii) CAP priority rule - batches are ordered in terms of a priority value allotted by
the co-ordination department. This priority value cannot
be changed by the cell operators.

iii) Operator priority rule - batches are ordered according to priority values given by
the cell operators themselves.

iv) Shortest processing time rule - batches are ordered according to estimated processing
time (no account is taken of sequence-dependent set-
up times).

v) Least set-up time rule - batches are sequenced in such a way as to minimize set-
up times on a "key" machine.

The last-mentioned rule is particularly important in the case of a turning cell in that it reflects
the fact that for lathes set-up times are dependent on the sequence of batches. In other words,
one particular sequence may incur significantly longer set-up times than another sequence of the
same batches. Various methods have been proposed by which set-up times are taken account of
in scheduling, for example, those proposed by Foo & Wager [83], Flynn [87] and Kekre [87].

Knight & Spurgeon [83] propose a pre-emptive approach, whereby cluster analysis
techniques are applied to tooling lists to help identify batches with common or similar tooling
requirements and to help in the specification of tooling set-ups that are capable of dealing with a
wide variety of different batches without requiring significant set-up changes. Daoud & Purcheck
[81] describe a similar method, which involves the formation of a set-up matrix showing the time to
change from one batch to another, this matrix then forming the basis for a least set-up time
sequencing rule. Elements of the work of both Knight & Spurgeon and Daoud & Purcheck are
incorporated in the cell computer software.

Figure 9.11 shows the information required to enable the use of the sequencing rules
described above. It is important to note that the only additional information that the user has to
input is the cell priority value for a particular batch. All other requisite information is read
automatically from the cell computer's databases. In the case of the least set-up time rule, when process plans are already available for the batches to be sequenced, set-up times are calculated from the given tool lists and workholding / workhandling information for the respective batches.

![Figure 9.11 Information Flow for Cell Production Planning and Control](image)

These data are compared for all batches to be sequenced, required changes identified and the corresponding sequence dependent set-up times calculated using estimated times for tool changing etc. stored in the cell computer's database. The result is the set-up time matrix shown in Figure 9.12 overleaf. The planning software contains routines that, given a particular starting batch, can then identify the batch sequence that minimizes set-up times for a given key machine.

As indicated above, the cell computer software is also used to support the cell operators in production control activities. As shown in Figure 9.13, a record is created for each job from information contained in the work-to list and from information contained in process plans (when already available). These records are stored in a database, where they are divided into categories according to the status of the job. Jobs that have already been accepted into the running schedule for the cell, but have not yet been processed, have waiting status, whilst batches currently being machined have in-process status. The records for those jobs that have already been finished are given the status completed and remain in the job records database until they are archived or erased. Estimated and actual times for setting-up and processing each job are contained in the job record. As will be described in more detail later, the cell operators notify the
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cell computer when a particular job is started or completed and also enter the actual times taken to machine a component or prepare the part programs required. Not only does this mean that the planned cell schedule is being constantly being brought into line with the actual state of production, but the storage of this information in the job records database, which can be read by the co-ordination department, provides a means for constant feedback on cell performance.

It is important to briefly point out some of the key assumptions underpinning the cell production planning and control software. In line with the current production planning methods of the “user company” Harmonic Drive, it has been assumed that there will be no batch splitting or overlapping, in other words, all batches will be machined at one go rather than being divided into “sub-batches”, and a batch cannot start being machined on the milling machine until all components have been completed on the lathe. It has also been assumed that for any batch, on any machine, that first operation machining is completed on all components to be immediately followed by second operation machining. Both these assumptions have been made to simplify the software, since the author’s prime focus of attention has been on the design process for the software and the user interface.

Figure 9.12 Matrix of Batch Set-up Times

<table>
<thead>
<tr>
<th>From</th>
<th>S₁</th>
<th>S₂</th>
<th>S₃</th>
<th>S₄</th>
<th>...</th>
<th>Sₙ</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>0</td>
<td>T₁₂</td>
<td>T₁₃</td>
<td>T₁₄</td>
<td>...</td>
<td>T₁ₙ</td>
</tr>
<tr>
<td>S₂</td>
<td>T₂₁</td>
<td>0</td>
<td>T₂₃</td>
<td>T₂₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₃</td>
<td>T₃₁</td>
<td>T₃₂</td>
<td>0</td>
<td>T₃₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S₄</td>
<td>T₄₁</td>
<td>T₄₂</td>
<td>T₄₃</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sₙ</td>
<td>Tₙ₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

where Sᵢ = Set-up for batch group i
  i.e. required set-up of tooling, workholding and workhandling equipment

Tᵢ = Time taken to change set-up from that for batch group i to that for batch group j
  i.e. \[ Tᵢ = tᵢ + wᵢ + hᵢ \]

where tᵢ = time to change tools

wᵢ = time to change workholding, and

hᵢ = time to alter workhandling equipment
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Figure 9.13 Feedback from Cell Production Planning and Control

Jobs offered to Cell

Factory-Level Production Planning & Control

Feedback on Job Status

Current Schedule

Completed Jobs

Job Records Database

Work-to List

Job Record N
- Job Number
- Part Number
- Due Date
- Batch Quantity
- Routing Information
- Estimated Times
- Actual Times

Heuristic Rules
- Least Set-Up Time
- Earliest Due Date
- Shortest Processing Time
- Operator Priority
- CAP Priority

It is also important to note that the screen displays for the sample session described below were produced with a version of the software that had been modified for use in the Rolls-Royce Demonstrator Turning Cell within ESPRIT Project 1217(1199). The cell at Rolls-Royce consists of two CNC turning centres with automated workhandling. Importantly, all jobs to be machined within this cell can be completely finished on a single machine. This is reflected in the displays shown by an obvious lack of precedence constraints, since jobs need not be transferred from one machine to the other. A further difference that is less visible is that the heuristic rules could be applied to the schedules for both machines, which are effectively independent. This difference, as well as others, will be explained in more detail in the description below.

Figure 9.14 (a) shows the title screen for this application, that is displayed whilst the program is initialized. The first screen of the application proper, shown in Figure 9.14 (b), shows a Gantt chart representation of the current schedule for both the cell machine tools. Various methods of displaying these schedules are possible, but mindful of the fact that bar charts are a familiar tool for scheduling in most machine shops, and of the need for compatibility, the Gantt chart was chosen as the most appropriate means of presenting the cell schedule. As will be seen later, the schedule...
can also be displayed in tabular form, but the active manipulation of the schedule by the cell operators is best carried out using the graphical representation. The user can change the view of the chart in the window by panning to the right and left and by magnifying or reducing the resolution of the horizontal, time axis.

Figure 9.14 (c) shows the "zoomed" view of the schedule. In this view the working hours and days are visible on the time axis. This information is derived from the cell information database and can be readily changed by the cell personnel. In this view the batch numbers can also be read. The jobs "in-process" on each machine are shown by hatched bars, while jobs waiting for processing are shown by solid bars.

Notable are the histograms, which are a special feature of the software developed for application at Rolls-Royce. As indicated by the key, the histograms show the estimated or calculated times for data preparation (process planning and part programming), set-up and machining. These are intended as a visual aid in helping the cell operators to sequence work so as to minimize set-up times.

As shown by Figure 9.14 (d), the display command is used to show not only the Gantt chart and tabular representations of the current schedule for the cell, but also the respective work-to lists and completed job lists for the cell (or in the case of the Rolls-Royce cell, for each machine). As can be seen from Figure 9.14 (e), the work-to list contains information on those jobs "offered" to the cell, that have not yet been accepted into the current schedule, which is shown in tabular form in Figure 9.14 (f). Here the in-process job for each machine is shown in red, whilst "waiting" jobs are shown in blue. Importantly, for the in-process job, the start time shown is the actual start time as entered by the user, whilst all other times are based on calculated or estimated set-up and processing times. In the completed jobs list, shown in Figure 9.14 (g), all times given are actual times, as entered by the cell operators. As indicated by the pull-down menu shown in Figure 9.14 (d), hard copy versions of all these lists can be printed.

The Info.. command is used to obtain detailed information on a specific batch. The operator simply pans the Gantt chart until the desired job is located, then "clicks" on the bar to select the job. As shown by Figures 9.14 (h), (i) and (j), various pages of information from the job record can then be viewed (see Figure 9.13). It is important to note that certain information in the job record can be modified, as shown in Figure 9.14 (k). The operators can set their own priority value for a particular job for use in a sequencing rule.

The operators are also encouraged to enter the actual times taken for activities such as part programming, set-up and machining for a particular batch or component. These actual times are stored in the job record together with the previously estimated times. As described above, these data can accordingly be read by the co-ordination department, and the intention is that feedback of this nature will assist in steadily improving the quality of the time estimates necessary for both inter- and intra-cell scheduling.
A further facility of the *Info.* command is the display of performance statistics. As shown in Figure 9.14 (l), various useful data relating to the schedule for a particular machine are listed in a pop-up window. The data listed can be configured to suit particular requirements. For example, in the case of the Rolls-Royce cell, two figures are particularly helpful in assisting the cell operators in generating an effective schedule, namely the set-up time represented as a percentage of machining time for the schedule, and the overall time expected to be necessary for the completion of the schedule.

The *schedule* command is used to resequence the jobs in the current schedule. As shown in Figure 9.14 (n), and as described above, there are five heuristic rules for the user to choose from. Importantly, each rule can be applied to different parts of the schedule and different rules can be applied to the schedules for each machine tool (mindful of precedence constraints). In other words, a number of batches might be sequenced according to one rule, subsequent batches according to another. It is important to note that the purpose of the operator priority rule is to enable the user to place a batch at any desired position in the schedule. As indicated above, the histograms are intended to help the operators visualise the effects of different sequences on set-up times.

In Figure 9.14 (m), the additional selections in the pull-down menu for *schedule* relate to the acceptance of jobs from, and return of jobs to, the work-to list. The principle here is that the cell operators should be free to choose the order in which jobs are introduced into the running schedule from the work-to list. This also enables the co-ordination department to direct unallocated jobs to other cells if this is likely to improve the overall delivery time for a particular product. If problems should prevent the completion of a batch in a particular cell, the job can also be returned to the work-to list for reallocation to another cell.

Importantly, "what if ?" experimentation with different rules or combinations of rules does not change the running schedule permanently until the *save* command is given. Accordingly, if such experimentation does not generate a better schedule than that already existing, the user simply cancels the modified schedule to return to the original.

As indicated above, the package is not only used for planning activities, but also for production control. Accordingly, there is a facility for entering the actual start and finish times for jobs in order to constantly update the running schedule. This assists the cell operators by showing the expected start and finish times for subsequent batches and, since the actual times are stored in the job record, also serves to provide feedback on progress to the co-ordination department.

As shown in Figure 9.14 (o), to "start" a job, the coloured bar representing the job is "clicked" on and the selection confirmed. Figure 9.14 (p) shows how the job start time can be entered, the bar for the job then being given a hatched pattern to show that the job is *in-process*. A similar procedure is followed when entering the finishing time for a job, although in this case the in-
process job is automatically selected. Figure 9.14 (r) shows the sequence from Figure 9.14 (c), after the first job in the sequence has been finished and the next job on the lathe started.

As with the other application packages, an on-line help function is implemented using a proprietary hypertext package.

Figure 9.14 Sample Screens from Cell Production Planning and Control Application

(Images of sample screens shown.)
Software Design for the Turning Cell Computer

Current Schedule - Gantt Chart

Data Prep.  Set Up 1  Operation 1  Set Up 2  Operation 2

Zoom In  Zoom Out  Pan Left  Pan Right

Left button to zoom and pan - Right button to return to main menu

Display

Work to List

Current Schedule (T)  Current Schedule (C)  Completed Jobs

Print Display List

Schedule - Gantt Chart

Data Prep.  Set Up 1  Operation 1  Set Up 2  Operation 2

Zoom In  Zoom Out  Pan Left  Pan Right

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Software Design for the Turning Cell Computer

9.6.1 Training Considerations

In-process job must first be completed

Job Finish Time: 00-01-08 11:09

Continue...

Current Schedule - Gantt Chart

Data Prep.
Set Up 1
Operation 1
Set Up 2
Operation 2

P1 D1 D2 D3 D4 P2
Zoom In Zoom Out Pan Left Pan Right

Left button to zoom and pan. Right button to return to main menu.
9.6 Training Considerations

In an earlier chapter it was argued that one of the most significant potential benefits to be gained from the implementation of AMT lies in its use as an enabling technology for cross-functional integration. This organizational integration is a pre-requisite for the "flat" management hierarchies and flexible, co-operative working relationships of future production systems. Apart from the technology, cross-functional integration also requires highly and broadly qualified personnel that are willing and able to learn. As outlined in Chapter 7, human-centred technology is intended to support the development of such a workforce by building on the present skills of the user and helping these skills to develop further.

The design of the software for the demonstrator turning cell has been based on the capabilities of a skilled and experienced machinist, but it is clear that additional skills will be required for the successful execution of the extended task list formulated for the cell operators. The knowledge and skill requirements for the cell have been analysed by Hancke [89] and cover the following areas:

- process and product related skills, such as:
  - knowledge about the products
  - metalworking skills for turning and milling
  - basic skills in inspection and quality control
  - NC part programming skills
- background knowledge on company organization and order processing procedures
- basic personal computer knowledge (MS-DOS operating system, BASIC programming language)
- knowledge of the cell system and its way of working
- general social skills in communication, group problem-solving etc.

In seeking to develop this skill profile two basic types of training must be considered:
- introductory training for newcomers to the system, and
- on-going training, or retraining, for maintenance of existing skills and development of new skills.

The former is comparatively easy to describe and training schemes can be readily established by comparing the existing skills of the intended users with the required skills. The latter is far more complex since it deals with a dynamic process as the required skills develop and change over time. As was mentioned earlier in the thesis, the question of how to teach and maintain craftsmanship in an AMT environment has troubled a number of the pioneers of the human-centred approach [Cooley, 87].

The required training can be provided in several forms: off- or on-the job, with or without supervision, with computer support etc. Hancke [89] recommends computer-based training courses for small and medium-sized companies, bearing in mind limited staff and financial resources for training. However, the training needs of such companies have to be surveyed more thoroughly before more definitive conclusions can be made. Such work is beyond the remit of the project at Imperial, which explains the superficial treatment here.
Training considerations for human-centred systems have been dealt with in more detail within ESPRIT Project 1217 [Rosenbrook et al., 87:40-47] and within DELTA, an EEC-funded project that is directly concerned with training issues relating to AMT [Hancke, 89].

9.7 Work Design Evaluation for The Human-Centred Turning Cell

In the early stages of the cell design process considerable use was made of discrete-event simulation techniques to assess the effects of, for example, automated workhandling etc. A model of the turning cell was formed using SIMFACTORY®, a proprietary software package distinguished by a powerful and simple to use graphics capability, and by comparatively simple model building.

Figure 9.15 (a) overleaf shows an example screen from a simulation run, whilst (b) shows a sample report screen. The simulation model, in particular the dynamic graphics representation of cell activities, proved exceptionally useful in discussing the effects of different task allocations with the user group. The model was also invaluable in formulating the functional specification for the cell management support software, in indicating those activities where computer support would bring the greatest benefits.

However, discrete-event simulation techniques alone could not provide any measure of the “human-centredness” of a particular task allocation. Accordingly, during the development of the cell management software a VEMAS analysis (see Section 7.3) was carried out by Barth [89], to help compare different task allocations.

Data from Harmonic Drive, with respect to batch sizes, machining times etc., was used as the basis for a simulation of one week’s operation of the turning cell, with various different task allocations for the cell operators being modelled. This study showed that the execution of the complete task list given in Figure 8.19 would impose an excessive workload on a single cell operator, even with computer support.

As reflected in the VEMAS analysis sheet shown in Figure 9.16 (a) below, the operator would be overtaxed and partly as a result of this, a satisfactory machine utilization would not be achieved. Moreover, the cell operator would have little opportunity for social contact or communication.

Figure 9.16 (b) shows the VEMAS evaluation for the situation in which two cell operators rotate between planning and physical tasks. As can be seen from the evaluation sheet, the latter task allocation gives higher average values for the “positive” first and second order criteria and a lower value for the “negative” third order criteria. Thus this task allocation registers a better value for “human-centredness” and the subsequent analysis by Barth shows a much improved machine utilization and, despite the additional costs of a second cell operator, significantly lower production costs overall [89:47-53]. Accordingly, on the basis of the data provided by Harmonic Drive and the previously stated desire that the extended task list shown in Figure 8.19 should be executed within the cell, this analysis shows that two operators should man the cell.
It is intended that before the end of the project the results of the VEMAS evaluation should be verified by means of an action simulation in which the turning cell will be used to produce Harmonic Drive components.

Figure 9.15 Sample Screens from Discrete-Event Simulation of the Turning Cell
## Software Design for the Turning Cell Computer

### Figure 9.16 VEMAS Evaluation of Work in the Human-Centred Turning Cell

#### a) Single Operator Cell

Function Group: Human-Centred Turning Cell - Single Cell Operator

<table>
<thead>
<tr>
<th>Key:</th>
<th>Individual Functions</th>
<th>Time-weighted average for each criterion</th>
<th>Module requirements and rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 = Criterion not established</td>
<td></td>
<td>AVG cell</td>
<td></td>
</tr>
<tr>
<td>5 = Criterion fully established</td>
<td></td>
<td>AVG order</td>
<td></td>
</tr>
<tr>
<td>Time Proportion Tₜ</td>
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<td></td>
<td></td>
</tr>
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<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Social control and communication</td>
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<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Mental challenge</td>
<td>4 4 4 2 2 2 2 3</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Physical challenge</td>
<td>1 0 2 1 2 2 1</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Application of skills and knowledge</td>
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<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Chance to learn</td>
<td>0 3 3 2 1 1 1 2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Chance to show creativity</td>
<td>0 3 3 2 1 1 1 2</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>2 3 2 3 1 2 2 3</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Supervisory control</td>
<td>3 3 3 3 3 3 3 3</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Physical dangers or ergonomic problems</td>
<td>1 1 1 1 2 2 1</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Pacing or time pressure</td>
<td>5 3 3 4 3 3 3 1</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Monotony</td>
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<td>2.0</td>
<td></td>
</tr>
<tr>
<td>External control</td>
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<td></td>
</tr>
<tr>
<td>Attentional demands</td>
<td>3 2 2 2 1 1 2</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

#### b) Two Operator Cell

Function Group: Human-Centred Turning Cell - Two Cell Operators

<table>
<thead>
<tr>
<th>Key:</th>
<th>Individual Functions</th>
<th>Time-weighted average for each criterion</th>
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<tr>
<td>Time Proportion Tₜ</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Responsibility</td>
<td>3 3 3 3 3 3 3 2</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Social control and communication</td>
<td>4 1 3 3 2 2 3 4</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Mental challenge</td>
<td>3 4 2 2 2 2 2 3 4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Physical challenge</td>
<td>1 3 3 3 2 2 2 1</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Application of skills and knowledge</td>
<td>3 3 3 2 2 2 2 3 3</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Chance to learn</td>
<td>3 3 2 2 2 2 2 2 3 4</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Chance to show creativity</td>
<td>3 3 3 2 2 2 1 3 3</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>2 3 2 3 3 2 3 3 3</td>
<td>2.7</td>
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<tr>
<td>Supervisory control</td>
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<td>2.3</td>
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<td>0 1 2 2 2 1 2 0</td>
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<td>1.5</td>
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<td>External control</td>
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<td></td>
</tr>
<tr>
<td>Attentional demands</td>
<td>2 2 1 2 1 1 1 2</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>
9.8 Further Software Development

As was pointed out in the preceding chapter, software for the programming of the automated workhandler, developed by Weidlich [89], has also been implemented on the cell computer. Efforts have been made to ensure consistency of the user interfaces for this package and the cell management support software as far as possible.

Further software packages are to be developed by other members of the project team to complete the functional specification laid out in Section 9.1. Of these the most important are for cell estimating and for statistical process control.

The former package is intended to provide information on the machining costs incurred in producing a particular batch within the cell. Accordingly, the cell operators will enter data on expected set-up, programming and machining cycle times. These data will be combined with values stored in the cell information database for the various hourly rates for each piece of equipment in the cell to provide cost estimates.

Software of this nature is essential for ensuring that the company can calculate costs more accurately and quickly when quoting prices on customer-specific products or variants. It is also a pre-requisite if the concept of bidding for work by different cells is to function effectively, since the co-ordination department is not only interested in the expected time required to finish a particular batch, but also estimated and incurred costs.

Statistical process control (SPC) software will provide an important aid in ensuring consistent quality. It is planned that the software should provide process control charts, histograms etc. to provide the cell operators with rapid, graphical information about the quality of the components produced in the cell.

Early experience with the cell management software has pointed to a number of general modifications that should be made to later versions of the existing packages:

- Improved search and sort routines should be implemented to assist the user in rapidly locating required plans or programs.
- Presently, no "short-cuts" are available to experienced users to enable them to increase their speed when using the current software. Subsequent versions of the software should incorporate such features as command keystrokes, whereby experienced users can execute particular commands by means of keystrokes rather than having to select using the mouse.
- Efforts should be made to increase the extent to which the user can configure the display, in terms of both colours used and layout.
- For future software versions means should be made available by which users can easily and rapidly generate and configure their own databases.
- In some situations it will prove advantageous to work with two applications on the screen at one time, for example, with the CAD part drawing on the screen when generating a process
The current software has been written as an integrated suite of application packages. For subsequent versions it would be more appropriate to develop the individual applications as modules that can be added as needed to suit particular requirements.

To avoid problems of consistency when switching from the cell management software to other proprietary applications software running on the cell computer, it would be advisable to use a de facto standard graphics environment, such as Microsoft Windows, or Digital Research GEM.

Also to improve consistency, it would be useful to have the same user interface for the CNC machine tools and the cell computer. As will be seen in the next chapter, this requirement is being dealt with as part of ESPRIT Project 2415 "Distributed Manufacturing, Planning and Control", which is essentially an extension of the project described above.
"All the models, all the plans, all the simulations of CIM do not represent the real world of what actually happens inside a factory. Sure, you can try to represent a factory by models, by schematics, by flow diagrams. But don't run away with the idea that you can capture your factory on a computer like that. People don't think in flow diagrams - a real factory is informal; things aren't written down; nothing happens in the same way twice."

"Your markets don't stay still. Your products don't stay still. And technology doesn't stay still. There will never come a time when you can stand back and say: I've planned it all out; I've bought all the equipment; I've done the implementation. Now I'm CIM'd"  

"As you automate, you take away the adaptibility of people and simple machines. There's no doubt that automation and flexible manufacturing systems can give you enormous flexibility for making products - but only in a limited size range. If you want to make parts outside that 'envelope', you can't cope. What in effect is happening is that companies are buying increasing flexibility over a very narrow range, at high cost. This makes it very difficult for them to adapt when the market or technology changes."

Contrary to expectations, these comments do not come from one of the established proponents of the human-centred approach to the design and implementation of AMT, but rather from an interview given by Bill Carter, the ex-President of CAM-I, an international organization with the remit to support research and development in computer-aided manufacturing aimed at the realization of the totally computerized factory [Dunn, 87:21]. The quotes do, however, serve to neatly summarize some of the key points underpinning the research described in this thesis. They reflect increasing doubts as to the true benefits of the current generation of Advanced Manufacturing Technology and in particular the vision of Computer-Integrated Manufacturing, which for many is synonymous with the workerless, paperless "Factory of the Future".

It has been argued here that many of the reasons for the unsatisfactory performance of many applications of AMT, and hence slower than expected diffusion, can be traced back to inadequate consideration of the human aspects of AMT during the system design and implementation phases. The predominant "technology-centred" approach to design and implementation leads system designers to follow a "sequential" design procedure, where they concentrate their efforts on the technological aspects of the system and to ignore the human aspects until the technology has been implemented. This leads to inconsistencies between the needs of the technology and its supporting human infrastructure that can limit flexibility and reliability. Moreover, the opportunity of using the integrative capabilities of AMT to facilitate organizational integration and thereby reduce organizational complexity and resultant "non-value-added" activities, is often missed. Accordingly, the full potential of the new technology is not successfully exploited, thereby greatly compromising its effectiveness, and in some cases, the competitiveness of the firm.
Despite the fact that the diffusion of AMT has been very uneven, and that AMT is not yet the primary technology in the vast majority of manufacturing establishments, the potential benefits are such that the penetration of AMT will undoubtedly accelerate. However, the negative experiences of many early users means that many companies are now paying much greater attention to how AMT is best used.

This thesis has described the author's contribution to the development and application of an alternative, "human-centred" approach to the design and implementation of AMT. This is a "parallel" design procedure, whereby technical and human aspects are considered together from the start of the system design or selection process. It is hoped that a holistic approach of this nature will lead to a better "fit" between technology and social infrastructure by ensuring that planned changes in organizational design are made when introducing the technology and that the technology itself reflects human factors requirements.

The focus of attention has been the research carried out within the SERC/ACME-funded project entitled "The Operation and Management of Flexible Human-Centred Turning Cells" in the Department of Mechanical Engineering of Imperial College. This project has had the primary objective of showing that the integration of technological design and job design in the planning of manufacturing systems can overcome many of the problems associated with the current generation of technology.

The centre-piece of this project is a demonstrator human-centred turning cell, incorporating a CNC lathe, CNC milling machine and gantry loading device, which has been used to evaluate hardware and software designed according to human-centred criteria, and to test the effects of different task allocations between the cell operators and the various machines and computers in the cell. This turning cell is distinguished by the fact that it has been designed in such a way that the cell operators can exercise complete responsibility for managing the activities of the cell. A cell computer and associated software provides assistance to the cell personnel in carrying out an extended range of tasks including production planning, process planning and NC part program generation.

In addition to collating design guidelines and formulating a parallel design procedure for the design of the turning cell, the author has also been responsible for the overall design of the cell and, in particular, the design of the cell computer software. These activities have been described in detail in the preceding chapters and in the Appendix the initial efforts of the author to apply human-centred principles in an industrial setting are also described.

The human-centred turning cell has been successfully demonstrated and many of the initiatives of the SERC/ACME-funded project are now being developed further within ESPRIT Project 2415 'Distributed Manufacturing, Planning and Control', in which Imperial College is a partner. The key objectives of this new project will be described later in this chapter.
Having briefly summarized the key points of the thesis, the remainder of this concluding chapter deals with two broad issues: First, various recommendations for further research in the field of human-centred design resulting from the project at Imperial College are examined. Second, the likelihood of the widespread adoption of a human-centred approach and, thereby, the possibility that the "Factory of the Future" will be designed and run along human-centred lines, is discussed.

One of the most important conclusions to be made from the project is that in order for research of this nature to be completely successful in the future there is a need for engineers to become more conversant with the techniques and theory of job and organizational design and for social scientists to acquire a better grasp of technological possibilities and, as importantly, business imperatives.

There can be little doubt that many engineers exhibit scepticism towards social science research as a result of their technology oriented educational background. Moreover, the qualitative nature of many of the decisions to be made in the design process for human-centred technology is clearly a problem for many engineers more familiar with decisions based on quantifiable factors. This problem has been highlighted by Blackler & Brown [86:292]:

"...People who have been trained to think in concrete terms and who are accustomed to deal with the quantification and control of variances can become impatient with the uncertainties of social science knowledge. It is easy to see how it can be concluded, not only that the disciplines of psychology and sociology are immature and unsatisfactory, but also that prudence dictates one should continue to develop technologies designed to cope with the uncertainties that are inevitably associated with human behaviour."

Nevertheless, as suggested by Clegg & Corbett [87:190], it is also necessary for the social science community to do more to convince others of the legitimacy and significance of the human aspects of AMT. Part of the problem is that the small amount of work that has been done has had a partial focus, concentrating on behavioural concerns to the exclusion of operating and financial issues. Equally important, and problematic, is the unintelligible way in which much of this limited research is then described, with the result that the author has experienced similar frustration to Eilon, who has been

"driven to despair by the pompous obscurantism that purports to portray 'new and meaningful insights'. The sceptic may be forgiven for doubting whether the vast literature that has sprouted in this field over the last two decades has done much to establish a theory of organization with any relevance to the problems that practicioners encounter in reality" [81:220].

As commented on by Barth [89:12], the difficulties experienced by the engineers in understanding the terminology used by the social science group in ESPRIT Project 1217 was a serious handicap to effective co-operation and also caused initial difficulties in the project at Imperial College as noted by Hancke [89]. The most effective way to overcome this problem in the short- to medium-term is simply to provide more opportunities for engineers and social scientists to work together and acquire multi-disciplinary knowledge. Despite the feeling in some quarters
that the "general climate" has not been conducive to such work in recent times [Blackler & Brown, 86:295], it will be seen later that there is an increasing amount of proactive research projects in the field of human-centred technology, through which the desired multi-disciplinary knowledge base is gradually evolving.

In the longer term, a significant improvement in mutual understanding can be expected from the increasing incorporation of social science subjects within engineering degree courses, with the result that engineering students are exposed at an early stage to the basic concepts of behavioural science and organizational theory. This is a positive development from which the author has benefitted personally.

In Chapter 6 the comparative lack of constructive aids to system designers when designing human-centred systems was highlighted. One of the positive aspects of the ESPRIT Project has been the development of a number of practical methods and tools to help engineers make appropriate choices in the design and selection of advanced manufacturing systems. However, despite such progress, the project at Imperial College has shown that still more work is needed in developing more comprehensive design guidelines and better methods for the prospective evaluation of work designs.

The design criteria listed in Chapter 7, intended to guide the allocation of functions and the design of screen displays, were the subject of extended discussions within the project team. It was found that the use of the criteria in the design process was a highly subjective activity, with room for different interpretations of almost all the design criteria offered. For some criteria this "vagueness" did not have a noticeable effect on the overall design, but for others the ramifications of different interpretations were far more significant. In particular, problems were encountered in deciding how many operating strategies should be offered to the user when allocating functions to the cell personnel.

As noted in Chapter 7, in an earlier project Corbett [85] used the concept of "choice-uncertainty" to identify those tasks contributing to tacit knowledge and thereby those tasks to be executed by the user rather than the computer. However, there is little guidance available in the literature to help the system designer identify how much of a role "choice-uncertainty" plays in a particular activity, and the discussion of "tacit knowledge" to date has also been sufficiently esoteric to offer the designer little practical help in deciding which tasks to allocate to humans [Dreyfus, 72] [Weizenbaum, 84]. Although it has already been stated that such design criteria should only be regarded as general guidelines, the difficulties described above indicate that more research is required to develop more comprehensive design guidelines for human-centred technology.

In addition to the need for more tightly defined design criteria, the need for better methods of prospective design evaluation has also been shown during the project. This is also a difficult problem to solve, since on the one hand a means of "quantifying" and comparing different work design options would be welcomed by many traditionally trained systems designers and
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engineers, whilst on the other hand such quantitative methods are regarded with suspicion by Trade Unions as just an extended form of work study [Martin, 84:299]. The latter are strong supporters of participative design procedures, but the inherent problems in this approach have been described in Chapter 7. The research by Kember on action simulation, also described in Chapter 7, is an interesting alternative, though it remains to be seen whether such methods can be applied in industry as successfully as in an educational environment.

Accordingly, there appears little option but to apply and continually improve methods such as VEMAS. The major difficulty experienced in applying this particular method within the project at Imperial College lay in deciding what weighting to give to particular criteria, which proved to be a highly subjective task. It has also proved essential that these techniques be combined with discrete-event simulation, since it is not only the proportion of time spent on a particular activity that should influence its weighting, but also the time function of the activity, that is, whether it can be carried out without being interrupted. The allocation of certain activities, such as NC part programming can have a positive effect on job satisfaction if they can be carried out without interruption, but can have an equally negative effect if continually disrupted by other activities.

Nevertheless, in acting as a "reminder" of positive work features to include, and negative features to avoid, the VEMAS method did fulfill an extremely useful function. Indeed, any tool that enables and thereby encourages an evaluation of job design and work organization for a manufacturing system should be regarded as a positive development.

A further difficulty revealed by the project is the question of how human-centred systems should be justified financially. This is crucial problem, since the primary strategic benefits of adopting a human-centred approach, such as increased flexibility and improved job satisfaction, are intangible and therefore difficult to quantify. It is therefore very difficult to demonstrate the advantages of adopting a human-centred approach at the project justification stage, since it is far easier to estimate the costs, in terms of labour and training costs, than the expected increase in revenue from improved responsiveness to the market. However, the evaluation of intangible benefits is a general problem for AMT, as described by Kaplan [86], who asks whether CIM should be "justified by faith alone?". As described in Chapter 3, a number of techniques have been proposed for taking account of such intangible benefits, but these rarely take account of human aspects. A notable exception is the recent work of Bullinger & Auch [88], where the negative consequences for work design of particular technological alternatives are given a "price" in the financial appraisal. The recommendation here is for an extension of these new techniques to cover human aspects more fully together with an analysis of how the costs and benefits of these human aspects might be appraised.

The above recommendations for further research all relate to the process of design and implementation, but other questions worthy of further research, relating to the applicability of the human-centred approach, were also raised during the project.
The first relates to the applicability of the human-centred approach to an existing plant. As noted by Bailey [83:2631, a "greenfield" site provides the opportunity for fresh thinking and approaches to be developed without the constraints of existing custom and practice and vested interests. This has been one of the major advantages assisting the author's attempts to employ a human-centred approach in an industrial setting, as described in the Appendix. It is still too early for the industrial demonstrations for ESPRIT Project 1217 to show clearly how a human-centred system performs and is received in an existing plant. Due to extenuating circumstances it is not clear whether either demonstration will continue to be operated in the way intended after the end of the project. As will be explained later in this chapter, considerable obstacles to a human-centred approach might be expected in an existing plant and, accordingly, more research is required to study the implementation process in such an environment.

An equally important question relates to work design in a plant employing a functional machine shop layout, that is, whether it is possible to achieve a human-centred work design whilst maintaining such a layout? As indicated in Chapter 2, a functional layout is highly flexible and hence essential for some companies who have high product "variability" (see Chapter 4), whereas the industrial demonstrators for ESPRIT and the project at Imperial College have concentrated on cellular manufacturing systems. By their very nature manufacturing cells provide the opportunity to readily satisfy a number of human-centred design criteria, for example, it is easier to delegate extra degrees of freedom in terms of planning autonomy to a cell, social communication is facilitated by the grouping of machines and task identity is increased. In other words, it can be argued that the selection of turning cells as the "test-bed" for human-centred technology has presented "an easy option", and there is the danger that cellular manufacturing could be perceived as a pre-requisite for human-centred work design.

Some human-centred design criteria will be compromised in a functionally laid out machine shop, for example, it is much more difficult to allocate production planning tasks to machine operators. There is thus also a need for more research to study how this might be counteracted, say by increasing the range of tasks of machine operators to include quality control and maintenance tasks. Another concept that needs further study is that of the "virtual cell", whereby machines are notionally grouped together into cells for the purposes of production control whilst being physically apart [Mclean et al, 83]. It will also be instructive to monitor the impact on factory layout of new CNC machine tools, such as turning and machining centres. By integrating a number of different machining operations on one machine tool, these new machines have similar capabilities to a cell of conventional machine tools and may therefore have a significant effect on factory layout.

Turning now to the factors that will determine whether a human-centred approach is widely adopted in the future, it is apt to start with the obstacles in terms of both attitude and practical problems of implementation.

As already mentioned above, and as confirmed by Hancke [89], both SERC/ACME and ESPRIT projects have been characterised by a notable scepticism towards the human-centred...
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approach of many, though by no means all, production and systems engineers assessing the work carried out. There appear to be a number of possible reasons for this attitude. One possible reason is the term "human-centred" itself, which implies to many that the design is centred on the human, to the detriment of operational and financial considerations. As already commented in an earlier chapter, this is somewhat misleading, since technical and human aspects are considered in parallel during the design process. Perhaps Broedner's term "skill-based manufacturing" is more appropriate, but the expression "human-centred" has achieved a certain currency and is therefore difficult to alter now.

Despite recognition of many of the fundamental flaws of the technology-centred approach, the vision of the unmanned factory seems embedded in the minds of many manufacturing and systems engineers. Stratta-Santucci describes the popular view of humans as a contaminant or source of problems, rather than as a problem-solving agent, and the corresponding desire to reduce human intervention in manufacturing systems to a minimum, as a reflection of the dominant "ideology of automation" [87:31]. Certainly, the concept of technological determinism seems to provide many systems designers with a convenient excuse to avoid thinking about the human effects of the systems they are designing. In this case it is little surprise that the human-centred approach should receive such a hesitant reception, since it is a challenge to the dominant "ideology" with respect to manufacturing automation. As shown by the studies of Dunbar et al [82] and Brunsson [82] it is thus likely to meet with resistance even though the advantages are obvious.

One criticism frequently levelled at the human-centred approach that should be dealt with here relates to the frequently-aired view that the human-centred approach is essentially "anti-technology" and hints of a desire to return to "cottage industry". As is clear from Chapters 8 and 9, the pursuit of human-centred manufacturing technology in no way means the adoption of "low technology". The demonstrator turning cell incorporates state of the art machine tool technology and, indeed, the attempt to provide "compliant" software capable of being used effectively by people with varying skill and experience levels, and providing the increased degrees of freedom desired, has posed technological problems that are arguably more challenging than those involved in trying to "crowd out" human intervention! Therefore this criticism can be refuted.

It is important also to reflect on the influence of advertising and "hype" with respect to new manufacturing technologies on the attitudes of systems and production engineers. The author concurs with the view of Sorge et al [83:166] that public debate in the UK is marked by a kind of "technology fetish", where new technology is regarded as a panacea for manufacturing problems. Handy [81:347] describes this phenomenon as "the seduction of technology", which he attributes to the dominating expert power of computer professionals and a fear on behalf of many managers of appearing conservative when rejecting new, if seldom understood technologies. Whilst the technical media have certainly played a role in "hyping" AMT it is noticeable that the Government, too, has encouraged this pre-occupation with technological "fixes" [Hughes,87:81]. Apart from grants supporting "leading edge" technologies such as FMS and industrial robots, Government involvement is at its most obvious in the form of "technology
events” such as the MAP demonstration CIMAP. When it is considered that MAP only deals with machine interfaces, that is, only deals with a tiny part of “integration”, and arguably has limited relevance to the great bulk of the metalworking industry, such “events” provide ample evidence of the great gap between the perception of the technological needs of industry, on behalf of the media and government, and actual needs.

The author made an interesting observation whilst visiting a number of leading users of AMT, namely that in almost all the companies visited no audit had been carried out to verify that expected benefits were in fact being realized. In a number of these companies it was conceded that these expected benefits were not being met and in most of these cases the project was described, euphemistically, as a "learning project". Certainly, this observation gives an impression more of "supply-push" rather than "demand-pull"...

Assuming that the negative attitudes of many engineers towards the basic "philosophy" underpinning the human-centred approach to the design and implementation of AMT can be overcome, other obstacles are likely to present themselves when this approach is applied. Indeed, expectations of such problems may act as a significant barrier to adoption.

The most significant obstacle is likely to be presented by a number of factors that can be collectively termed organizational inertia. The changes in job design and work structuring implicit in the human-centred approach are likely to have two effects on the rest of the organization - a 'shunt' effect upon the distribution of authority and the nature of hierarchical control, and a 'ripple' effect laterally upon relations with other jobs and work groups within the overall production process [Child, 84: 40]. If these effects are not recognized, or are resisted, then the planned organizational change will be threatened.

Considering 'shunt' effects on management control and supervision first, the granting of greater autonomy and the allocation of new tasks to shop-floor operators has clear implications for line management. As Hancke [89] warns, middle management may well resent the idea of decentralizing responsibility, control and the related information, as it may be perceived as indicating a loss of power and authority. However, experience with semi-autonomous work groups in Sweden indicates that the enrichment of shop-floor tasks can relieve supervisors of everyday ‘fire-fighting’ pressures, so allowing them to concentrate on more important tasks [Child, 84: 40]. As suggested in an earlier chapter, this also provides the opportunity to ‘flatten’ the organization by increasing spans of control.

Turning to 'ripple' effects, the incorporation of indirect activities into the work of shop-floor staff may have a significant effect on traditionally established job boundaries. The addition of quality control and maintenance tasks to the normal activities of a machine operator may require the redrawing of the boundaries between the operator and other jobs. This could be seriously impeded if traditionally specialized job boundaries are reinforced by the established demarcation lines and collective bargaining units. The case studies of Buchanan and Boddy [83] show that this is a very real problem in the UK, the fear of a dispute between white and blue collar unions leading management in one company studied to make the decision not to allocate NC part programming activities to shop-floor personnel.
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It is also instructive to consider here the experience of ZF in West Germany when implementing their FMS. As described in Chapter 6, this FMS is distinguished by being manned by an "FMS-team" consisting of highly skilled operators with responsibility for certain planning tasks in addition to normal operating activities. As such, the practical problems encountered in the implementation of this system provide a useful indication of those likely to be experienced in implementing a human-centred system.

The most significant problem relates back to a point made earlier, in that it proved difficult to integrate the homogeneous job structures of the FMS-team into the existing hierarchical work organization. It was found the members of the FMS-team would be allocated to other departments to carry out specialized tasks, or specialized workers would be allocated to the FMS to the extent that the fear was expressed that over time the distinctive new work design would "regress" to the traditional hierarchical job structure [Koehler & Schultz-Wild, 831].

As outlined in Chapter 7, the implementation of human-centred technology demands work context modifications which could also lead to problems. Training and payment systems will need to be designed to complement and reinforce the flexibility and skill enhancement expected from human-centred work design. The experience at ZF was that the comprehensive training, needed to equip the members of the "FMS-team" with the required breadth of skills, necessitated a costly infrastructure in the form of teaching staff, manuals etc. The real problem, which relates back to an earlier point regarding financial appraisal, is that the resulting high training costs are tangible whereas the expected improvements in flexibility and productivity due to the cross-functional integration enabled by the training are less easy to quantify. In the UK, the prospect of high initial costs is likely to be regarded with particular caution, since the comparatively high labour mobility, when compared to countries such as Japan and West Germany, means that there is often the fear that personnel will leave after a considerable investment in their training has been made.

It was also found at ZF that friction resulted from the fact that since they performed a greater number of skilled tasks, the wages offered to the members of the FMS-team were higher than those of conventional workers. Any change in the design of jobs which improves rewards, either intrinsic or extrinsic, is likely to be interpreted as signifying a change in status of the workers concerned and hence have wider potential consequences within the organization.

Even if a company makes the decision to adopt a human-centred approach when designing or selecting new manufacturing equipment, to what extent can that company shape the technology to be used? This is a question of crucial importance, since although the user still has certain degrees of freedom in organizing work around the technology, it is clear from earlier chapters that the design of the technology, in particular of computer control systems, can place significant constraints on work design.

In the case of companies designing their own manufacturing system, or purchasing a tailor-made system, then the opportunity to shape the technology according to human-centred principles presents itself. However, the great majority of companies will be purchasing stand-alone
equipment designed for the general market. Due to a lack of commercial "clout" small and medium-sized companies will experience particular problems in motivating AMT suppliers to provide equipment congruent with human-centred principles. Even ZF, a comparatively large company, experienced problems due to the lack of interactive control systems that could be readily programmed by shop-floor personnel.

Here the technology made available depends on the vendor's own perceptions of how the technology will be used. As noted by Sorge et al [83:164] in the case of flexible machining cells, different machine tool manufacturers have developed equipment to suit quite different strategies.

It is thus essential that vendors, too, accept the basic tenets of the human-centred approach and supply "compliant" control systems that enable the enrichment of shop-floor jobs and that allow different organizational options in their use. As will be described in more detail later, there are positive developments in this direction in the form of projects such as the EC-funded ESPRIT Projects 1217 and 2415, in which a number of vendors have joined together to develop such technology. Importantly, such projects are providing these vendors with new skills in areas such as software ergonomics and in the management of projects where human as well as technical aspects must be considered.

Clearly there are a great number of potential obstacles standing in the way of the widespread adoption of a human-centred approach to AMT. However, there are signs of hope in that there is increasing support in the literature and an increasing number of further research initiatives aimed at answering many of the questions left open in the above discussion.

As pointed out in Chapter 4, the literature is largely unanimous in the view that future manufacturing systems will need to exhibit increasing flexibility to match new market requirements. There is a widely held view that new computer-based manufacturing technologies are encouraging a fundamental change in the dominant techno-economic paradigm [Perez,85:447]. In other words, it is expected that the economies of scope provided by CIM, will act as both the catalyst and vehicle for a change from the post-war mass production concept with global sourcing to a new flexible production concept with regional sourcing [Roobeeke & Abbing,88:3-12]

There is also increasing recognition that this increased flexibility is not only dependent on technology but also on a flat, integrated organization that can rapidly respond to the requirements of the market. Indeed, as was also mentioned earlier, many commentators have expressed the view that the latter is the essential element and the main contribution of the new technologies is in enabling such organizational changes to take place. These views are summarized in Figure 10.1 below, which although directed primarily at US companies, applies equally well to their British counterparts. A number of very important predictions implicit in Figure 10.1 will encourage the adoption of a human-centred approach.
The first important factor is the fact that the "economies of scope" associated with AMT are encouraging a trend towards smaller manufacturing units. The perceived ability of technologies such as FMS to produce small batches of parts rapidly and efficiently undermines the traditional advantages of scale economy, so making small plants economically viable. Furthermore, Peters [88:16-20] and Bessant & Haywood [85: 53-54] both argue that smaller firms, with their greater organizational flexibility, are in the best position to exploit the flexibility of new manufacturing technologies.

In the latter study, Bessant & Haywood found that in a number of smaller firms, "Internal flexibility - what they termed 'Being quick on our feet' - allied to efficient use of skilled and experienced men working on advanced CNC stand-alone equipment, had so far helped them to achieve lead times and qualities comparable or better than the large scale FMSs in operation elsewhere."

This quote calls to mind the study of Dodgson [85], described in detail in Chapter 4, which showed that smaller companies are more conducive to a "polyvalent" work organization, which shares many common features with human-centred work design.

The second key factor shown in Figure 10.1 is the need to "add value" through people. Authoritative commentators such as Skinner [85] and Peters [88:20-22] exemplify the growing
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body of opinion that multi-skilled shop-floor personnel are an essential element of a flexible manufacturing strategy. This view reflects the recognition that a highly trained workforce is one of the major factors underpinning the industrial success of countries like Japan and West Germany [Porter, 90].

The author's own experience of working in Japan has indicated that Japanese factories, by and large, are no more highly automated than European ones, but that the efficiency of Japanese plants is often higher, primarily due to factors such as the motivation and attention to detail of shop-floor personnel, the incorporation of quality control tasks within the job of machine operators and the flexible working practices made possible by the almost complete absence of demarcation.

Unfortunately, there is also a widely held view that cultural differences make it impossible to adopt such "Japanese-style" production techniques and working practices. This is despite the fact that many of them are adaptations of Western ideas that have fallen out of favour, and that studies by White & Trevor [83] and by the author [Slatter, 84] indicate that Japanese companies with manufacturing plants in the UK achieve productivity and quality levels approaching those of the parent plants in Japan. This view only serves to legitimise a concentration on technological answers to competitive failings and allows management to ignore what may be basic faults in the organization of production [Bessant & Haywood, 85:51].

The recognition that the UK suffers from a "skills gap" when compared to major industrial competitors, has been the subject of much recent media attention [Beresford, 87]. On the one hand this presents an obstacle to human-centred technology in that sceptics will ask where the initial skills needed as the basis for enriched shop-floor jobs are to come from? But on the other hand, a human-centred approach will at least provide the means of maintaining those skills that are available and will enable them to develop into new skills to match evolving technology.

Here it is important to refer back to the point made in Chapter 5, that traditional engineering craft skills constitute a pre-requisite for the rapid mastery of new manufacturing technologies and, therefore, are essential for the effective utilization of AMT. Ample proof is provided by the study of Daly et al [85] which examined the roles of machinery and skills in explaining comparative productivity differences between British and West German companies. Whilst it was found that the average age of British machinery was not very different from that of the machines in the German plants studied, it was subject to more frequent breakdowns and these breakdowns took longer to correct. It was also found that the full capabilities of the more advanced machines in British companies were often not fully exploited. Moreover, although British machinery was at least as new as German, it was much less technically advanced in terms of peripheral automation and control systems.

These results can all be attributed directly to the significant differences in the breadth and level of skill of the machine operators in the two countries. The key advantage of human-centred technology is that it is consciously designed to take account of and further develop craft skills and will, in effect, assist companies with their in-house training. This is especially important at a time when the system of vocational training in Britain is so weak [Sorge et al, 83:167] [Bessant & Haywood, 85:46].
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It would thus appear that a broad distribution of skills, in a work organization that encourages cohesiveness across functional and departmental boundaries, is a pre-requisite for achieving the combination of flexibility and increased productivity demanded by the market. In line with this, there is increasing evidence in the literature of the enrichment of shop-floor jobs associated with AMT, albeit with significant differences between the situation in the UK and other European countries.

For example, Haywood and Bessant [88], in a comparison of FMS/FMC in Sweden and the UK, found a much greater commitment in the former to the enhancement of shop-floor skills, the flattening of management hierarchies and devolution of responsibility to the shop-floor. This is reflected by the fact that on average just 6% of the overall system cost was spent on computer control in Sweden, as against 20% in the UK. This fact was attributed to both an over-dependence on data collection for close control in UK systems and a persistence in justifying systems on the basis of labour savings. This contrasts with the Swedish aim of freeing up skilled labour and redeploying it, but retaining what is held to be a necessary threshold of operator skills and numbers in the interest of both quality and flexibility. Despite the extra costs associated with the more important role played by humans in the Swedish systems studied, it is important to note that the turnover per employee was more than double that of the UK companies studied! It is also important to note that Haywood and Bessant perceived a cultural element in the importance attached to labour in the production process in Sweden, such that simple de-manning did not feature as a significant management objective when implementing new manufacturing technology.

Presented with such survey results it is interesting to reflect on the extent to which necessity will prove to be the mother of invention with respect to human-centred work design and the associated high level of shop-floor skills. As pointed out in an earlier chapter, disturbances in modern production systems are typically stochastic in nature, that is, unpredictable as to time and as to nature. Due to the high cost of advanced manufacturing technology, these disturbances must be overcome as rapidly as possible, which has important implications for those who operate the system. First, the system operators must have a wide range of skills, because the specific intervention that will be required is not known. Secondly, they cannot depend on supervision, because they must respond immediately to events that occur irregularly and without warning. Thirdly, they must be committed to undertaking the necessary tasks on their own initiative. The resultant dependence on the individual means that companies implementing highly automated systems will have no choice but to build into jobs the characteristics that will develop commitment on the part of the individual, that is, autonomy in the form of planning, self-control and self-regulation.

There is not only increasing support for a human-centred approach in the literature, but also an increasing number of projects adopting this approach and providing practical examples of the design and implementation of human-centred systems. Such experiments are essential, since, as pointed out by Blackler & Brown [86:305]:
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"Important though it is to challenge the rhetoric of technological determinism, on its own this is not enough. It is a mistake to assume that, once people have been alerted to the general principle of organizational choice, the versatility of the technologies in particular situations will become either immediately apparent or readily exploitable."

To date the most significant projects dedicated to the development of Human-Centred manufacturing systems have been the SERC/ACME-funded project "The Operation and Management of Flexible Human-Centred Turning Cells" and the CEC-funded ESPRIT Project 1217 entitled "Human-Centred CIM Systems". The key research themes have already been described in earlier chapters.

Further support for research to establish exemplary human-centred AMT projects has been forthcoming from the Department of Forecasting and Assessment in Science and Technology (FAST) within the Commission of European Communities (CEC). The role of FAST is to contribute to the definition of long-term CEC research and development objectives and priorities, and thus to the formulation of long-term science and technology policy. A recent FAST report has examined state-of-the-art AMT production systems in Europe and recommends the adoption of a human-centred perspective in the design of "third-generation AMT", that is, computer-integrated manufacturing systems [Broedner, 86c]. This report argues that the emphasis on traditional high volume mass production has fostered a "technocentric" approach to the design of manufacturing systems, with the objective of unmanned production. However, the future of European manufacturing seems to lie in "flexible specialization", that is, in the production of complex, customer-tailored, high quality products. It is argued that this type of production can be built on human resources and knowledge that already exists in European industry, and it is recommended that research be undertaken to develop the corresponding "computer and human-integrated manufacturing (CHIM) systems.

One of the significant successes of the project at Imperial College has been that it has provided the initiative for the CEC-funded ESPRIT Project 2415, entitled "Distributed Manufacturing, Planning and Control". In this project, which commenced in January 1989, Imperial College have been joined by RD Projects Ltd., Krupp Atlas Datensysteme GmbH and Harmonic Drive Antriebstechnik GmbH (User Company) from West Germany, and Delft University of Technology from the Netherlands. The project is based on the recognition of the fact that the majority of advanced manufacturing systems for small and medium batch production have been designed so as to reduce the amount of decision-making at the lower levels in the organizational hierarchy and to centralise authority at higher levels as far as possible. As has been described in earlier chapters, not only does this have the result that the systems do not perform satisfactorily, but has the deleterious side-effects of deskilling and lowering job satisfaction.

The primary stated objective of Project 2415 is to develop equipment to demonstrate that a higher level of efficiency and a greater level of job satisfaction can be obtained by maximising decision-making at the lowest possible levels. The three main aims are:

1) Decisions on alternative and most appropriate choices of action, which most closely match the company's overall plan, will be made at the lowest possible levels in the management hierarchy.
ii) Minimisation of the data transfer between adjacent levels of the manufacturing organization.

iii) The provision of hardware and software to achieve points i) and ii) in different versions suitable for small and medium batch production, and applicable to both small and large factories, whether new or existing.

It is believed that this will lead to greater manufacturing efficiency, together with a growth of job skills and job satisfaction, because:

- Authority and responsibility will be delegated to the lowest levels possible, that is, the levels that have the relevant experience and the most immediate data necessary to make the best judgements.
- The volume of data passing through the system will be substantially less than with present systems, resulting in a reduced communications overhead, a decrease in complexity and a more rapid response time.

The two key "products" to be developed as part of this project are the so-called Operator Management System (OMS), and Production Management Support System (PMS). The latter essentially is a computer with associated software for production planning at the cell level. The OMS incorporates a further development of the cell management support software developed by the author and described in Chapter 9.

An important innovation is that the OMS will be available in both a stand-alone PC-based version and in an on-machine version, where the software for cell production planning and control etc. is implemented on a CNC controller. The ability to split functions between the two versions of the OMS makes the software "compliant" in the sense that it can support different work organizations. As implied by the above description, the systems will be designed to satisfy human-centred design criteria.

Apart from offering an opportunity to extend present knowledge on the design of human-centred systems, the emphasis on developing distributed systems has interesting implications for both vendors and users. From the viewpoint of equipment suppliers, an important point made in Chapter 2 should be remembered, namely that the real expansion in the use of NC came with cheap distributed systems - perhaps the same will be true for other elements of CIM? For the user it is instructive to reflect on the following opinion, expressed by Williamson [71:154] almost twenty years ago, which has been confirmed many times by experience subsequently:

"Once an activity is expanded beyond its effective span of control it starts to go wrong, because minor errors and omissions are not detected and corrected immediately and become cumulative. These undetected errors have bedevilled attempts to use electronic data collection and processing systems to control large-scale batch manufacture. Only by redesigning the process to shrink the span of control, so that all the people concerned work in a closely knit environment conducive to detecting and eliminating errors as they occur, does data collection become reliable and control easy."
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As with the preceding projects, this new research is based on the belief that the importance of humans in advanced manufacturing systems in the future will not be reduced by AMT, but for reasons explained earlier in the thesis will increase! The continuing importance of humans rests, in turn, on the belief that technology will not crowd humans out. To date, attempts to develop unmanned manufacturing systems have not been marked by ubiquitous success and doubts are raised whether "tacit" knowledge can in fact be "automated". However, this debate has ethical and philosophical aspects beyond the scope of this thesis [Dreyfus,72] [Weizenbaum,84].

If, however, it is accepted on the basis of the above arguments that technology alone is not the answer, that is, the performance of a manufacturing system is dependent on human skills, then it is clear that if a revolution is to be brought about in manufacturing by the new technologies it will not be through integration of machine and computers alone, but will also depend, critically, on the successful integration of the technological hardware with its human and organizational "software".

The key pre-requisites for a Human-Centred Factory of the Future are then enlightened users and equipment suppliers, who recognize the "synergistic" benefits to be derived from adopting and promoting a human-centred philosophy respectively. Both are necessary if companies are to maximise the benefits of the new technologies whilst fully utilizing human resources and providing tasks and a working environment to attract, motivate and retain the required calibre of personnel at all levels.
Appendix

Notes on the Application of a Human-Centred Approach in an Industrial Setting

The objective of this Appendix is to briefly describe the author's efforts to employ a human-centred approach in the development of the production facility of Harmonic Drive Antriebstechnik GmbH, of Limburg an der Lahn, West Germany.

It is instructive to first describe the company history and the type of products to be produced by the new manufacturing plant. The name Harmonic Drive originates from the unique Harmonic Drive gears invented some 30 years ago in the USA by Walt Musser. Harmonic Drive gears combine very high reduction ratios (up to 320:1) with high torsional stiffness, high efficiency and minimal space requirements. This combination of features led to these gears being applied extensively in the US aerospace industry.

A joint-venture was subsequently undertaken with an established Japanese gear manufacturing company and the harmonic drive was developed further for more general application in mechanical engineering. A process of continuous development has resulted in a variety of different gearbox configurations and the extensive research programme has culminated in the development of the new, patented, IH tooth profile, which still further improves the properties of the gearboxes in terms of increased torsional stiffness and increased overload capacity.

Harmonic Drives are now widely used in industrial robots, printing machines, machine tools, medical equipment and increasingly in the European aerospace industry and other applications where compact, high precision gearing is needed.

In 1972 Harmonic Drive System GmbH (HDS) was founded in West Germany to sell Harmonic Drive gears and gearboxes from Japanese production throughout the European market. The increasing importance of electronics in motion control and increasing customer requirements for system solutions led, in 1984, to the founding of Harmonic Drive Antriebstechnik GmbH (HDA). This company is engaged in the development of special customer-specific servo systems and complete motion control systems.

Both HDS and HDA were originally situated in Langen near Frankfurt am Main, but the facilities there proved too small for the increasing range of activities and in 1988 a new factory building was constructed in Limburg an der Lahn, situated some 60 km north from Frankfurt am Main. The joint company has at the time of writing 60 employees and had a turnover of over 40 million DM in 1989.
Appendix

The newly established Production Department, which the author manages, currently has 9 employees and deals with the manufacture, assembly and test of customer-specific servo systems and motion control systems. This work includes the assembly and test of servo amplifiers and position control systems, but here the discussion will focus on machining activities, that is, the manufacture of gearboxes, such as the HDGM series described in Chapter 8.

For these gearboxes and customer-specific servo actuators incorporating Harmonic Drive gearsets, various housings, flanges and shaft-type components must be machined to exacting precision and quality requirements. Accordingly, the machine shop equipment implemented to date features a high proportion of computer-numerically controlled (CNC) machine tools, including turning and machining centres, as shown in Figures A.1 and A.2. This advanced manufacturing equipment is matched by comprehensive inspection equipment including a co-ordinate measuring machine, as shown in Figure A.3. The layout of the Machine Shop, Material Stores and Metrology Room are shown in Figure A.4.

For the purposes of machining rotational components for the HDGM series gearboxes described earlier, a cell is currently being completed, that will ultimately incorporate two turning centres, a machining centre and a CNC slotting machine. This cell will form the shop-floor end of the proposed demonstration for ESPRIT Project 2415.

Figure A.1 Index GFG 250 CNC Turning Centre

![Index GFG 250 CNC Turning Centre](image)
Appendix

Figure A.2  Maho MH700S CNC Milling Machine

Figure A.3  Mitutoyo B706 Co-ordinate Measuring Machine
b) Material Stores

\[\text{Appendix}\]

\[\text{Sheet-metal Storage}\]

\[\text{Bar Stock}\]

\[\text{BL}\]

\[\text{BL}\]

\[\text{BS}\]

\[\text{S}\]

\[\text{KASTO HB360 autom. Saw}\]

\[\text{Moessner Rekord Bandsaw}\]

\[\text{Sheet-metal machines}\]

\[\text{Saw}\]

\[\text{c) Metrology Room}\]

\[\text{Workbench}\]

\[\text{Autom. doors}\]

\[\text{MITUTOYO B706 Coordinate-measuring m/c}\]

\[\text{JFA Surface Plate}\]

\[\text{TESA Micro-Hite Measuring m/c}\]

\[\text{Storage}\]

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The company has already implemented computer-aided design (CAD) and computer-aided production planning and control (PPC) systems, as shown in Figure A.5. This figure shows already the Operator Management System (OMS), to be implemented as part of the ESPRIT Project. In its current form the HDGIVI cell is manned by three operators. One operator mans the turning centre (later both turning centres), the second the milling and slotting machines, whilst the third prepares CNC part programs and undertakes production control tasks. These operators rotate jobs at regular intervals to develop a comprehensive skill-base. To facilitate shop-floor programming great attention has been paid to the selection of CNC controls and PC software suitable for workshop use.
Appendix

Great importance has also been attached to training, to ensure that production personnel are well equipped to deal with the high level of individual responsibility. All the senior workshop personnel had prior knowledge of CNC programming from technical college evening courses, and one had extensive experience from previous employment. This knowledge has been increased by further courses at the machine tool manufacturers on more advanced CNC programming techniques and machine maintenance. The company has also sponsored evening courses on Personal Computer fundamentals, such as the MS-DOS operating system and the BASIC programming language. These additional skills have already been put to good use in the preparation of tooling data files and in various work planning tasks.

Although a good working atmosphere is more likely anyway in a "polyvalently" organized small company, morale is exceptionally high (reflected in extensive unpaid overtime!!) and all major objectives to date have been met on time and within budget.

It must be pointed out, however, that great care has been taken in selecting new personnel, to ensure that new staff react positively to high levels of responsibility and to "team-working". Experience has shown that different people respond more or less favourably to the perceived intrinsic rewards, such as increased autonomy and task identity, characteristic of human-centred work design.

The importance of a "project champion" for the implementation of a human-centred system or work design has also been shown clearly. The author has weathered considerable initial scepticism from both colleagues and equipment vendors with respect to the benefits of devolving responsibility to the shop-floor in terms of CNC programming and work planning. However, the obvious benefits to the company of highly-motivated shop-floor personnel have greatly moderated initial doubts.

It has been interesting to note the influence of the technical media and advertising on the attitudes of fellow engineering staff. The author's decision to encourage shop-floor programming, despite the comparative complexity of the components to be machined, was viewed as "heretical" by some design staff convinced of the apparent advantages of integrated CAD/CAM and office-based programming. Subsequent experience of the importance of feedback from the shop-floor on "design for manufacture" and "design for assembly" has again modified the initial standpoint, such that the high level of responsibility enjoyed by machine-shop personnel is widely accepted and approved of.

Clearly at this comparatively early stage it is difficult to make definite conclusions, but the progress from initial machine installation to series production of gearboxes in under 12 months is a thoroughly satisfactory performance in its own right and is, in the author's view, directly attributable to the high job satisfaction resulting from a human-centred approach to the selection of technology and to work design.
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